SEAONC 1999 Spring Seminar

Seismic Risk Analysis: Probable Maximum Loss and Related Topics

1999 Spring Seminar
March 11 & 18, 1999

Presented by the
Structural Engineers Association of Northern California

SEISMIC RISK ANALYSIS: PROBABLE MAXIMUM LOSS AND RELATED TOPICS

INDEX

Earthquake Damage and Loss Estimation
FEMA/NIBS Methodology - HAZUS

Presenter: CHARLES A. KIRCHER
Kircher & Associates

SEAONC 1999 Spring Seminar
Seismic Risk Analysis: Probable Maximum Loss
and Related Topics

Earthquake Damage and Loss Estimation FEMA/NIBS Methodology - *HAZUS*

Charles A. Kircher, Ph.D., P.E.
Kircher & Associates

March 11, 1999

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Presentation Topics

- Background - Regional Earthquake Loss Estimation
- Overview of FEMA/NIBS Project (*HAZUS*)
  - Methodology Components
  - Building Damage and Loss Functions
- Building Damage Examples - 1995 Kobe Earthquake
- *HAZUS* Building Damage Functions
  - Building Types and Occupancies
  - Structural and Nonstructural Damage States
  - Capacity Curves - Estimating Building Response
  - Fragility Curves - Estimating Building Damage
- Comparison of Predicted and Observed Losses
  - Economic Loss to Residences - 1994 Northridge Earthquake
- Building-Specific Analysis - Judging Mitigation Benefits

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Seismic Risk Glossary

- *Hazard* - Earthquake (ground shaking or failure)
- *Damage* - Physical effects of *hazard* on infrastructure
- *Loss* - Direct or indirect economic, social or functional consequence of occurrence of *damage*
- *Fragility* (or *Vulnerability*) - Degree or extent of *damage* (or *loss*) associated with *hazard.*
- *Risk* - Potential *loss* associated with *hazard*

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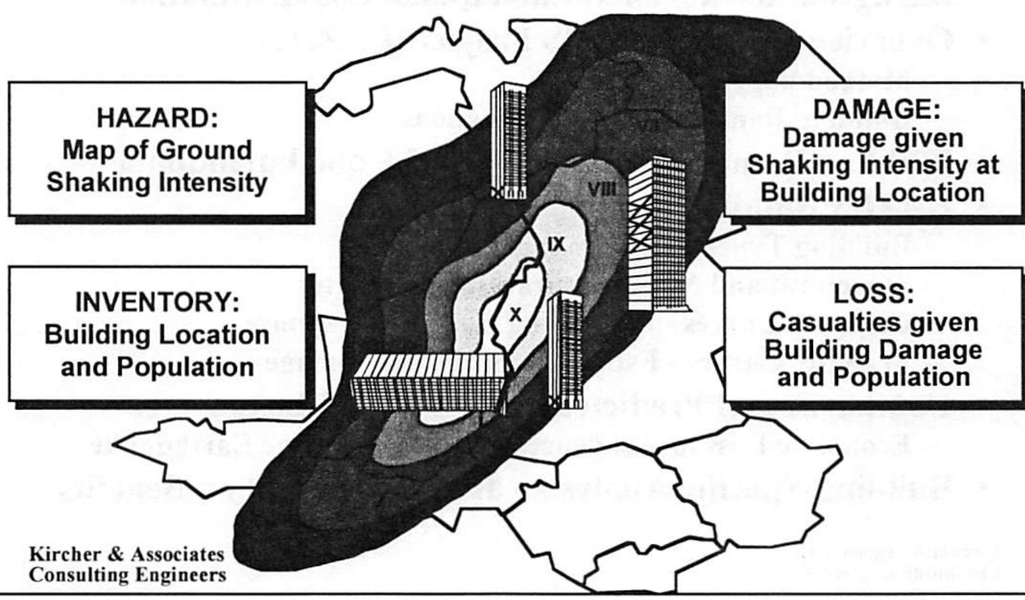
Example Regional Earthquake Loss Estimate: Predicting Building Casualties



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Regional Loss Estimation Milestones

- **1971 San Fernando Earthquake**
- **1972/1973 San Francisco and Los Angeles Studies**
  - ***A Study of Earthquake Losses in the San Francisco Bay Area*, Algermissen, Rinehart, Steinbrugge, Degenkolb, Cluff, McClure, Gordon, Scott, Lagorio (NOAA, 1972)**
  - ***A Study of Earthquake Losses in the Los Angeles Area*, Algermissen, Hopper, Campbell, Rinehart, Perkins, Steinbrugge, Lagorio, Moran, Cluff, Degenkolb, Duke, Gates, Jacobsen, Olsen, Allen (NOAA, 1973)**
- **1985 Applied Technology Council Study - *ATC-13***
  - ***Earthquake Damage and Evaluation Data for California***
- **1989 National Research Council - *Panel Report***
  - ***Estimating Losses From Future Earthquakes***

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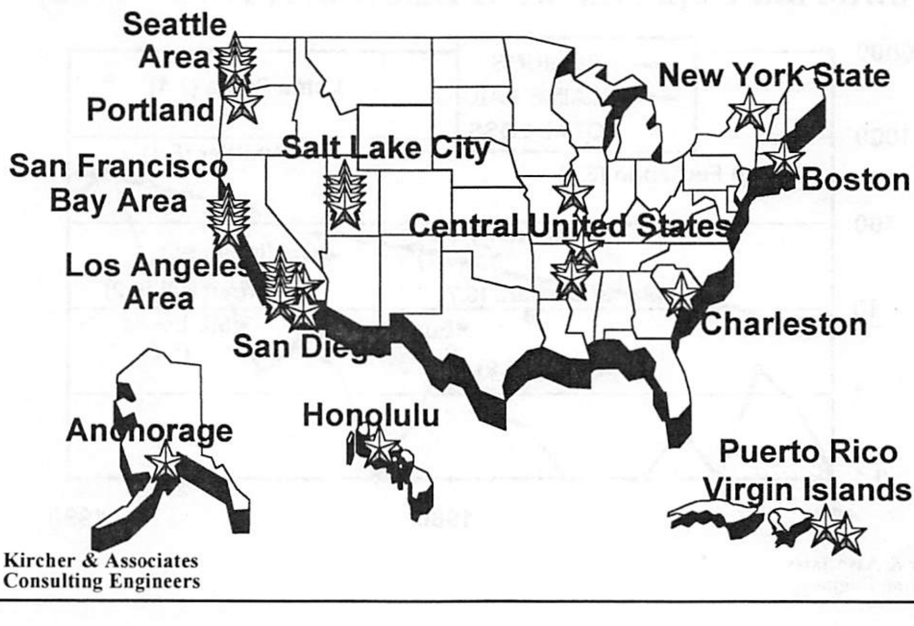
Major Regional Earthquake Loss Studies



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An Assessment of the Consequences of a Catastrophic California Earthquake (FEMA, 1980)

Fault Creating the Earthquake	Magnitude	Deaths	Hospital Injuries	Property Damage
San Andreas (Los Angeles)	8.3	3,000 to 12,000	12,000 to 48,000	$20 Billion to $50 Billion
Newport-Inglewood	7.5	4,000 to 21,000	16,000 to 84,000	$30 Billion to $60 Billion
San Andreas (San Francisco)	8.3	3,000 to 11,000	12,000 to 44,000	$20 Billion to $40 Billion
Hayward	7.5	1,000 to 3,000	4,000 to 10,000	$5 Billion to $20 Billion

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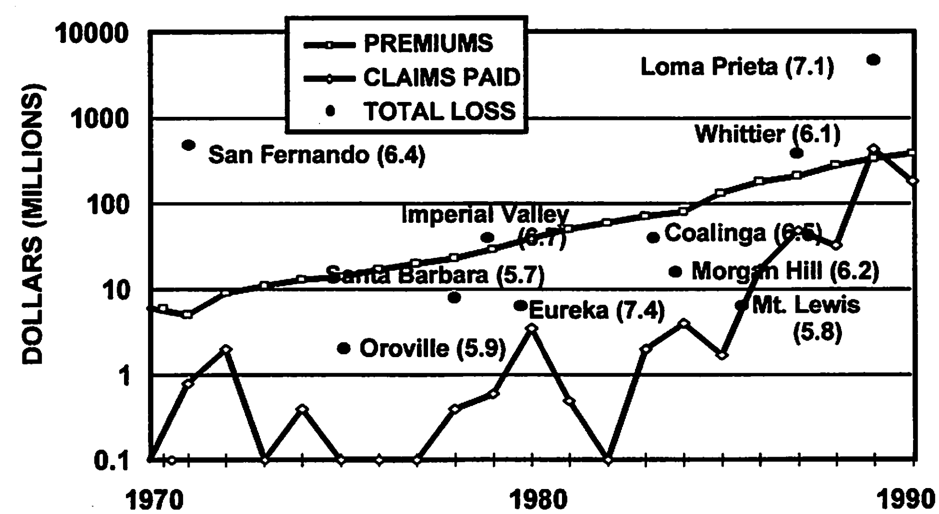
Earthquake Insurance - Premiums and Claims Paid (California Department of Insurance, 1970 - 1990)



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Potential Users of Earthquake Loss Studies

- **Local, State and Regional Officials:**
  - Stimulate earthquake mitigation efforts
  - Prepare for emergency response and recovery
- **Federal Officials:**
  - Assess nationwide risk of loss from earthquakes
- **Emergency Personnel:**
  - Prepare detailed emergency response plans
  - Assist post-earthquake response and recovery actions
- **Owners:**
  - Identify (strengthen) vulnerable structures and lifelines
- **Insurance and Financial Personnel:**
  - Establish appropriate premiums and loan criteria
- **Building Officials and Engineers:**
  - Improve development of seismic codes and guidelines

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HAZUS Earthquake Loss Estimation Project Sponsors, Advisors & Consultants

- **Funding Agency**
  - Federal Emergency Management Agency (FEMA)
    - Earthquake and Natural Hazard Programs
- **Conducting Agency**
  - National Institute of Building Sciences (NIBS)
    - Project Working Group - Technical Oversight
    - Project Oversight Committee - User Perspectives
- **Contractors**
  - RMS Team - Methodology and HAZUS software
  - EQE and Dames & Moore Teams - Pilot Studies

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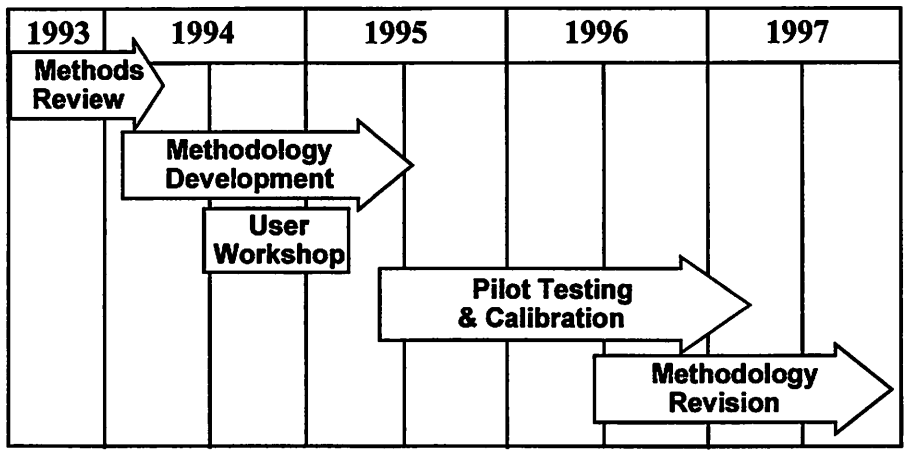
HAZUS Earthquake Loss Estimation Project Tasks and Schedule



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HAZUS Earthquake Loss Estimation Project Summary of Key Features

- State-of-the-Art-Methods
  - Response spectra (rather than MMI) characterize ground shaking demand
  - Nonlinear capacity "pushover" curves characterize building capacity/response properties (engineering approach)
  - Fragility curves estimate probability of physical damage to the structure, nonstructural components and contents
  - Loss functions "de-couple" damage from loss prediction
- Multiple Levels of Analysis
  - Level 1 - Crude estimates based on minimum User input
  - Levels 2/3 - More detailed estimates based on improved inventory information, soil profile data, etc.
- Software - GIS platform (MapInfo) runs on PC's

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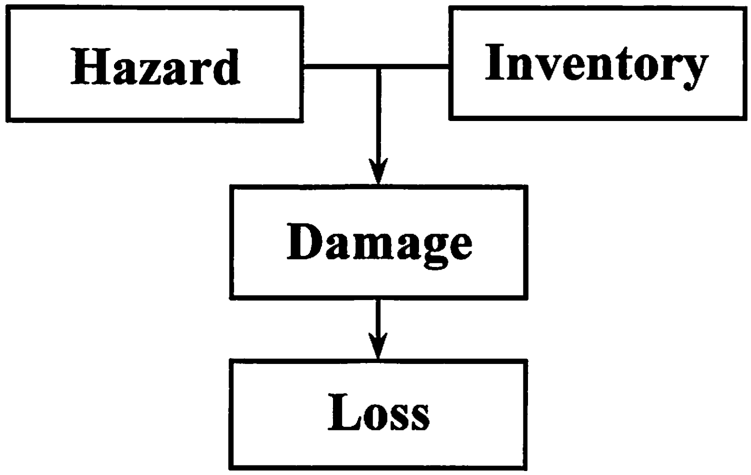
HAZUS Methodology Components



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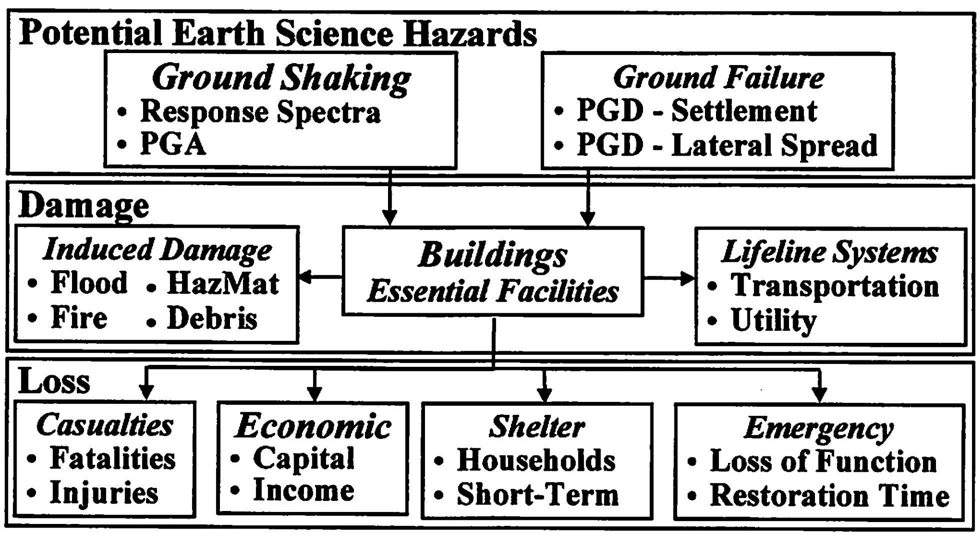
HAZUS Building-Related Components



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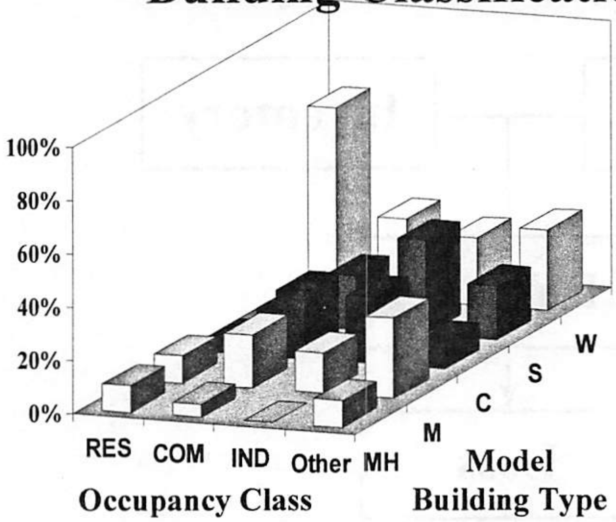
Building Classification Schemes



28 Occupancy Classes

- Residential (6)
- Commercial (10)
- Industrial (6)
- Other (6)

36 Building Types

- Wood (2)
- Steel (13)
- Concrete (13)
- Masonry (7)
- Mobile Home

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Seismic Design/Performance Levels

Current-Code Design Level *UBC Zone (NEHRP Area)*	Performance Level		
	Superior	*Ordinary*	*Inferior*
Zone 4 (Map Area 7)	Special High-Code	High-Code	
Zone 2B (Map Area 5)		Moderate-Code	
Zone 1 (Map Area 3)		Low-Code	Pre-Code

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Building Damage States

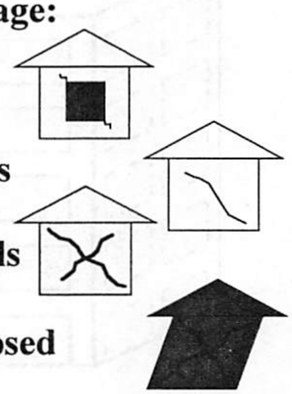
- Described in terms of physical damage to the structural system and nonstructural components of the building
- Example Descriptions of Structural Damage:

SLIGHT Small cracks at openings

MODERATE Small shear cracks in walls

EXTENSIVE Large shear cracks in walls

COMPLETE Structure racked or collapsed



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Building Damage Functions

- **Capacity (Push-Over) Curves:**

  Describe peak building response (e.g., peak lateral displacement) as a function of ground shaking demand, explicitly considering the nonlinear, inelastic properties of the structural system

- **Fragility Curves:**

  Describe the probability of either Slight, Moderate, Extensive or Complete damage to the structural system, nonstructural drift-sensitive components and nonstructural acceleration-sensitive components, respectively

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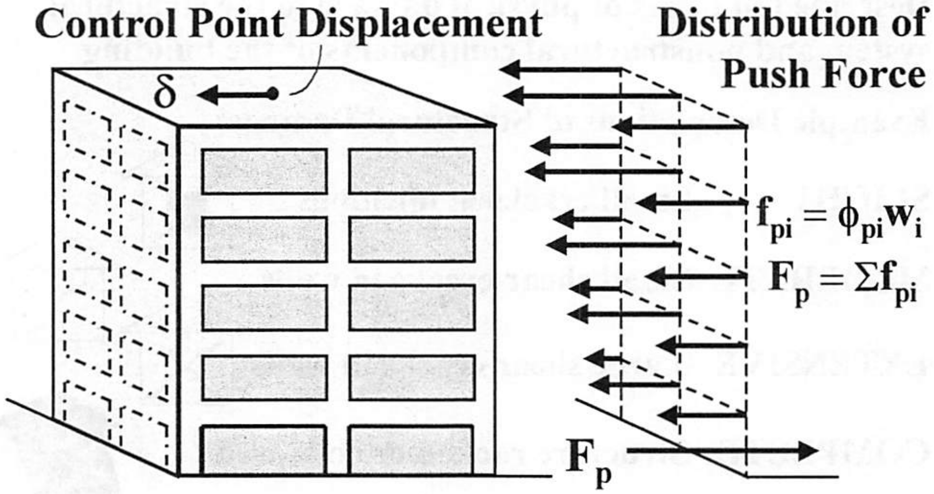
Example: Lateral Push on Building



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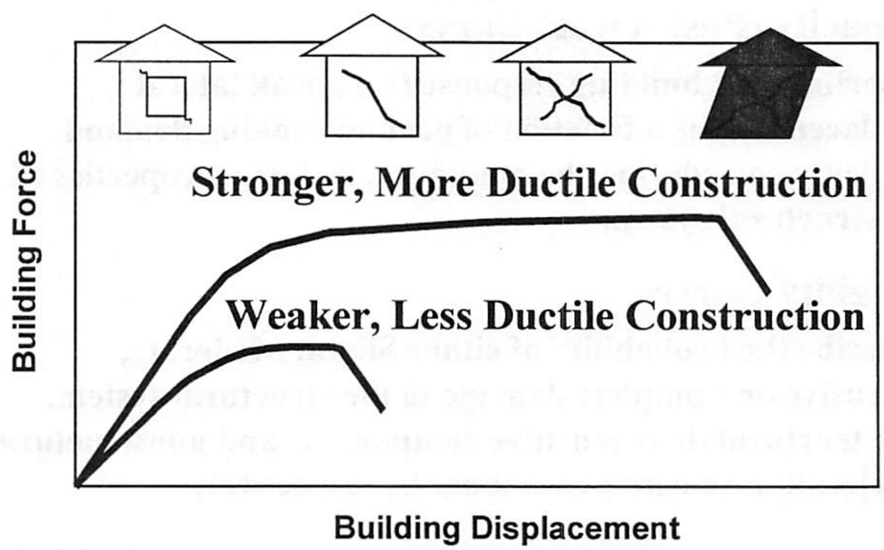
Schematic Building Capacity



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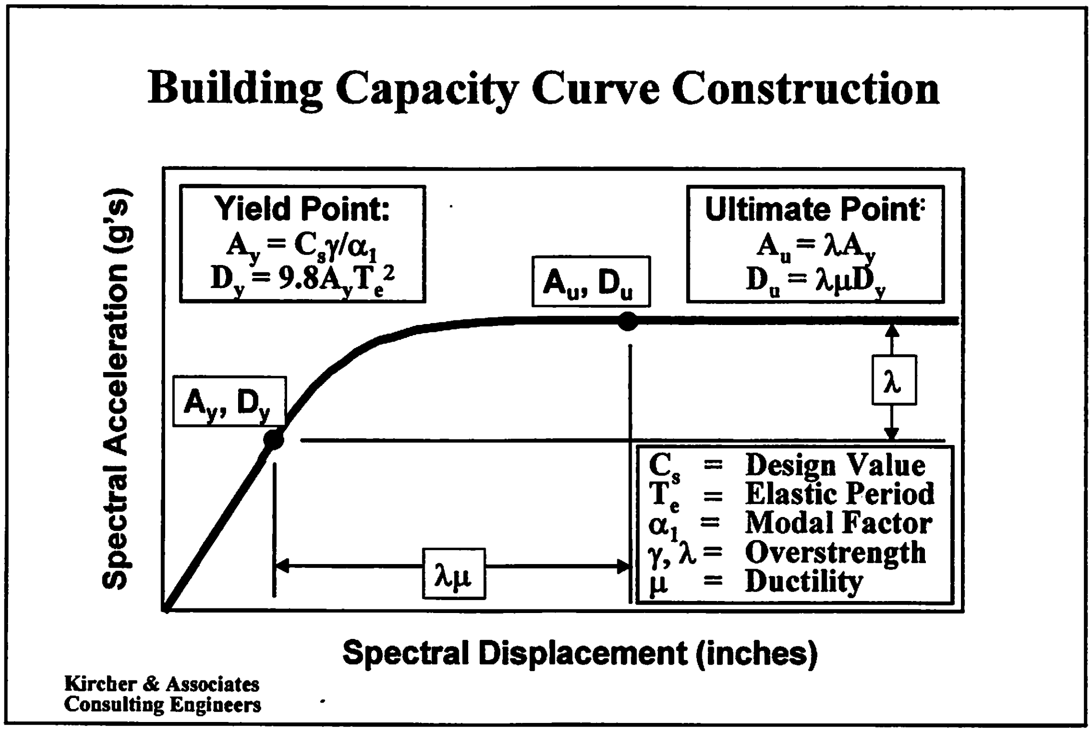
Building Capacity Curve Construction
Yield Point:
A_y = C_sγ/α_1
D_y = 9.8A_yT_e^2
Ultimate Point:
A_u = λA_y
D_u = λμD_y
A_u, D_u
A_y, D_y
λ
λμ
C_s = Design Value
T_e = Elastic Period
α_1 = Modal Factor
γ, λ = Overstrength
μ = Ductility
Spectral Acceleration (g's)
Spectral Displacement (inches)
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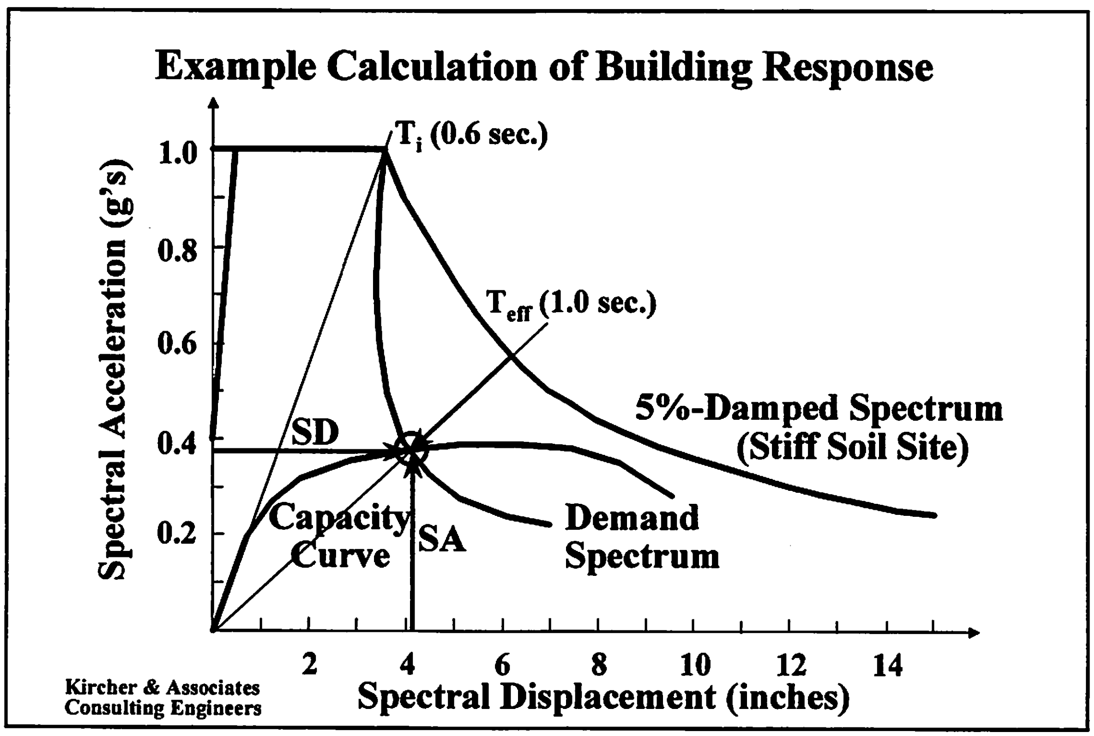
Example Calculation of Building Response
T_i (0.6 sec.)
T_eff (1.0 sec.)
5%-Damped Spectrum
(Stiff Soil Site)
SD
SA
Capacity
Curve
Demand
Spectrum
1.0
0.8
0.6
0.4
0.2
2
4
6
8
10
12
14
Spectral Acceleration (g's)
Spectral Displacement (inches)
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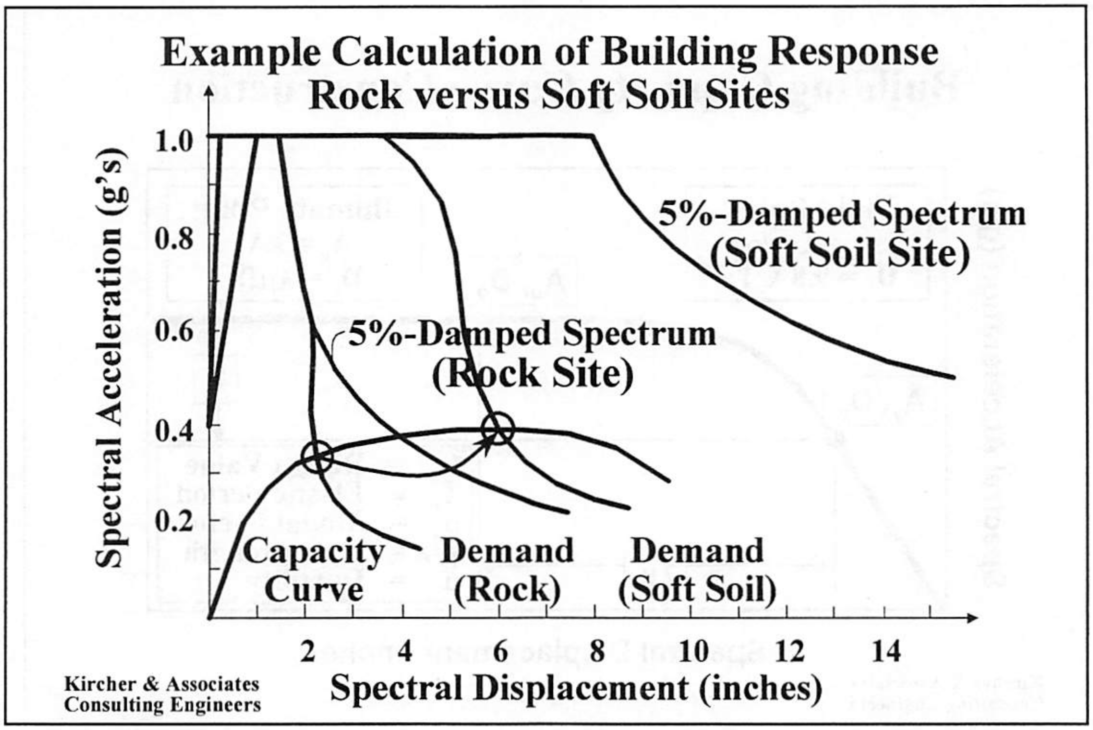
Example Calculation of Building Response
Rock versus Soft Soil Sites
1.0
0.8
0.6
0.4
0.2
Spectral Acceleration (g's)
5%-Damped Spectrum
(Soft Soil Site)
5%-Damped Spectrum
(Rock Site)
Capacity
Curve
Demand
(Rock)
Demand
(Soft Soil)
2
4
6
8
10
12
14
Spectral Displacement (inches)
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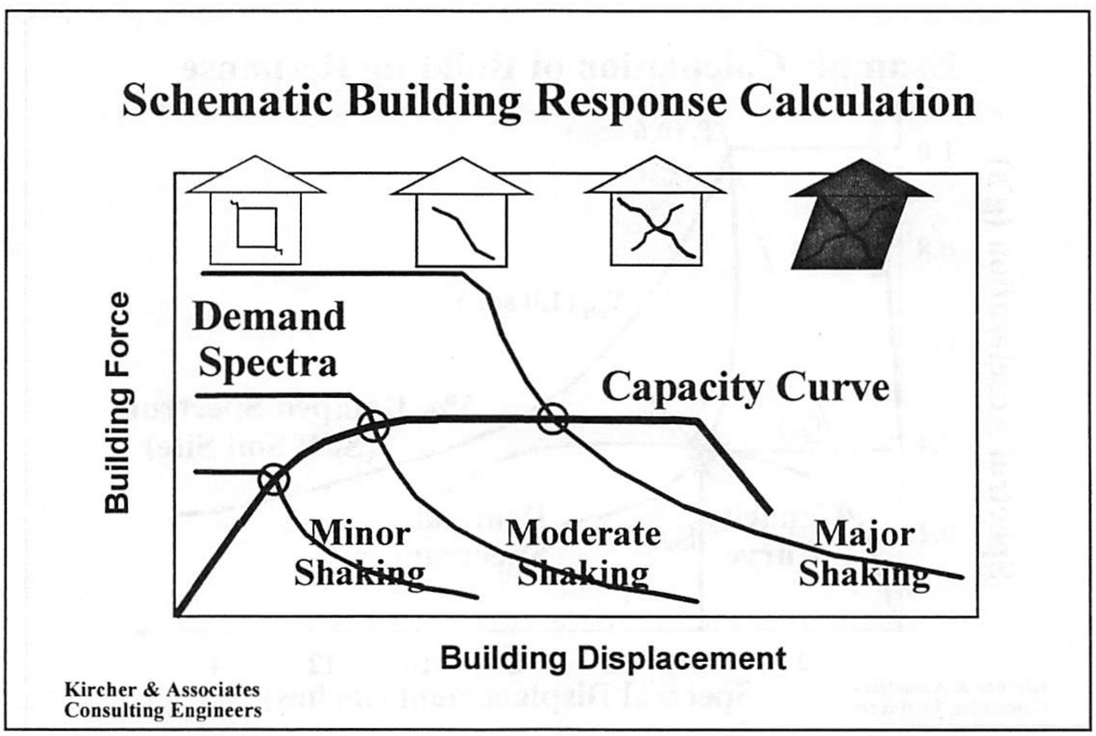
Schematic Building Response Calculation
Demand
Spectra
Capacity Curve
Building Force
Minor
Shaking
Moderate
Shaking
Major
Shaking
Building Displacement
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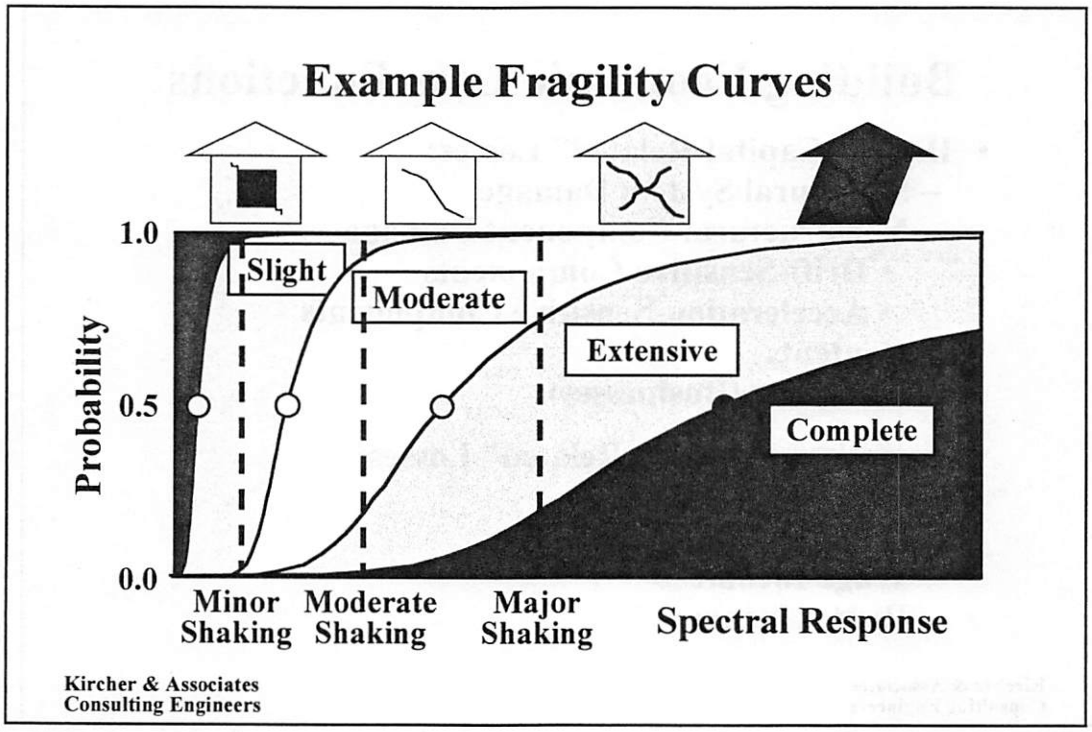
Example Fragility Curves
1.0
0.5
0.0
Probability
Slight
Moderate
Extensive
Complete
Minor Shaking
Moderate Shaking
Major Shaking
Spectral Response
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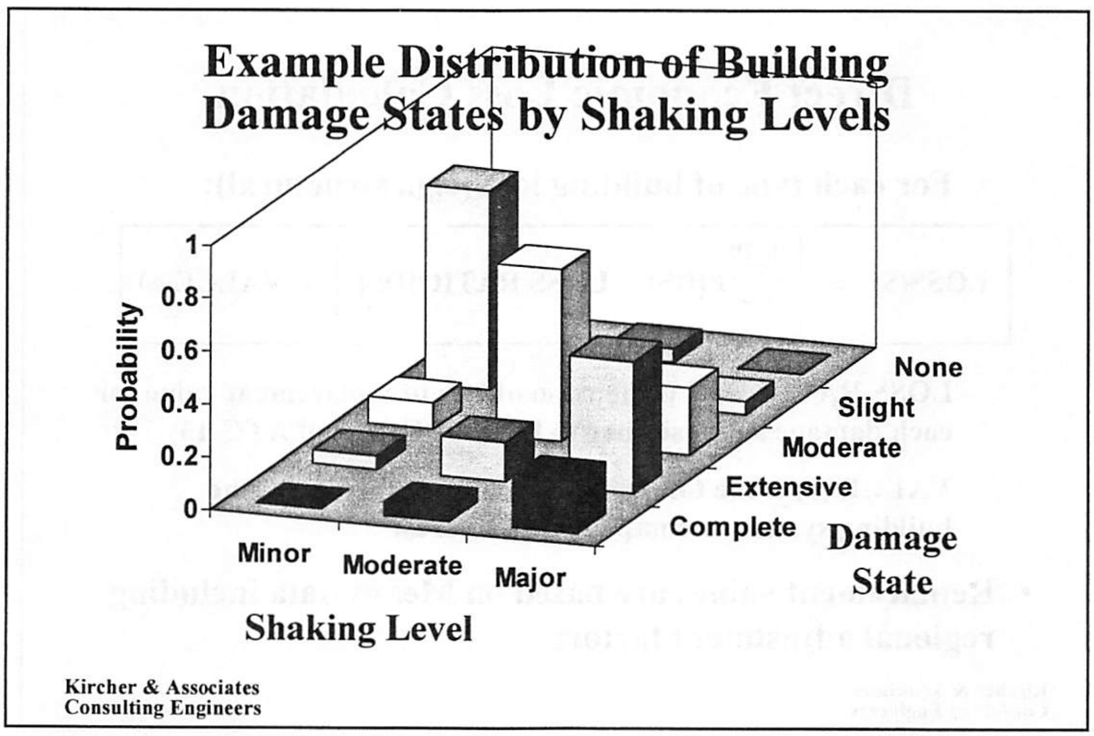
Example Distribution of Building Damage States by Shaking Levels
Probability
1
0.8
0.6
0.4
0.2
0
None
Slight
Moderate
Extensive
Complete
Damage State
Minor
Moderate
Major
Shaking Level
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Building Economic Loss Functions

- Direct "Capital-Related" Losses:
  - Structural System Damage
  - Nonstructural Component Damage
    - Drift-Sensitive Components
    - Acceleration-Sensitive Components
  - Contents
  - Inventory (Businesses)
- Secondary "Income-Related" Losses:
  - Relocation Expenses
  - Investment Income
  - Wage Income
  - Rental Income

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Direct Economic Loss Calculation

- For each type of building loss (e.g., structural):

$$\text{LOSS(\$)} = \left\{ \sum^{\text{all}\cdot\text{DS}} \text{P[DS]} \cdot \text{LOSS RATIO[DS]} \right\} \times \text{VALUE(\$)}$$

  - LOSS RATIO [DS] is the ratio of loss to replacement value for each damage state (similar to Damage Factor of ATC-13)
  - VALUE ($) is the total dollar replacement value of the building system or component of interest
- Replacement values are based on Means data including regional adjustment factors

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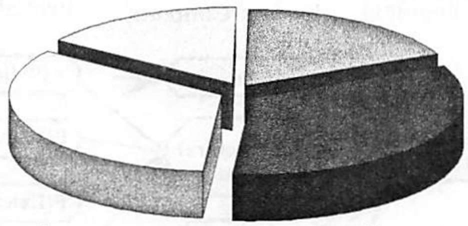
Example Single-Family Residence Replacement Values (Los Angeles County)

Structural System
(RES1/W1: $18.00)

Building Contents
(RES1/W1: $38.40)



Nonstructural - Acceleration Sensitive
(RES1/W1: $20.40)

Nonstructural - Drift Sensitive
(RES1/W1: $38.40)

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Loss Ratios for the Structural System, Nonstructural Components and Contents of Single-Family Residences (L. A. County)

Damage State	Loss Ratio	Example Loss[1]
Complete	100% (50% Contents)	$100/sq. ft.
Extensive	50% (25% Contents)	$50/sq. ft.
Moderate	10% (5% Contents)	$10/sq. ft.
Slight	2% (1% Contents)	$2/sq. ft.

1. Based on replacement values of $80/sq. ft. for the structural system and nonstructural components, and $40/sq. ft. for building contents

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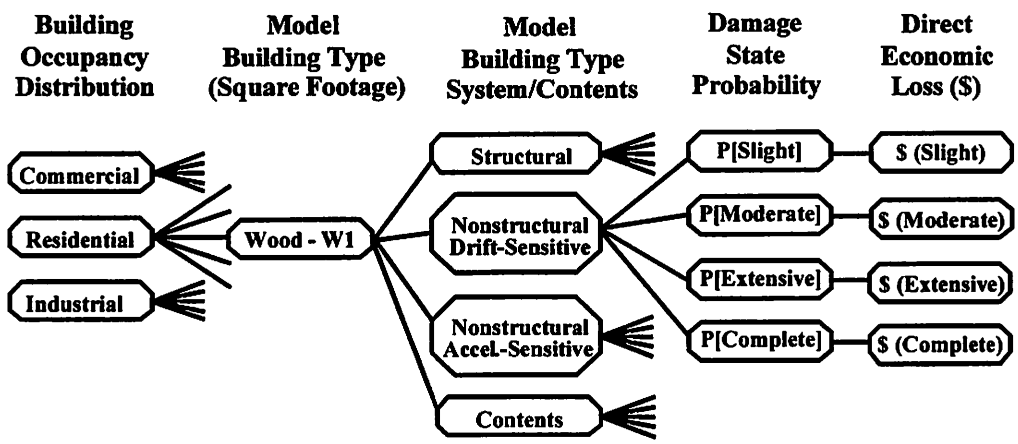
Logic Tree for Calculation of Direct Economic Loss to Buildings



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1994 Northridge Earthquake Calibration Study

- **Inventory - Los Angeles County Study Region**
  - 2,254,000 buildings worth $465 billion (w/o contents)
  - 2,023,000 residences worth $339 billion (w/o contents)
  - Residential buildings are more than 95% wood frame, 29% Pre-1941, 55% 1941 - 1976, 16% Post-1976
- **Observed Direct Economic Loss**
  - $26 billion in property damage
  - $20 billion in building damage
  - $13 billion in residential building damage

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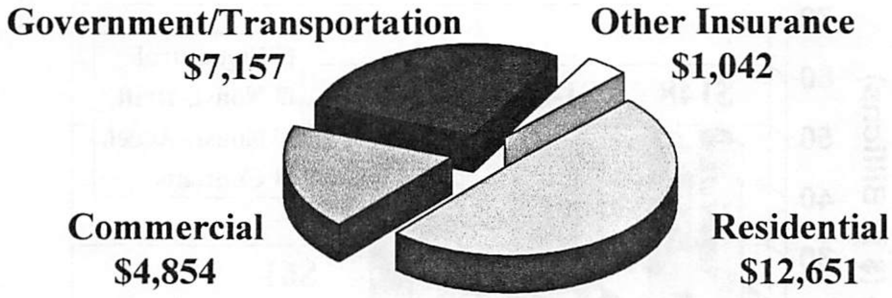
Distribution of Northridge Recovery and Reconstruction Funds by Major Use[1]



Funds in Millions
(Total = $25.7 Billion)

1. Comerio, 1997, based on California Department of Insurance, U.S. Office of Management and Budget, Governor's Office of Emergency Services

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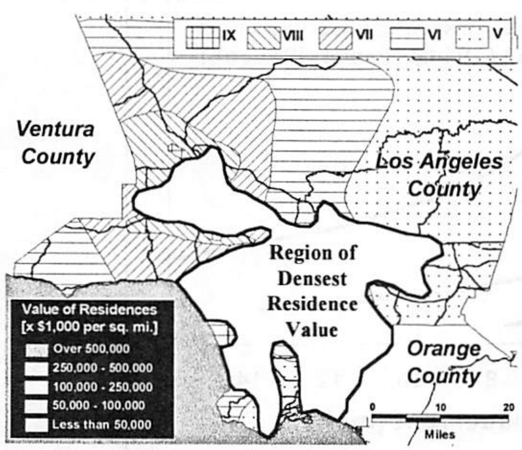
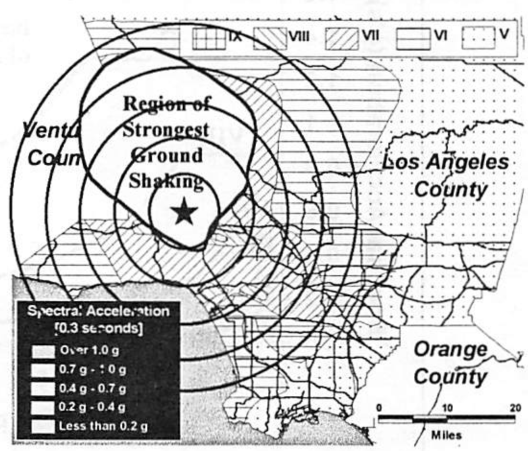
Maps of Los Angeles County 1994 Northridge Earthquake Ground Shaking

Residential Value/MMI **Spectral Acceleration/MMI**





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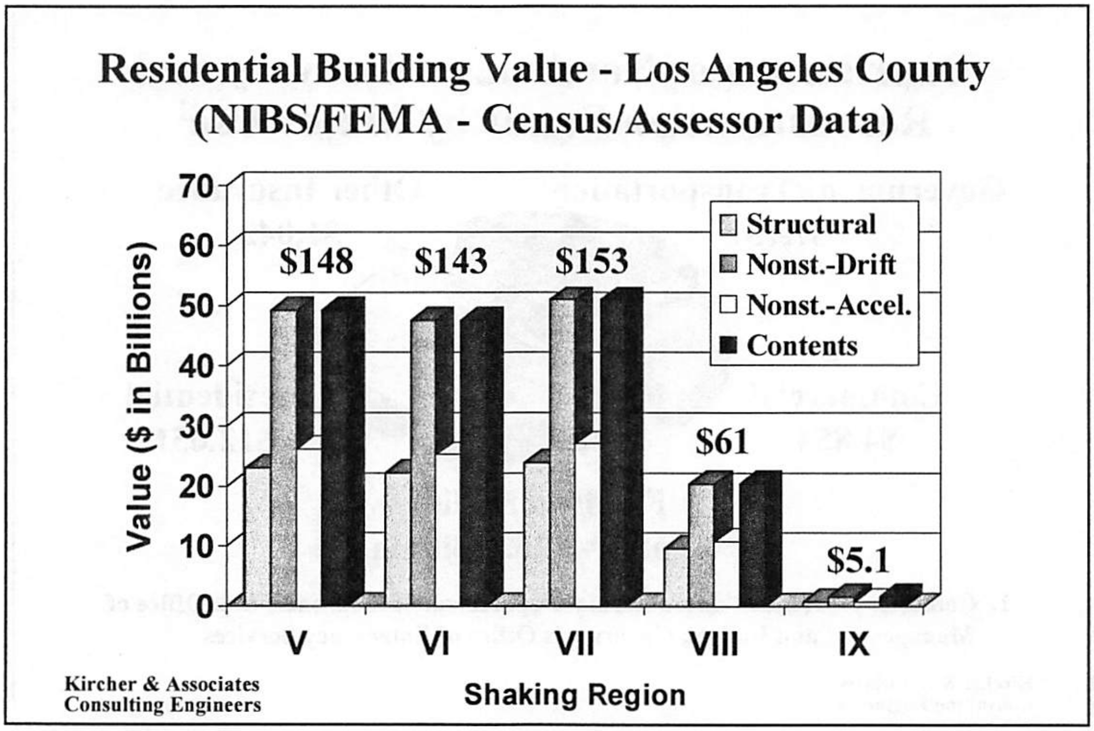

Residential Building Value - Los Angeles County
(NIBS/FEMA - Census/Assessor Data)
Structural
Nonst.-Drift
Nonst.-Accel.
Contents
$148
$143
$153
$61
$5.1
Value ($ in Billions)
0
10
20
30
40
50
60
70
V
VI
VII
VIII
IX
Shaking Region
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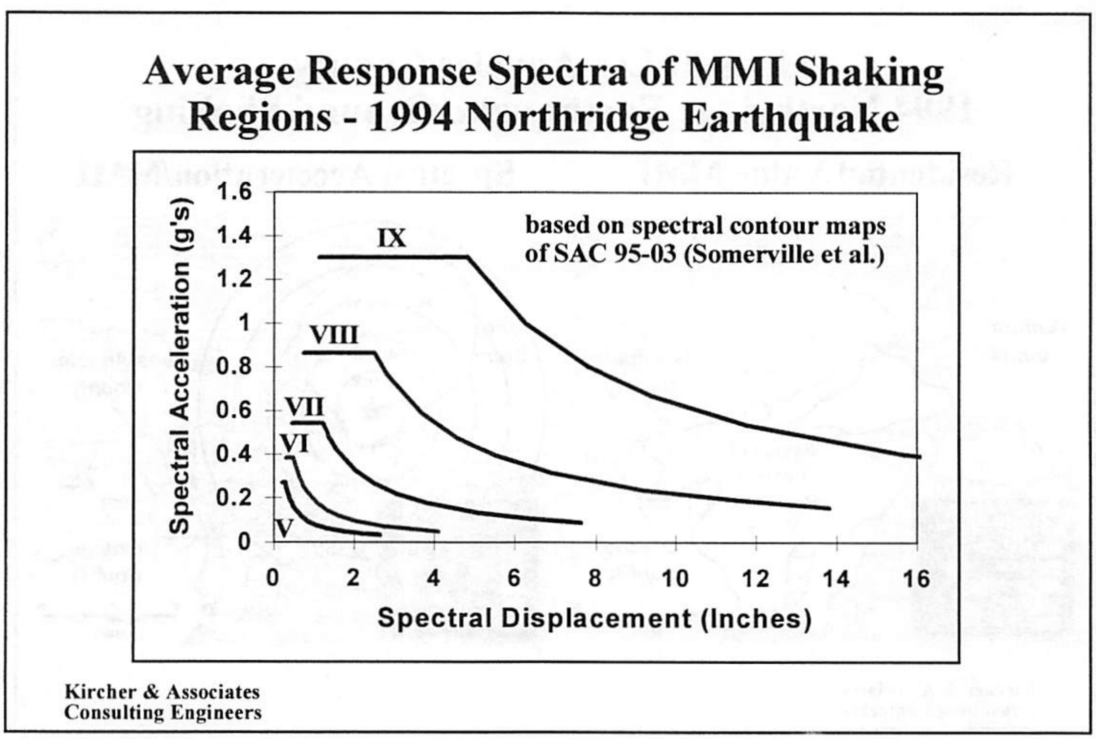

Average Response Spectra of MMI Shaking Regions - 1994 Northridge Earthquake
based on spectral contour maps
of SAC 95-03 (Somerville et al.)
IX
VIII
VII
VI
V
Spectral Acceleration (g's)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
2
4
6
8
10
12
14
16
Spectral Displacement (Inches)
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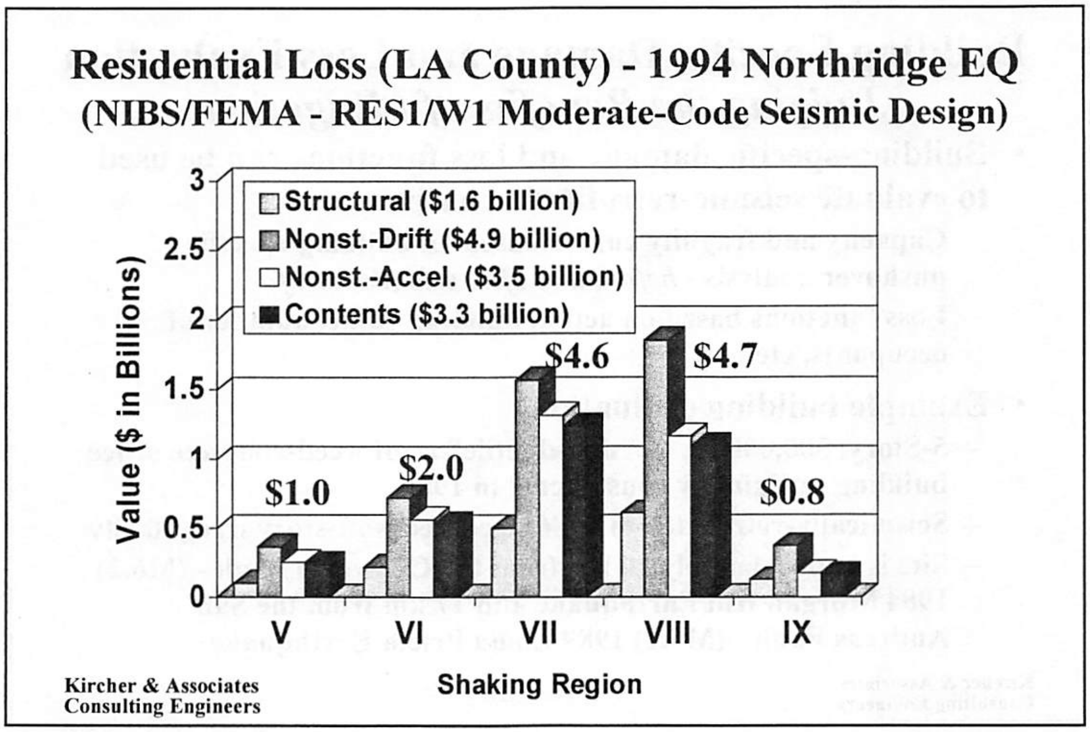
Residential Loss (LA County) - 1994 Northridge EQ
(NIBS/FEMA - RES1/W1 Moderate-Code Seismic Design)
Structural ($1.6 billion)
Nonst.-Drift ($4.9 billion)
Nonst.-Accel. ($3.5 billion)
Contents ($3.3 billion)
Value ($ in Billions)
3
2.5
2
1.5
1
0.5
0
$1.0
$2.0
$4.6
$4.7
$0.8
V
VI
VII
VIII
IX
Shaking Region
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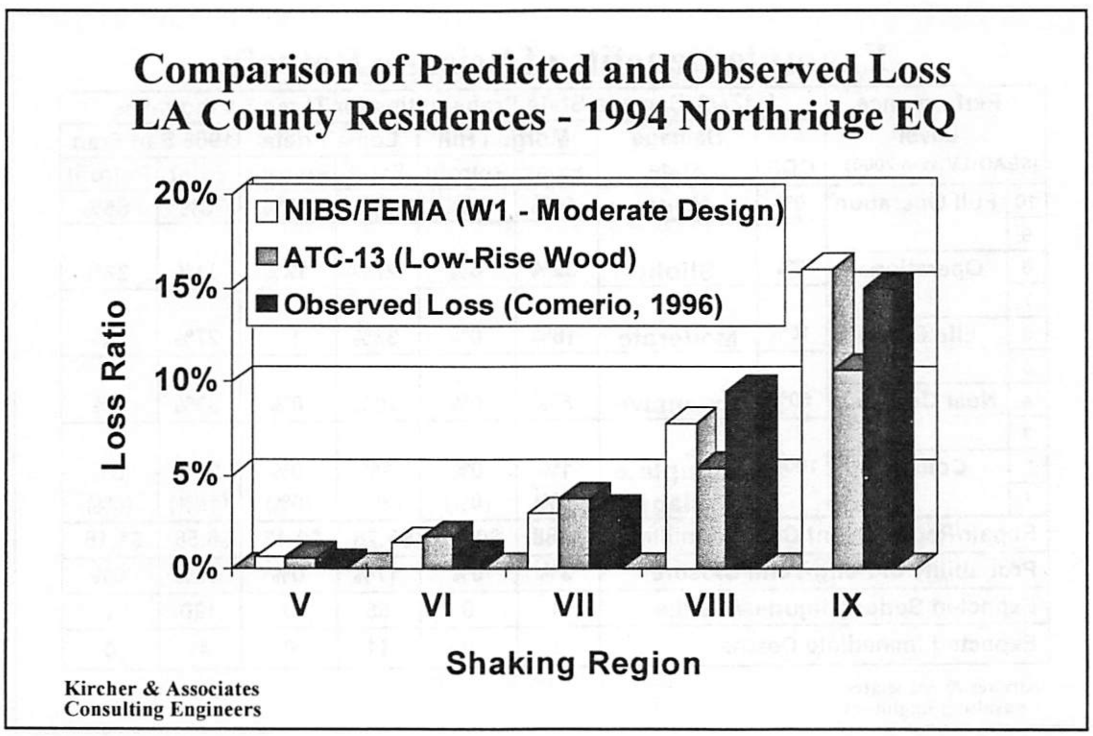
Comparison of Predicted and Observed Loss
LA County Residences - 1994 Northridge EQ
NIBS/FEMA (W1 - Moderate Design)
ATC-13 (Low-Rise Wood)
Observed Loss (Comerio, 1996)
Loss Ratio
20%
15%
10%
5%
0%
V
VI
VII
VIII
IX
Shaking Region
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Building-Specific Damage and Loss Evaluation
Judging the Benefits of Mitigation

- **Building-specific damage and loss functions can be used to evaluate seismic-retrofit alternatives**
  - Capacity and fragility curves based on building-specific pushover analysis - *before and after seismic retrofit*
  - Loss functions based on actual building value, number of occupants, etc.
- **Example building evaluation**
  - 5-Story, 300,000 sq. ft. "non-ductile" reinforced-concrete office building - originally constructed in 1968
  - Seismically-retrofitted in 1986 to correct soft-story irregularity
  - Site is approximately 10 km from the Calaveras Fault - (M6.2) 1984 Morgan Hill Earthquake and 17 km from the San Andreas Fault - (M7.1) 1989 Loma Prieta Earthquake

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Example Benefits of Seismic Retrofit

Performance Level (SEAOC Vision 2000)		*HAZUS* Damage-State Probabilities for Three Earthquakes							
		CDF	Damage State	Morgan Hill		Loma Prieta		1906 San Fran	
				Exist	Retrofit	Exist	Retrofit	Exist	Retrofit
10	Full Operation	0%	None	44%	93%	13%	87%	3%	66%
9									
8	Operational	2%	Slight	32%	6%	27%	12%	11%	27%
7									
6	Life Safety	10%	Moderate	18%	0%	33%	1%	27%	6%
5									
4	Near Collapse	50%	Extensive	5%	0%	20%	0%	33%	0%
3									
2	Collapse	100%	Complete	1%	0%	7%	0%	26%	0%
1			(Collapse)	(0%)	(0%)	(3%)	(0%)	(10%)	(0%)
Repair/Replacement Cost (in millions)				$0.88	$0.28	$3.78	$0.47	$8.56	$1.16
Probability of Long-Term Closure				3%	0%	17%	0%	43%	0%
Expected Serious Injuries/Deaths				9	0	55	0	190	1
Expected Immediate Deaths				2	0	11	0	41	0

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Summary and Conclusions

- *HAZUS* building damage functions are based on "new" loss estimation concepts:
  - Ground shaking demand is characterized by response spectra (rather than MMI)
  - Building capacity/response properties are characterized by nonlinear "pushover" curves
- Estimates of building damage and loss compare well with actual earthquake observations
- "Engineering approach" is consistent with state-of-the-art building analysis methods (e.g., FEMA 273 and ATC-40)
- Building-specific applications of technology will assist evaluation of mitigation benefits (seismic retrofit)

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5. Development of a National Earthquake Loss Estimation Methodology

Robert V. Whitman, M.EERI, Thalia Anagnos, M.EERI, Charles A. Kircher, M.EERI, Henry J. Lagorio, M.EERI, R. Scott Lawson, M.EERI, and Philip Schneider, M.EERI

This paper summarizes the development of a geographic information system (GIS)-based regional loss estimation methodology for the United States funded as part of a four-and-one-half year project by the Federal Emergency Management Agency (FEMA) through the National Institute of Building Sciences (NIBS). The methodology incorporates state-of-the-art approaches for: characterizing earth science hazards, including ground shaking, liquefaction, and landsliding; estimating damage and losses to buildings and lifelines; estimating casualties, shelter requirements and economic losses; and data entry to support loss estimates. The history of the methodology development; the methodology's scope, framework, and limitations; supporting GIS software; potential user applications; and future developments are discussed.

INTRODUCTION

The FEMA/NIBS earthquake loss estimation methodology is intended primarily for use by state, regional and community governments. It evaluates a wide range of losses resulting from scenario earthquakes to provide a basis for decisions concerning preparedness and disaster response planning and to stimulate and assist planning for mitigation to reduce potential future losses.

The methodology represents several important new advances in loss estimation technology.

- It is implemented in a software package (HAZUS) that operates through MapInfo, a GIS application.

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(RSL) Risk Management Solutions, 149 Commonwealth Drive, Menlo Park, CA 94025
(PS) National Institute of Building Sciences, 1201 L Street, N.W., Washington, D.C. 20005-4024

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- Transportation and utility lifeline losses are combined in one package with losses associated with the general building stock and essential facilities, e.g., hospitals.
- Extensive default databases for all states containing information concerning the built infrastructure and demographics are included in the software. Use of these databases make it possible to carry out preliminary losses studies with a minimum of effort, and serve as starting point for development by users of more complete and accurate databases.
- Ground shaking is characterized quantitatively using peak ground motions and spectral response, rather than relying upon Modified Mercalli Intensity (MMI).
- Long-term effects upon the regional economy are evaluated in addition to immediate economic and social losses.

The methodology aggregates the general building stock on a census tract basis, but is site-specific regarding essential facilities and components of lifelines. Studies may be made at various levels of sophistication, depending upon the scope of inventory and other data provided by the user. Inevitably, many compromises were made in formulating the methodology, so as to achieve generality in application and to permit meaningful studies without requiring enormous time and effort to inventory individual structures. As with any complex computational method, judgment must be exercised in the interpretation of the results. Some losses are not evaluated in the current version of HAZUS. Methodology for loss estimation is still evolving, and the software has been formulated so that additional computational methods can be added.

This paper provides an overview of the methodology and implementing software, and discusses potential uses and applications. Other papers in this issue (Brookshire et al., Kircher et al.) examine key parts of the methodology in some detail.

HISTORY OF THE PROJECT

Earthquake loss estimation began with the 1972 National Oceanic and Atmospheric Agency (NOAA) study for San Francisco Study (Algermissen et al., 1972), followed by over thirty major regional earthquake loss studies (NIBS, 1994). Understandably, none of these have been nationally applicable since the studies' methodology, assumptions, and approaches differed. In 1989, FEMA published the National Academy of Sciences report *Estimating Losses from Future Earthquakes* (NRC, 1989). This seminal report, listing a consensus set of guidelines for conducting loss studies, laid the groundwork for a loss methodology structure and provided the momentum for methodology development. In 1992, FEMA entered into a cooperative agreement with NIBS to develop a nationally applicable standardized methodology for estimating potential earthquake losses on a regional basis.

NIBS initially organized an eight-member Project Work Group (PWG) consisting of earthquake experts to provide technical oversight and an eighteen-member Project Oversight Committee (POC) to represent user interests in the earthquake community and provide user/client input. In 1993, the PWG and POC defined the components of the loss estimation methodology, prepared an extensive set of objectives for developing the methodology, and generated a standardized list of methodology outputs for: earthquake-related damage to essential facilities, high potential loss facilities and transportation lifelines; secondary effects including exposure to inundation, fire-following and hazardous materials release and debris generation; and social losses including casualties, shelter requirements and economic losses.

Parallel to this effort, NIBS contracted a joint venture between Risk Management Solutions, Inc. (RMS) of Menlo Park, California and the California Universities for Research in Earthquake Engineering (CUREe) to identify and evaluate the potential of existing studies for use in developing the standardized loss estimation methodology. A report was published in the spring of 1994 (NIBS, 1994). Beginning in 1994, RMS and a consortium of thirty earthquake experts, under contract to NIBS, developed the earthquake loss estimation methodology. Methodology calibrations utilizing existing literature and damage data from Northridge, Loma Prieta and previous earthquakes were conducted by RMS between 1994 and 1997 (NIBS, 1997a).

Two pilot studies served to test both the methodology and the functioning and usability of the software. Dames & Moore initiated the first pilot study of the methodology in early 1995 in Portland, Oregon, and EQE International undertook a second study in Boston, Massachusetts in early 1996 (see Dames & Moore, 1996; EQE, 1997). Changes were made in both methodology and software as a result of the pilot studies. Results for a scenario earthquake were also provided to the two communities for their use.

METHODOLOGY FRAMEWORK

The framework of the methodology includes the six major modules shown in Figure 1. As indicated by the arrows in the figure, the modules are interdependent with the output of one module acting as input to another. In general, each of these components is required for a comprehensive loss estimation study. However, the degree of required sophistication (and associated cost) varies greatly by user and application and it is necessary and appropriate that modules have multiple levels of detail or precision. The modular approach of the methodology permits both estimates based on simplified models and limited inventory data, as well as refined estimates based on more extensive inventory data and detailed analyses. Another advantage of the modular methodology is that it enables users to limit their studies to selected losses. For example, a user may wish to ignore induced damage when computing direct losses or to study the effect of proposed code changes upon losses to buildings without having to consider lifelines. This would eliminate a portion of the flow diagram in Figure 1 along with corresponding input requirements. A limited study may be desirable for a variety of reasons including budget and inventory constraints, or the need for answers to very specific questions.

To better understand and describe the methodology, the features of each module element will be described in the following sections. Detailed technical descriptions of the methods can be found in the methodology's technical manual (NIBS, 1997b).

Starting from a user-chosen earthquake, the Potential Earth Science Hazard (PESH) module estimates ground motion and ground failure (landslides, liquefaction and surface fault rupture). Ground motion demands are estimated based on the location, size and type of earthquake and the local geology. For ground failures, permanent ground deformation and probability of occurrence are determined. Any available, separately developed GIS-based

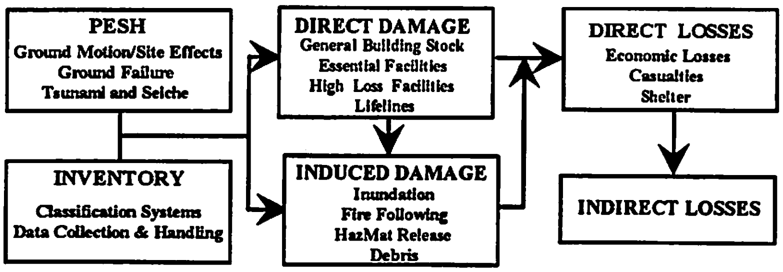

Figure 1. Components of the earthquake loss estimation methodology

maps for other earth science hazards, such as tsunami and seiche inundation, can be entered and utilized to assess potential impacts.

The Inventory Module contains tools for describing the physical infrastructure and demographics of the region being studied. It uses standardized classification systems for four distinct groups of infrastructure: (1) general building stock, (2) essential and high potential loss facilities, (3) components of transportation systems, and (4) components of utility systems. The groups are defined to address distinct inventory and modeling characteristics. The module is the vehicle for entering locally collected information concerning existing or possible future inventory.

The Direct Damage module provides damage estimates in terms of probabilities of occurrence for specific damage states given the specified level of ground motion and ground failure. Estimates also include loss of function to essential facilities and lifelines and the anticipated service outages for potable water and electric power. This module is the heart of the methodology.

Once estimates of direct damage are available, induced damage can be evaluated. Induced damage is defined as the secondary consequences of a natural hazard other than damage due to the primary hazard that led to losses. The methodology's Induced Damage module calculates damage due to fire following an earthquake and tonnage of debris generation. The module locates dams and levees whose failure might cause inundation and locates hazardous material sites.

Both direct and induced damage can lead to Direct Losses. Two types of direct economic loss are evaluated in the methodology. The first type quantifies the cost of repair and replacement of structures and lifeline systems that are damaged as a consequence of the earthquake. Structural and nonstructural damage as well as losses to contents and business inventory are included. In addition, dollar losses that are the direct consequence of building or lifeline loss-of-function, such as costs of relocation, income loss and rental loss are included as direct economic losses. Social losses are quantified in terms of casualties, displaced households and short-term shelter needs. The Indirect Economic Loss module assesses the broad and long-term implications of the direct impacts. Examples of indirect economic impacts are changes in employment and personal income.

GROUND MOTION/ SITE EFFECTS

One key decision rendered at the outset of the project was to use quantitative measures of ground shaking as the starting point for evaluation of damage. For the general building stock and essential facilities, spectral response is used. For lifelines, peak ground acceleration and velocity are employed. Permanent ground displacement affects all infrastructures. This represented a major departure from the use of MMI found in nearly all prior loss estimation methodologies.

This decision was not simple since no general agreement exists concerning appropriate equations ("attenuation equations") giving spectral ordinates as a function of magnitude, distance and type of earthquake. This is particularly true in the eastern United States, owing to the paucity of measured ground motions. In addition, this decision required further development of still-evolving procedures for relating spectral response to damage. On the other hand, it was time to begin using state-of-the-art knowledge and technology since there are well-understood logical and practical difficulties with the use of MMI to estimate damage to a broad range of buildings, facilities and lifelines.

The PESH module was developed to estimate site-specific spectral demands and use these demands to estimate the damage to the building and lifeline inventories. Estimating the ground shaking demands in the GIS-based program requires the following three steps:

1. ***Select a scenario earthquake event.*** The methodology provides three approaches for characterizing an earthquake: the deterministic scenario event, the scenario event based on probabilistic seismic hazard maps, and the scenario event based on user-supplied ground shaking maps. The user creates a deterministic scenario event using either the methodology-supplied database of historical earthquakes, existing seismic source maps supplied with the software, or a hypothetical event customized by the user. The methodology allows the user to generate estimates of damage and loss based on the probabilistic spectral response contour maps developed by the United States Geological Survey (USGS) for the National Earthquake Hazard Reduction Program (NEHRP) Provisions (Frankel et al., 1996). The user can also describe a scenario event by supplying digitized maps representing ground motion demands that occurred from or are predicted to occur from an earthquake event. This option was created so that the user could develop a scenario event that could not be adequately described by a theoretical attenuation relationship or to replicate a well-recorded past event.
2. ***Determine the input ground motion levels for the baseline site-soil conditions using attenuation relationships.*** Attenuation equations adopted by the USGS for the building-code related Project 97 national mapping effort (Frankel et al., 1996) are utilized in HAZUS. Site-specific response spectra are generated by fitting standardized spectra to ground motions at periods of 0.3 seconds and 1 second.
3. ***Overlay high resolution geologic information and modify ground motion demands using site amplification factors based on local site conditions.*** To account for site effects, a user-supplied map of geologic data can be overlaid on the baseline shaking demands to modify ground motion demands. The information in these maps is based on a standard definition of soil types. Assistance from qualified geotechnical experts will generally be necessary to develop such maps. Alternatively, a user can designate a

characteristic soil type for each census tract. Effects of local soil conditions upon ground motions are accounted for using soil factors developed by the Building Seismic Safety Council for the NEHRP-recommended building code standards (BSSC, 1997). If no user-supplied map exists, the module will default to one soil condition for the entire study area. This is a soil of medium stiffness, characterized by a shear wave velocity between 180 and 360 m/sec. Experience has shown the importance of replacing the default soil assumption with maps based upon local knowledge.

GROUND FAILURE

Ground deformations due to liquefaction, landslides, and surface fault rupture are quantified in terms of median permanent ground displacement (PGD) and probability of occurrence, and the damage to building and lifelines is adjusted to account for the associated ground failure. The methodology utilizes the GIS capability to overlay susceptibility maps and ground motion contour maps to determine the landsliding and liquefaction consequences of the event. These maps must be provided by the user, and expert assistance in their preparation is necessary. The default is no liquefaction or landsliding. The methodology computes the expected deformation due to surface fault rupture as a function of the scenario event. An option is provided to assume that all or part of the fault rupture does not extend to the surface, thus limiting the effects of the displacements on damage and loss estimates.

INVENTORY COLLECTION AND DEFAULT DATA

The infrastructure within the study region must be inventoried in accordance with the standardized classification tables used by the methodology. The general stock of buildings is classified by occupancy (residential, commercial, etc.) and by model building type (structural system and material, height). There are 36 model building types, each of which can be assigned different levels of seismic resistance. Certain key features of components of lifelines must be identified, including specific location.

The collection of inventory can without question be the most time consuming and costly aspect of performing a loss estimation study and is often a limiting factor in the development of a comprehensive study. Since many municipalities have limited budgets for performing an earthquake loss estimation study, the methodology was developed to accommodate users with different levels of resources.

An extensive amount of data on buildings, essential facilities, lifelines, population and economic parameters is provided with the methodology. Information from the most recent census was used to estimate square footage for each occupancy class, for every census tract in the country. Characteristic relationships between occupancy and model building types were developed, in part via local workshops, for several broad regions of the nation. Partial listings of essential facilities, principal highways and major bridges, major gas pipeline locations, etc. were taken from federal or other national databases. Typical key features of electrical and water distribution systems, such as number of electrical switching stations and miles of pipelines, as a function of population, have been inferred from nationwide information. The default data are limited for certain components of the methodology (especially utility lifelines). While most users will develop an enhanced inventory that reflects the characteristics of their study region, the methodology is capable of producing loss estimates based upon default data. Such estimates of course will have a great deal of uncertainty associated with them.

The quality of results can be improved by enhancing the inventory data. This will require the cooperation and input from utilities, transportation and local agencies. Software has been developed to assist in converting locally available databases concerning the general building stock and essential facilities, e.g., tax assessor's records, into the format required by HAZUS. Assembling information concerning transportation and utility systems can be very time consuming.

DIRECT DAMAGE—BUILDINGS

In previous loss estimation methodologies, the extent and severity of damage to buildings was typically evaluated for generic groups of buildings using expert opinion and non-engineering parameters such as MMI. In this methodology, a method based on the inelastic building capacity and site-specific response spectra was developed to describe the damage incurred in both structural and nonstructural components. (This approach is described in detail in the paper by Kircher et al. in this issue.) The method uses a simple and practical procedure to estimate the peak inelastic seismic response of buildings. The predicted building response (in terms of displacement or acceleration) is used to interrogate fragility curves to obtain probabilistic estimates on the extent and severity of damage to structural and nonstructural components of a building. These damage estimates are expressed in terms of the probability that the building is in one of five damage states: none, slight, moderate, extensive, and complete. This procedure can be applied by the engineering community for use on specific structures as well as for generalized groups of structures.

Although building damage varies from "none" to "complete" as a continuous function of building response, it is impractical to linguistically describe building damage as a continuous function. Instead, it becomes necessary to develop general descriptions for ranges of damage or damage states for which the fragility curves can be developed. To service adequately all the needs of the methodology, the damage state definitions must be descriptive (i.e., the user must be able to glean the nature and extent of the physical damage to a building type from the damage prediction output) so that life-safety, societal and monetary losses which result from the damage can be estimated. For example, moderate structural damage to a concrete frame with unreinforced masonry infill walls is defined as "Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections. Diagonal shear cracks may be observed in concrete beams or columns."

Since damage to nonstructural building components (i.e., architectural components, such as partition walls and ceilings, and building mechanical/electrical systems) affect losses differently than damage to structural components (i.e., the gravity and lateral load resisting systems), the methodology estimates structural and nonstructural damage separately. The damage to certain nonstructural components is primarily a function of interstory drift (e.g., full-height drywall partitions) while for other components (e.g., mechanical equipment), damage is a function of the floor acceleration. Developing fragility curves for each possible nonstructural component is not practical; therefore nonstructural building components are grouped into drift-sensitive and acceleration-sensitive components. For a given spectral displacement and acceleration, damage to nonstructural components and their damage descriptions are considered to be independent of the building type (i.e., partitions, ceilings, cladding, etc., are assumed to incur the same damage in a steel frame building or in a concrete shear wall building).

For both the essential facilities and general building stock, damage state probabilities are determined for each facility or structural class. Damage and loss of function are key issues with respect to essential facilities, as the functionality of these facilities directly affects emergency response. Based upon the level of structural and nonstructural damage, loss of function (e.g., 50% of capacity) and recovery time are estimated.

DIRECT DAMAGE—LIFELINES

The methodology currently focuses primarily upon estimating damage and restoration times for *components* (e.g., airport fuel facilities, highway bridges, water treatment plants) for thirteen transportation and utility lifeline systems. In general, each such component has subcomponents. Overall fragility curves for a component are evaluated using fault tree logic to combine subcomponent fragility curves. The hazard is typically represented by peak ground acceleration and permanent ground displacement. Data on which to base the subcomponent fragility curves has been derived from a number of sources. Using the overall fragility curves, damage state probabilities are calculated for the lifeline components. Restoration times are evaluated from very simplified rules, relating to degree of damage and size of component.

The current lifeline module provides only very simple estimates of service outages (e.g., percent of households without service) for electric power and potable water *systems*. These estimates are based upon experience and are unrelated to calculated behavior of components. Ideally a loss estimation methodology would use component damage probabilities to evaluate the overall performance of each lifeline system. Doing so requires an understanding of the interactions among components and the potential for alternative pathways. Inclusion of such capability awaits development of reasonably simple and nationally applicable algorithms for analyzing redundant systems, plus meaningful rules for expressing system performance in terms of probabilities of damage to components.

INDUCED DAMAGE—FIRE FOLLOWING EARTHQUAKE

Fires following an earthquake is a major problem well documented in historical events and the recent earthquake in Kobe, Japan. For estimation of the impacts from the fires that follow an earthquake, the methodology utilizes Monte Carlo simulation techniques to assess the potential impacts and separates the module into three major elements: fire ignition, spread, and suppression.

Based on empirical information from previous earthquakes, the number of fire ignitions is estimated from the size and type of building inventory and the ground motion to which it is subjected. Spread is a function of the density of the construction, the presence of wind, fire breaks (e.g. wide streets, lakes) and low fuel areas (e.g. parks, cemeteries, golf courses). Suppression is a function of the available fire fighting capabilities. The spread and suppression modules use damage and loss of function outputs of the essential facilities and lifeline modules to determine the response capabilities and effectiveness of the fire-fighting personnel. Thus, to perform a fire following earthquake analysis, information about the number and location of fire stations and the estimated speed fire engines can travel after an earthquake is required.

The combination of ignition, spread, and suppression determines a fire spread area. Based on the fire spread area, the module determines the population and value of building stock exposed to the fires. The outputs of the fire module are estimates of the number of serious fire ignitions and projections of the population and value of property exposed to fire.

INDUCED DAMAGE—HAZARDOUS MATERIALS RELEASE

Currently, the module is restricted to a standardized method for classifying materials and using a default database (EPA Tri-Services Database) to identify those facilities that are most likely to have significant releases in future earthquakes. The methodology-supplied database is limited to those chemicals that are considered highly toxic, flammable or highly explosive and to those facilities where large quantities of these materials are stored.

INDUCED DAMAGE—INUNDATION DUE TO DAM OR LEVEE FAILURE

The National Inventory of Dams Database (NATDAM) is provided with the methodology software. The dams included in the database have been ranked according to their hazard potential, and the user can quickly query the data to assess qualitatively the impact potential for the dams in the study region. HAZUS does not include software to develop a dam-failure inundation map. However, inundation maps already may exist for many of the dams. HAZUS can easily import and overlay the inundation maps with population and building information to estimate the population and value of property exposed to potential inundation. The problem with using existing inundation maps is that they may have been developed for a different scenario and may not reflect the inundated area for the earthquake of interest.

INDUCED DAMAGE—DEBRIS

Limited research has been done in the area of estimating debris from earthquakes. Some of the early regional loss estimation studies (e.g., Algermissen, et al., 1973; Rogers, et al., 1976) included simplified models for estimating the amount of debris from shaking damage to unreinforced masonry structures. The methodology adopts a similar empirical approach to estimate two different types of debris. The first type is debris that falls in large pieces, such as steel members or reinforced concrete elements. These require special treatment to break into smaller pieces before they are hauled away. The second type of debris is smaller and more easily moved with bulldozers. This includes brick, wood, glass, building contents, and other materials.

The module estimates debris based on the results from the direct damage module, tables which quantify the generated debris from different structural and nonstructural damage states, and the typical weights of structural and nonstructural elements. The aggregated estimates (by census tract) of generated debris are presented in terms of type (brick versus reinforced concrete and steel) and origin (structural versus nonstructural components).

DIRECT LOSSES —ECONOMIC LOSSES

Direct economic losses are discussed in detail by Brookshire et al. in this issue. These direct economic losses include the cost of repair or replacement of structures that are damaged as a consequence of the earthquake. Both structural damage and nonstructural damage (e.g. damage to interior finishes and contents) are included. In addition, costs of relocation, losses to business inventory, capital-related losses, income losses and rental losses are included as direct economic losses. Rental losses, income losses and relocation costs occur as a consequence of how long a business is inoperable, which is a function of the level of damage and the type of structure or facility.

Damage information from the direct damage module is combined with regional economic data to compute the direct economic losses. Examples of economic data used to calculate direct economic losses include cost of construction per square foot by occupancy type, average rental rates per foot and annual gross sales. Regional variations in construction cost are provided by the methodology. All direct economic losses can be mapped/queried by census tract, by loss type and by general/specific occupancy type.

DIRECT LOSSES—CASUALTIES

The module combines the output from the Direct Damage module with building inventory and population data to quantify casualties. Casualty rates, which vary according to model building type, are based upon expert opinion developed by the Applied Technology Council (1985), modified by recent experience. Casualties arising from damage to highway bridges are also included. The methodology estimates casualties for three times of day: 2:00 P.M. (during office hours), 5:00 P.M. (at commute time), and 2:00 A.M. (at night) based on census-derived migration patterns of the region's population. Casualties caused by secondary effects, such as heart attacks or injuries while rescuing trapped victims, are not included in the casualty estimates.

The output of the casualty module contains estimates of four casualty severities by general occupancy and time, and aggregated by census tract. The casualty severities range from "Severity 1: First aid level injuries not requiring hospitalization" to "Severity 4: Instantaneously killed or mortally injured." The user can display maps or tables of the casualty estimates that can be used to plan the amount and type of medical attention that will be required following the event. By combining casualty information with loss of function estimates for hospitals, the user can develop alternate plans for treatment of victims outside of the affected area.

DIRECT LOSSES—SHELTER REQUIREMENTS

Homelessness due to an earthquake is derived by combining damage to residential building stock with utility service outage relationships to estimate the number of households that are uninhabitable. (The loss of function to utilities can drastically change the short-term shelter needs in severe climates.) The uninhabitable household estimates are combined with methodology-supplied demographic data to quantify the number and composition of the population requiring short-term shelter. The output of the shelter module is expressed as estimates of the number of displaced households and short-term shelter requirements. While it is understood that shelter needs can also be driven by induced damage (fire, inundation, or hazardous material releases), the quantification of the shelter needs associated with these factors must be addressed outside of the current methodology.

INDIRECT LOSSES

Long-term effects on the regional economy that occur as a result of earthquakes are evaluated by the methodology's indirect economic loss module. These indirect economic losses are also discussed in detail in the paper by Brookshire et al. in this issue. Examples of indirect economic losses include changes in unemployment, losses in tax revenue, losses in production, reduction in demand for products, and reduction in spending. Essentially, indirect economic effects are a consequence of direct economic effects, major interruption to lifelines, length of time to relocate, repair and rebuild, aid that flows into a region and the ability of a region to adjust to changes in demand and supply. Estimation of indirect economic losses requires the user to supply social and economic information about the region, such as population, employment base, and the nature of business activity. Outputs of the indirect economic module include income change and employment change by industrial sector. (Indirect economic losses are discussed in detail in the paper by Brookshire et al. in this issue.)

HAZUS GIS SOFTWARE

The objective of providing a useful regional loss estimation tool for local, state and federal agencies requires a software system that is flexible, accommodating to various user needs, and able to support the uniformity of a standardized approach. Additional goals of the HAZUS software system were identified as: (a) easily used in an interactive mode, (b) designed to run with minimal computer hardware requirements, and (c) capable of incorporating new and improved information as it becomes available to the user.

A GIS provides the ideal framework to accomplish the objectives of the HAZUS application. A GIS is a specialized data management system which is capable of compiling, storing and analyzing information based upon spatial or geographic references. The interactive features of a desk-top GIS system provide a user-oriented environment for entering and accessing data and allows the user to overlay input and output data on shaded maps of the region. The inherent nature of a GIS permits the rapid identification of locations with the potential for high damage associated with localized soil conditions. Figure 2 shows the locations, in an area around Los Angeles, of electrical substations, oil refineries and gas pipes—overlaid upon shaded areas representing different soil conditions. The GIS technology also provides a powerful visual tool for displaying outputs and permits users to "see" the geographical distribution of impacts from different earthquake scenarios and assumptions. Figure 3 is a typical HAZUS output showing the estimated total economic losses for downtown Los Angeles for a simulation of the 6.7 Magnitude, 1994 Northridge event.

The use of a dynamic GIS-based model overcame many of the limitations of previous methodologies. The flexible GIS technology permits multiple levels of analysis as dictated by levels of funding. Scenarios can be developed that use simplified estimates of damage and loss generated from limited inventory collected on a modest budget. The scenarios can be easily upgraded to allow for more precise estimates based on more extensive inventory information. Once the data are collected and organized, they can be readily updated, and any number of hazard scenarios/assumptions can be evaluated. An additional advantage is that once the inventory databases are compiled, they can be used for other purposes such as city planning, public works, or multi-hazard emergency preparedness.

However, HAZUS uses more than just GIS technology, which by itself is a cumbersome environment for the execution of complex numerical algorithms. Programming languages, such as C++, have been applied to encode otherwise complex algorithmic and rule-based relationships. The technology of Knowledge-Based Expert Systems (KBES) is used for executing the complex algorithms dictated by risk assessment models. For managing the large amounts of inventory data that characterize a regional study, a relational database management system (RDBMS) is required. Used alone, each of these technologies has shortcomings. HAZUS was created as a system that integrates each of the software strategies. To the user the resulting system can have the look and feel of a GIS-based program. However, embedded within the GIS are the RDBMS and KBES technologies necessary to support the database management and computational requirements of a regional risk assessment study.

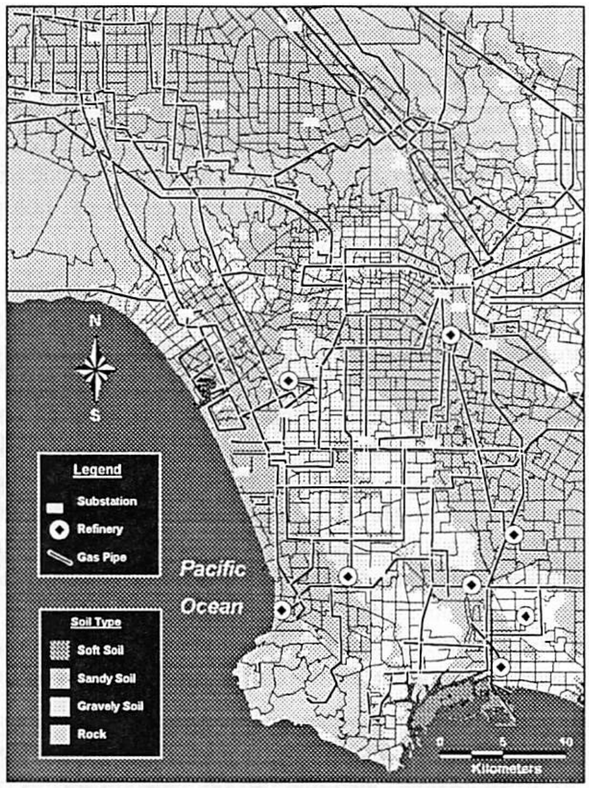

Figure 2. Map showing lifelines overlaid on a geologic soil map. *In color:* see plates following p. 738.

GIS-based software systems often require the use of expensive, high performance computers using complex operating systems, significant amounts of memory and large storage requirements. While there are a certain number of fundamental constraints, the objective was to design a system that requires a minimum system configuration, yet could be scaled up for increased system performance, so as to provide access to the technology to a larger group of potential users. HAZUS is designed to run on a standard IBM-compatible computer using a '486 or Pentium microprocessor and will run on Windows 3.1, '95 and NT operating systems.

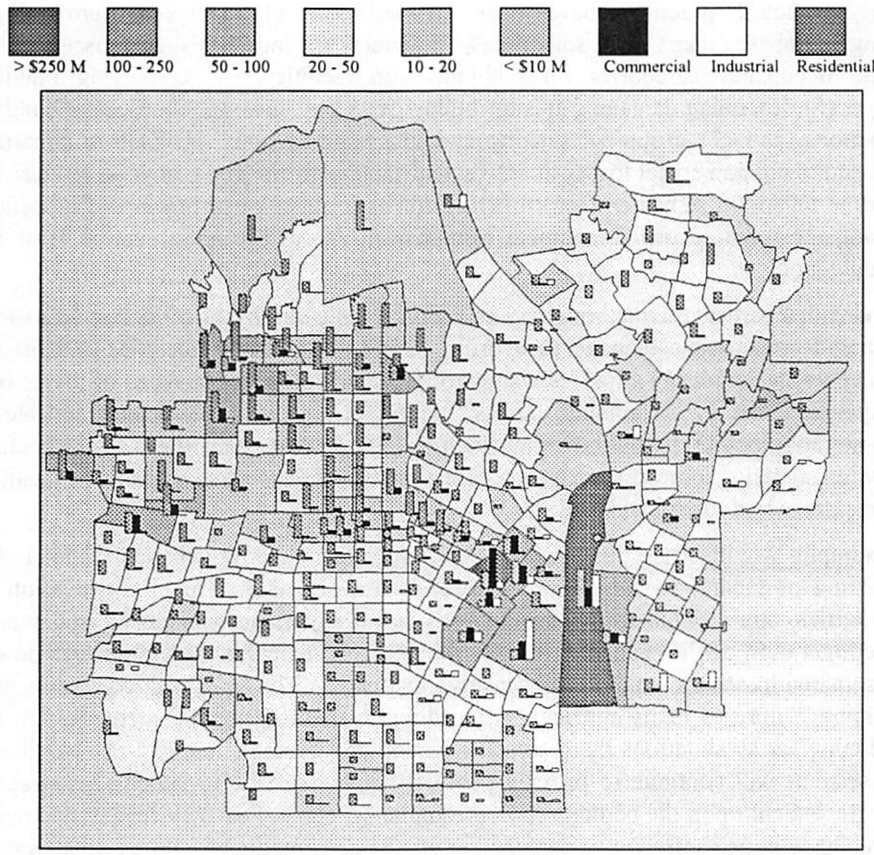

Figure 3. Thematic map of total economic losses for a scenario event. *In color:* see plates following page 738.

Since the application and accompanying data are shipped on a CD-ROM, the user must also have access to a CD-ROM reader. MapInfo must also be installed on the computer. An ArcView version of HAZUS will be available at a later date.

COMMENTS CONCERNING SCOPE OF THE METHODOLOGY

A fundamental conflict between two objectives, standardization and flexibility, was recognized at the outset of the project. On one hand, there was a desire for standardization to enable comparison of loss estimates for different regions of the country. On the other hand, potential users at state and local levels stressed the desire for flexibility, permitting adaptation to their particular needs.

This conflict between standardization and flexibility has essentially been resolved in favor of the local user. In particular, there is no standardization concerning the choice of earthquake(s) selected for analysis. As previously noted, the methodology consists of a set of modules that can be activated or deactivated by the user. In addition, the methodology has been made flexible enough to permit different levels of detail in inventory collection as dictated by the available funding.

However, standard practices have been defined for: (1) technical terminology, (2) classifying database maps for soil types, liquefaction and landslide susceptibility, (3) classifying occupancy categories for buildings and facilities, (4) classifying building structure type, (5) describing damage states for buildings and lifelines, (6) developing building damage functions, and (7) grouping, ranking and analyzing lifelines. HAZUS summarizes damage and economic and social losses in convenient tabular form. Thus, anyone so desiring can adopt some minimum standards (return period for earthquake occurrence, use of default inventory data, etc.) and secure comparable results from across the nation for at least the general building stock.

As was detailed earlier, the methodology estimates a wide variety of economic and social losses resulting from possible damage to a broad scope of buildings, facilities and lifeline systems. However, while ideally a loss estimate would include all possible types of losses that might be experienced by every building, facility, lifeline, etc., it was deemed not feasible to provide one methodology that would meet all such desires. In particular, there are difficulties associated with estimating losses from "high potential loss facilities," such as dams or facilities that might release hazardous substances.

A few examples will illustrate the difficulties and problems: (1) A reliable loss estimate for any one building or facility would require a careful study of as-built plans, evaluation of material properties, and a detailed dynamic analysis by an experienced engineer, and would require the cooperation of the owner, especially when, as for example with a nuclear power plant, any estimated losses are a politically sensitive matter, (2) The foregoing comments also apply to possible failure of dams and levees. In addition, there is no one methodology for reliably predicting for all situations the resulting flooding and damage, and (3) The likelihood that lifeline systems will continue to provide post-earthquake service to specific geographic areas is very dependent upon the configuration (redundancy, etc.) of each system. While many utility systems have in use software to analyze the effects of component failures upon system performance, it is not clear at this time that there is generic software applicable to the wide variety of systems existing throughout the country.

Hence it was recognized that the FEMA/NIBS methodology could not reliably estimate all possible losses. The decision was to adopt protocols that assist in identifying and calling attention to unevaluated losses, to in some cases evaluate the potential exposure to possible losses, and to encourage and facilitate incorporation into the predicted losses any already-available results from damage/loss studies to particular buildings, facilities and lifeline systems.

The FEMA/NIBS methodology is currently geared to deal with "scenario earthquakes"—events described by magnitude, epicentral location, and type (thrust fault, etc.) of earthquake. The result of each analysis is thus a deterministic "best estimate" for the losses that might result from a specified event.

The probability of exceeding thresholds of loss, or annualized losses, can be evaluated by making multiple runs assuming different earthquake events, each with an assigned probability of occurrence. For example, HAZUS can estimate losses for 500, 1,000 and 2,500 year ground shaking by utilizing maps prepared by the USGS. (Frankel et al., 1996), and included with the software. In addition to uncertainty concerning the occurrence of earthquakes, there are also uncertainties with the inventory of buildings, etc., and the parameters that go into evaluation of damage and loss. The effect of these latter uncertainties upon probability of loss can be estimated through sensitivity studies. Obviously any such studies involve considerable time and effort.

HAZUS is an ambitious advance in earthquake loss estimation. As has been discussed, the methodology is not perfect. Some potentially important losses are not estimated by the software now included in HAZUS. Those losses that are evaluated are subject to uncertainties. It is doubtful whether it will ever be possible and feasible to develop a perfect inventory for a region. Even with a perfect inventory, the accuracy of estimated losses is limited by shortcomings in scientific knowledge concerning ground motions caused by earthquakes, the collateral hazards such as liquefaction, landsliding, tsunamis, and seiches, and the manner in which the many types of buildings, other structures and lifeline components respond to ground shaking and other hazards. Losses estimated using HAZUS for a specific earthquake scenario should be regarded as being uncertain by a factor of perhaps two, and in some cases greater.

IMPLEMENTATION STATUS

As a result of the Portland pilot study, changes were made to make the software easier to use, including printing of appropriate summary tables. That study also pointed to some technical shortcomings, particularly concerning liquefaction, lifelines and casualties. At that stage, the methodology was benchmarked using the Northridge and Loma Prieta experiences so as to correct for such shortcomings (Kircher et al, 1997; NIBS, 1997a). In the Boston pilot study, the main concern was the attenuation equations used for the Eastern United States. The software has subsequently been used to "predict" losses caused by earthquakes in several parts of the country (NIBS, 1997a). In the eyes of the project team, the results of these several "tests" were, overall, generally satisfactory for earthquakes of magnitude 6.5 and greater. However, the methodology did not necessarily predict particular losses, such as the collapse of freeways in Oakland in 1989 or possible damage to some unusual high potential loss of buildings or facilities. There still is concern as to the correctness of estimated losses for smaller magnitude events, particularly for locations in Central and Eastern United States, and to a lesser degree concerning very large magnitude events.

The methodology and the software were released in early 1997 on a preliminary basis, along with a technical manual for use in performing loss estimation studies and a user's manual to explain the methodology to local, state, and regional officials (NIBS, 1997b, 1997c). Representatives from the fifty states and the U.S. territories were trained in four FEMA/NIBS sponsored workshops held at the RMS training facility in Menlo Park, California in March, April, and May, 1997. In addition, a training course on mitigation planning using HAZUS has been under development for state, regional and local officials and individuals in the private sector.

Three major initiatives are in progress: (1) a mitigation module to enable users to select mitigation alternatives based on losses calculated with HAZUS to determine the cost effectiveness of alternatives selected by recalculating losses, (2) a PC-based ArcView platform for HAZUS to initiate a means of enabling communities with Arc/Info databases to employ the Earthquake Loss Estimation Methodology GIS software, and (3) expansion of the Earthquake Loss Estimation Methodology into a multi-hazard methodology by initiating development of nationally applicable standardized modules for estimating potential losses from wind and flood hazards.

USERS AND APPLICATIONS

From an application's perspective, the FEMA/NIBS HAZUS methodology has the potential of becoming a valuable integrating tool to bring together key state and local players in a community-based approach to risk assessment and mitigation. Because of its comprehensive base, it has an extraordinary range of potential applications for a wide range of users. However, it is important to recognize that while the HAZUS software program is a powerful tool for estimating potential losses from future earthquakes, the level of detail of analysis is directly related to building stock and soil conditions data and other variables. By design, HAZUS is a flexible, versatile decision-support tool that can be used by a variety of individuals and organizations for analyzing mitigation policies, programs, goals, and options (Durham, 1997).

For illustrative purposes, Table 1 indicates examples of some of the types of government agencies and departments that could find loss estimation results potentially useful in their organizational capacities.

Four examples of potential application aspects include:

- Developing earthquake loss scenarios to illustrate dimension and complexity of the earthquake risk, locally and regionally.
- Demonstrating the costs and benefits over time of adopting and enforcing building codes and the implementation of other mitigation measures.

Table 1. List of Potential Government Agency and Department Users

• Office of Emergency Services (OES)	• Public Utility Commission
• Housing Department	• Transportation/Highway Departments
• Seismic Safety Commission	• Department of Water Resources
• Police and Fire Departments	• Building Department
• Office of Education	• Public Health Services
• Office of the Governor	• Department of Public Works
• Planning Commission	

- Providing land use and development agencies with a basis for planning, zoning, building code and development regulations and policy that would reduce the risk posed by violent ground shaking and ground failure.
- Developing disaster response planning, earthquake recovery measures, and targeting long-term post earthquake reconstruction goals and priorities.

In such terms, it is clear that the methodology can also be used to estimate losses for a series of comparative scenario earthquake events and become the basis for seismic safety legislation, programs, and policies (Durham, 1997).

In view of major physical and economic losses generated by recent earthquakes (Loma Prieta, 1989, Northridge, 1994, and Kobe, 1995), the FEMA/NIBS earthquake loss estimation methodology is becoming increasingly recognized as a useful tool in identifying, stimulating, and planning mitigation efforts prior to the event in order to seek viable measures to diminish the impact of potential casualties and economic losses. During post-earthquake recovery actions taken only a few hours after the 1994 Northridge earthquake, loss estimation modeling was used by the California Office of Emergency Services (OES) to obtain an immediate assessment of total economic losses incurred at the time in order for the Governor to issue an emergency disaster proclamation and request a Presidential Disaster Declaration for recovery assistance (Goltz, 1996), and HAZUS can in the future be used for such a purpose.

AGGREGATION OF LOSSES ON A NATIONAL BASIS

At the national level, results of earthquake loss scenario application studies completed on a standardized basis by state, regional and community governments may be compiled for FEMA to obtain aggregated results of potential losses as an indication of the nation's total exposure to major seismic events. Such an aggregation of total losses would be of great assistance toward: (1) projection of effective public policy goals and objectives in earthquake hazard mitigation efforts, and (2) identification of the scope of the emergency response needed to cope with earthquake-related disasters.

CONCLUSIONS

A methodology has been developed that will allow a wider group of individuals to participate in and have access to results of regional loss estimation studies. The methodology has been implemented using an integrated GIS technology that provides the user with a very powerful tool to display and query results. The choice of a personal computer-based GIS fulfills the needs of users, such as emergency response organizations and local government agencies, and yet balances conflicting issues such as moderate cost and accuracy. Flexible data entry and modularity of the methodology make for easy inventory augmentation and parameter modification. The ability of the user to rapidly perform multiple scenarios using the same inventory provides a mechanism to examine alternatives, explore the sensitivity of results to input data and ask "what if" questions.

HAZUS is the best overall comprehensive tool currently available to states, regions and cities for estimating and extrapolating losses from possible future earthquakes. As is true of any computational technology, it must be used with judgment and an understanding of its underlying parameters. Methods for estimating those losses not now included can be developed and easily incorporated into the software modules. Results from research, especially new knowledge and data obtained by continued investigation of past and future earthquakes, can be used to reduce uncertainty in estimated losses. Its strength is in the fact that it is a flexible tool, put together so as to allow it to improve over time.

ACKNOWLEDGMENTS

The development of the methodology was the work of organizations and individuals listed in the credits below and was supported by funding from the Federal Emergency Management Agency (FEMA), under a cooperative agreement with the National Institute of Building Sciences (NIBS). The authors are solely responsible for the accuracy of the statements and interpretations contained in this publication. Such interpretations do not necessarily reflect the views of FEMA, NIBS, or members of the committees that oversaw the production of this work.

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6.

Development of Building Damage Functions for Earthquake Loss Estimation

Charles A. Kircher, M.EERI, Aladdin A. Nassar, M.EERI, Onder Kustu, M.EERI, and William T. Holmes, M.EERI

This paper describes building damage functions that were developed for the FEMA/NIBS earthquake loss estimation methodology (Whitman et al., 1997). These functions estimate the probability of discrete states of structural and nonstructural building damage that are used as inputs to the estimation of building losses, including economic loss, casualties and loss of function (Kircher et al., 1997). These functions are of a new form and represent a significant step forward in the prediction of earthquake impacts. Unlike previous building damage models that are based on Modified Mercalli Intensity, the new functions use quantitative measures of ground shaking (and ground failure) and analyze model building types in a similar manner to the engineering analysis of a single structure.

INTRODUCTION

This paper describes methods for estimating the probability of discrete states of structural and nonstructural damage to buildings that were developed for the FEMA/NIBS earthquake loss estimation methodology. The FEMA/NIBS methodology has many components, or modules, as described in the paper by Whitman et al. (1997) in this issue. Components specific to the estimation of building losses are described in a companion paper by Kircher et al. (1997) in this issue. At the heart of loss estimation are the probabilities of structural and nonstructural damage calculated using building damage functions.

BUILDING DAMAGE FUNCTIONS

Two sets of functions, or curves, are used in the FEMA/NIBS methodology to estimate damage to buildings resulting from ground shaking: (1) capacity curves and (2) fragility curves. Capacity curves estimate peak response of buildings for a given level of spectral demand. These curves are analogous to "pushover" curves of individual buildings and are based on engineering parameters (e.g., yield and ultimate strength) of the structural system that characterize the nonlinear behavior of different model building types.

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(WTH) Rutherford & Chekene, San Francisco, CA 94107

The fragility curves predict the probability of reaching or exceeding specific damage states for a given level of peak earthquake response. The probability of being in a particular state of damage, the input used to predict building-related losses, is calculated as the difference between fragility curves.

Specific details are provided in the following sections on: (1) building classification by model building type and occupancy, (2) building design and performance levels, (3) structural and nonstructural systems and contents, and (4) building damage states.

BUILDING CLASSIFICATION

Buildings are classified both in terms of their use, or occupancy class, and in terms of their structural system, or model building type. Damage is predicted based on model building type, since the structural system is considered the key factor in assessing overall building performance, loss of function and casualties. Occupancy class is important in determining economic loss, since building value is primarily a function of building use (e.g., hospitals are more valuable than most commercial buildings, primarily because of their expensive nonstructural systems and contents, not because of their structural systems).

Twenty-eight occupancy classes are defined to distinguish among residential, commercial, industrial or other buildings, and 36 model building types are used to classify buildings within the overall categories of wood, steel, concrete, masonry or mobile homes. Building inventory data relate model building type and occupancy class on the basis of floor area, as illustrated in Figure 1, so that for a given geographical area the distribution of the total floor area of model building types is known for each occupancy class. For presentation purposes, Figure 1 shows only the four overall categories of occupancy and the five overall categories of construction, whereas FEMA/NIBS methodology calculations are based on all 28 occupancy classes and 36 model building types.

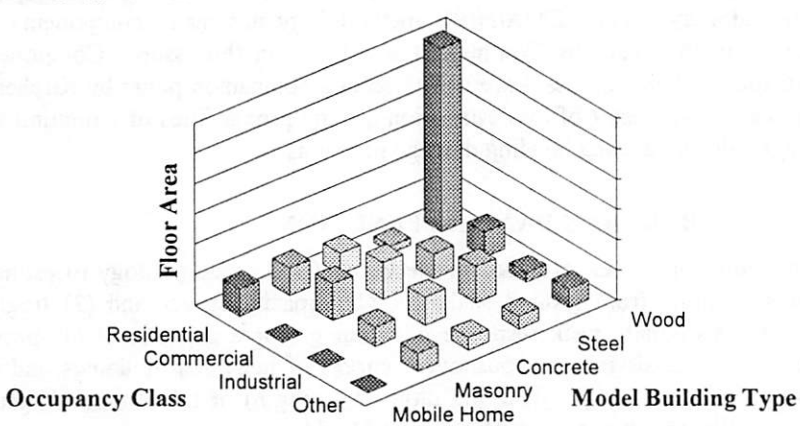


Figure 1. Example inventory relationship of model building type and occupancy class

Model building types are derived from the classification system of the *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* (FEMA, 1992), expanded to include mobile homes, and considering building height. Table 1 describes model building types and their heights. Typical building heights are used in the determination of capacity curve properties.

Table 1. Model building types of the FEMA/NIBS methodology

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1	W1	Wood, Light Frame (≤ 5,000 sq. ft.)		All	1	14
2	W2	Wood, Greater than 5,000 sq. ft.		All	2	24
3	S1L	Steel Moment Frame	Low-Rise	1-3	2	24
4	S1M		Mid-Rise	4-7	5	60
5	S1H		High-Rise	8+	13	156
6	S2L	Steel Braced Frame	Low-Rise	1-3	2	24
7	S2M		Mid-Rise	4-7	5	60
8	S2H		High-Rise	8+	13	156
9	S3	Steel Light Frame		All	1	15
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise	1-3	2	24
11	S4M		Mid-Rise	4-7	5	60
12	S4H		High-Rise	8+	13	156
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	2	24
14	S5M		Mid-Rise	4-7	5	60
15	S5H		High-Rise	8+	13	156
16	C1L	Concrete Moment Frame	Low-Rise	1-3	2	20
17	C1M		Mid-Rise	4-7	5	50
18	C1H		High-Rise	8+	12	120
19	C2L	Concrete Shear Walls	Low-Rise	1-3	2	20
20	C2M		Mid-Rise	4-7	5	50
21	C2H		High-Rise	8+	12	120
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	2	20
23	C3M		Mid-Rise	4-7	5	50
24	C3H		High-Rise	8+	12	120
25	PC1	Precast Concrete Tilt-Up Walls		All	1	15
26	PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1-3	2	20
27	PC2M		Mid-Rise	4-7	5	50
28	PC2H		High-Rise	8+	12	120
29	RM1L	Reinforced Masonry Bearing Wall s with Wood or Metal Deck Diaphragms	Low-Rise	1-3	2	20
30	RM1M		Mid-Rise	4+	5	50
31	RM2L	Reinforced Masonry Bearing Wall s with Precast Concrete Diaphragms	Low-Rise	1-3	2	20
32	RM2M		Mid-Rise	4-7	5	50
33	RM2H		High-Rise	8+	12	120
34	URML	Unreinforced Masonry Bearing Walls	Low-Rise	1-2	1	15
35	URMM		Mid-Rise	3+	3	39
36	MH	Mobile Homes		All	1	12

BUILDING DESIGN AND PERFORMANCE LEVELS

The building damage functions distinguish among buildings that are designed to different seismic standards, or are otherwise expected to perform differently during an earthquake. These differences in expected building performance are determined on the basis of seismic zone location, design vintage and use (i.e., special seismic design of essential facilities).

The 1994 *Uniform Building Code* (ICBO, 1994) is used to establish differences in seismic design levels, since the 1994 *UBC* or earlier editions of this model code likely governed the design, if the building was designed for earthquake loads. For the purpose of loss estimation, buildings designed in accordance with the 1994 *NEHRP Provisions* (FEMA, 1995) are assumed to have similar damage functions to buildings designed to meet the 1994 *UBC*. Damage functions are provided for three "Code" seismic design levels, labeled as High-Code, Moderate-Code and Low-Code, and an additional design level for Pre-Code buildings. The Pre-Code design level includes buildings built before seismic codes were required for building design (e.g., buildings built before 1940 in California and other areas of high seismicity).

High-Code, Moderate-Code and Low-Code seismic design levels are based on 1994 *UBC* lateral force design requirements of Seismic Zones 4, 2B and 1, respectively. Damage functions for these design levels are directly applicable to modern code buildings of 1973 or later design vintage. Pre-1973 buildings and buildings of other *UBC* seismic zones are associated with Moderate-Code, Low-Code or Pre-Code design levels, based either on the expertise of the user or on default relationships provided with the FEMA/NIBS methodology. For example, Moderate-Code (rather than High-Code) damage functions are used to estimate damage to *UBC* Seismic Zone 4 buildings built before 1973 (but after 1940).

The FEMA/NIBS methodology also includes "Special," above-Code, building damage functions for those essential facilities (e.g., post-1973 California hospitals) that are known to be of superior design and construction. Building damage functions for Special buildings are based on the same theory as that of Code buildings, except that the parameters of the capacity and fragility curves reflect greater seismic capacity and reliability of these buildings. While essential facilities are important, they typically represent only a very small fraction of buildings. This paper focuses on Code (and Pre-Code) building damage functions.

STRUCTURAL AND NONSTRUCTURAL SYSTEMS AND CONTENTS

Buildings are composed of both structural (load carrying) and nonstructural systems (e.g., architectural and mechanical components). While damage to the structural system is the most important measure of building damage affecting casualties and catastrophic loss of function (due to unsafe conditions), damage to nonstructural systems and contents tends to dominate economic loss. Typically, the structural system represents about 25% of the building's worth.

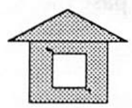
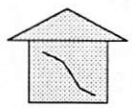
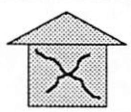
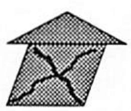
To better estimate different types of loss, building damage functions separately predict damage to: (1) the structural system, (2) drift-sensitive nonstructural components, such as partition walls that are primarily affected by building displacement, and (3) acceleration-sensitive nonstructural components, such as suspended ceilings, that are primarily affected by building shaking. Building contents are also considered to be acceleration sensitive. Distinguishing between drift- and acceleration-sensitive nonstructural components and contents permits more realistic estimates of damage considering building response.

BUILDING DAMAGE STATES

Damage states are defined separately for structural and nonstructural systems of a building. Damage is described by one of four discrete damage states: Slight, Moderate, Extensive or Complete. Of course, actual building damage varies as a continuous function of earthquake demand. Ranges of damage are used to describe building damage, since it is not practical to have a continuous scale, and damage states provide the user with an understanding of the building's physical condition. Loss functions relate the physical condition of the building to various loss parameters (i.e., direct economic loss, casualties, loss of function). For example, direct economic loss due to Moderate damage corresponds to 10% replacement value of structural and nonstructural components, on the average.

The four damage states of the FEMA/NIBS methodology are similar to the damage states defined in *Expected Seismic Performance of Buildings* (EERI, 1994), except that damage descriptions vary for each model building type based on the type of structural system and material. Table 2 provides structural damage states for W1 buildings (light frame wood) typical of the conventional construction used for single-family homes.

Table 2. Example damage states - light-frame wood buildings (W1)

Damage State		Description
	**Slight**	Small plaster cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneers. Small cracks are assumed to be visible with a maximum width of less than 1/8 inch (cracks wider than 1/8 inch are referred to as "large" cracks).
	**Moderate**	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
	**Extensive**	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations.
	**Complete**	Structure may have large permanent lateral displacement or be in imminent danger of collapse due to cripple wall failure or failure of the lateral load resisting system; some structures may slip and fall off the foundation; large foundation cracks. Five percent of the total area of buildings with Complete damage is expected to be collapsed.

BUILDING CAPACITY CURVES

A building capacity curve is a plot of a building's lateral load resistance as a function of a characteristic lateral displacement (i.e., a force-deflection plot). It is derived from a plot of static-equivalent base shear versus building displacement at the roof, known commonly as a pushover curve. In order to facilitate direct comparison with spectral demand, base shear is converted to spectral acceleration and the roof displacement is converted to spectral displacement using modal properties that represent pushover response. Pushover curves and related-capacity curves, are derived from concepts similar to those of the *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA, 1997), and in *Seismic Evaluation and Retrofit of Concrete Buildings* (SSC, 1996), known as ATC-40.

Building capacity curves are constructed for each model building type and represent different levels of lateral force design and building performance. Each curve is defined by two control points: (1) the "yield" capacity, and (2) the "ultimate" capacity. The yield capacity represents the lateral strength of the building and accounts for design strength, redundancies in design, conservatism in code requirements and expected (rather than nominal) strength of materials. Design strengths of model building types are based on the requirements of current model seismic code provisions (e.g., 1994 *UBC* or *NEHRP Provisions*) or on an estimate of lateral strength for buildings not designed for earthquake loads. Certain buildings designed for wind, such as taller buildings located in zones of low or moderate seismicity, may have a lateral design strength considerably greater than those based on seismic code provisions.

The ultimate capacity represents the maximum strength of the building when the global structural system has reached a full mechanism. Typically, a building is assumed capable of deforming beyond its ultimate point without loss of stability, but its structural system provides no additional resistance to lateral earthquake force. Up to yield, the building capacity curve is assumed to be linear with stiffness based on an estimate of the expected period of the building. From yield to the ultimate point, the capacity curve transitions in slope from an essentially elastic state to a fully plastic state. The capacity curve is assumed to remain plastic past the ultimate point. An example building capacity curve is shown in Figure 2.

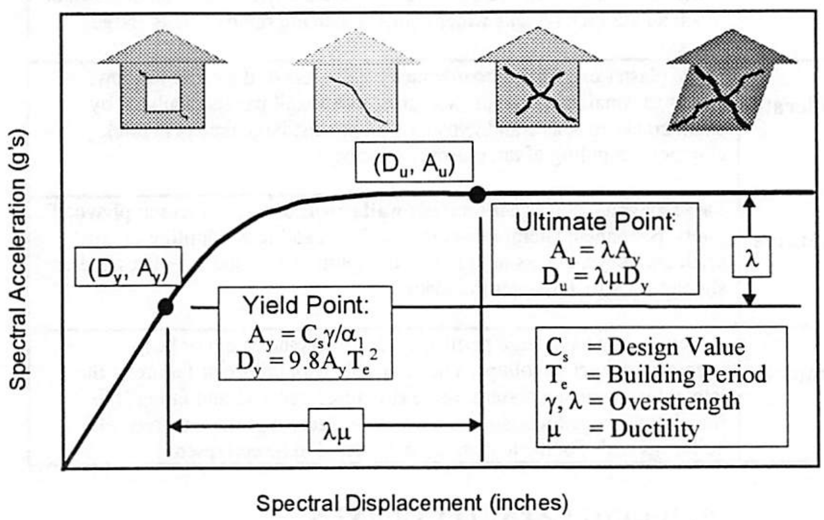


Figure 2. Example building capacity curve and control points

The following parameters define the yield point and the ultimate point of capacity curves as shown in Figure 2:

- C_s design strength coefficient (fraction of building's weight),
- T_e expected "elastic" fundamental-mode period of building (seconds),
- α_1 fraction of building weight effective in the pushover mode,
- α_2 fraction of building height at the elevation where pushover-mode displacement is equal to spectral displacement (not shown in Figure 2),
- γ "overstrength" factor relating "true" yield strength to design strength,
- λ "overstrength" factor relating ultimate strength to yield strength, and
- μ "ductility" ratio relating ultimate displacement to λ times the yield displacement (i.e., assumed point of significant yielding of the structure)

The design strength, C_s, approximately corresponds to the lateral-force design requirements of current seismic codes (e.g., 1994 *UBC or* 1994 *NEHRP Provisions*) and is a function of the building's seismic zone location and other factors including site soil condition, type of lateral-force-resisting system and building period. Example design strength values are given in Table 3 for selected building types.

Table 3. Example building capacity parameters - design strength (C_s)[1]

Building Type	Seismic Design Level			
	High-Code	Moderate-Code	Low-Code	Pre-Code
W1	0.200	0.150	0.100	0.100
S1L	0.133	0.067	0.033	0.033
S1M	0.100	0.050	0.025	0.025
S1H	0.067	0.033	0.017	0.017
C2L	0.200	0.100	0.050	0.050
URML	N/A	N/A	0.067	0.067

1. Shaded boxes indicate that URM buildings are not permitted by current seismic codes in zones corresponding to High-Code and Moderate-Code design levels.

The expected fundamental-mode period of the building, T_e, is calculated using the period formula of the *1994 UBC,* modified to reflect true building properties, and a height typical of the model building type (Table 1). Since the period specified by seismic codes is purposely set short to effect a conservative estimate of design force, the expected period of the building will typically be longer. Expected building periods are also used to account for flexing of diaphragms of short, stiff buildings, cracking of elements of concrete and masonry structures, flexibility of foundations, and other factors known to affect building stiffness.

For each Code design level (i.e., High-Code, Moderate-Code, Low-Code), building capacity is based on the best estimate of typical design properties (or effective design properties for Pre-Code buildings). Example values of expected building period, T_e, pushover mode parameters α_1 and α_2, the ratio of yield to design strength, γ, and the ratio of ultimate to yield strength, λ, are summarized in Table 4. Example values of the "ductility" factor, μ, are given in Table 5 for different code design levels.

Table 4. Example building capacity parameters - period (T_e), pushover modal response factors (α_1, α_2) and overstrength ratios (γ, λ)

Building Type	Height to Roof (ft)	Period, T_e (Seconds)	Modal Factors		Overstrength Ratios	
			Weight, α_1	Height, α_2	Yield, γ	Ultimate, λ
W1	14	0.35	0.75	0.75	1.50	3.00
S1L	24	0.50	0.75	0.75	1.50	2.50
S1M	60	1.08	0.75	0.75	1.25	2.00
S1H	156	2.21	0.65	0.60	1.10	2.00
C2L	20	0.35	0.75	0.75	1.50	2.50
URML	15	0.35	0.50	0.75	1.50	2.00

Table 5. Example building capacity parameters – ductility ratio (μ)

Building Type	Seismic Design Level			
	High-Code	Moderate-Code	Low-Code	Pre-Code
W1	8.0	6.0	6.0	6.0
S1L	8.0	6.0	5.0	5.0
S1M	5.3	4.0	3.3	3.3
S1H	4.0	3.0	2.5	2.5
C2L	8.0	6.0	5.0	5.0
URML	N/A	N/A	3.3	3.3

BUILDING RESPONSE

Building response is determined by the intersection of the demand spectrum and the building capacity curve. Intersections are illustrated in Figure 3 for three example demand spectra representing what can be considered as weak, medium and strong ground shaking, and two building capacity curves representing weaker and stronger construction, respectively. As shown in Figure 3, stronger and stiffer construction displaces less than weaker and more flexible construction for the same level of spectral demand, and less damage is expected to the structural system and nonstructural components sensitive to drift. In contrast, stronger construction will shake at higher acceleration levels, and more damage is expected to nonstructural components and contents sensitive to acceleration.

The demand spectrum is based on the 5%-damped response spectrum at the building's site (or centroid of a study area containing a group of buildings), reduced for effective damping when effective damping exceeds the 5% damping level of the input spectrum. Background on the 5%-damped response spectrum of ground shaking is provided in the next section.

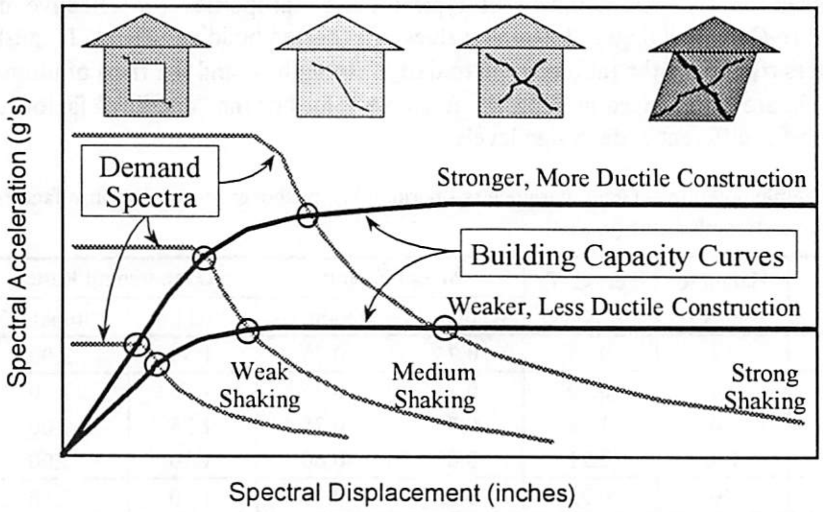


Figure 3. Example intersection of demand spectra and building capacity curves

GROUND SHAKING INPUT SPECTRUM

The FEMA/NIBS methodology characterizes ground shaking using a standard response spectrum shape, as shown in Figure 4, for spectra representing rock, stiff soil and soft soil conditions, respectively. The standard shape consists of two primary parts: (1) a region of constant spectral acceleration at short periods and (2) a region of constant spectral velocity at long periods. Short-period spectral acceleration, S_S, is defined by 5%-damped spectral acceleration at a period of 0.3 seconds. The constant spectral velocity region has spectral acceleration proportional to 1/T and is anchored to the 1-second, 5%-damped spectral acceleration, S_1. A region of constant spectral displacement exists at very long periods, although this region does not usually affect calculation of building damage and is not shown in Figure 4.

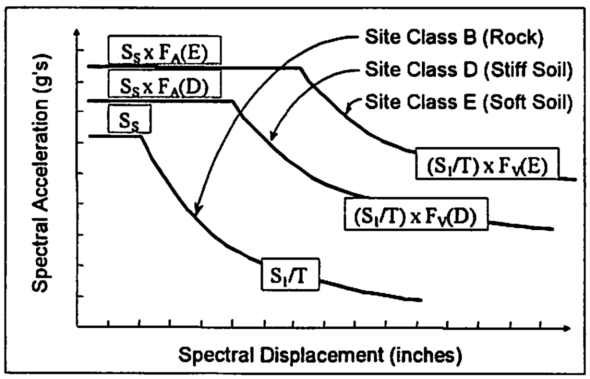


Figure 4. Example 5%-damped response spectra for three site classes

The FEMA/NIBS methodology predicts spectral response as a function of distance from scenario earthquake sources based on the same attenuation functions as those used by the United States Geological Survey to create national seismic hazard maps for *Project 97* (Frankel et al., 1996). These functions define ground shaking for rock (Site Class B) conditions based on earthquake magnitude and other source parameters (e.g., fault type).

Amplification of ground shaking to account for local site conditions is based on the soil factors of the *NEHRP Provisions*. The *NEHRP Provisions* define a standardized site geology classification scheme and specify soil amplification factors (i.e., F_A for the acceleration domain and F_V for the velocity domain). Figure 4 shows construction of demand spectra for stiff soil sites (Site Class D) and soft soil sites (Site Class E). These spectra illustrate the importance of soil type on spectral demand (and building response), particularly in the velocity domain.

DEMAND SPECTRUM - DAMPING REDUCTION

Extensive work has been published in the last two decades on modeling inelastic response of buildings. This work includes both explicit consideration of structural-system ductility (e.g., Miranda, 1993, Nassar, Osteraas and Krawinkler, 1992, Uang, 1991) and modification of elastic system properties (e.g., Kircher, 1996, Mahaney et al., 1993, Iwan and Gates, 1979). A recent study by Tsopelas et al. (1997) concludes that both approaches predict similar displacements for most buildings at ground shaking levels of design interest.

The FEMA/NIBS methodology is based on the latter modification of elastic system properties that simulates inelastic response by use of "effective" stiffness and damping properties of the building. Effective stiffness properties are based on secant stiffness, and effective damping is based on combined viscous and hysteretic measures of dissipated energy. Effective damping greater than 5% of critical is used to reduce spectral demand in a manner similar to the capacity-spectrum method of ATC-40 (SSC, 1996).

Figure 5 illustrates the process of developing an inelastic response (demand) spectrum from the 5%-damped elastic response (input) spectrum. The demand spectrum is based on elastic response divided by amplitude-dependent damping reduction factors (i.e., R_A at periods of constant acceleration and R_V at periods of constant velocity). The demand spectrum intersects the building's capacity curve at the point of peak response displacement, D, and acceleration, A. The amount of spectrum reduction typically increases for buildings that have reached yield and dissipate hysteretic energy during cyclic response.

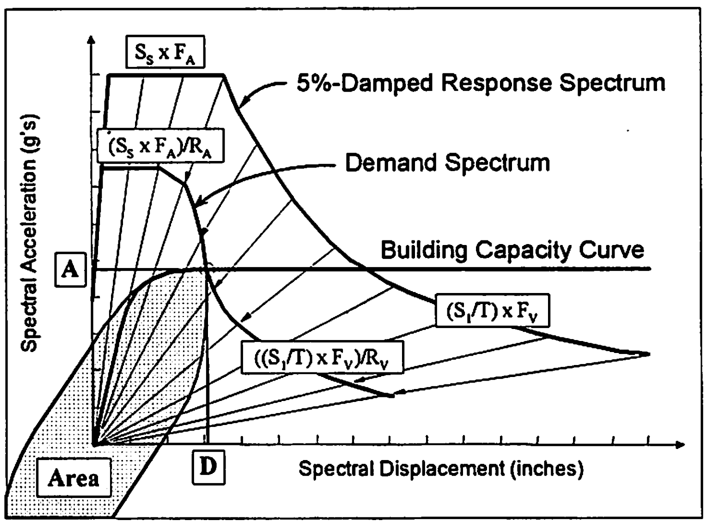


Figure 5. Example demand spectrum construction

Spectrum reduction factors are a function of the effective damping of the building, β_{eff}, as defined by Equations (1) and (2):

$$R_A = 2.12/(3.21 - 0.68\ln(\beta_{eff})) \quad (1)$$

$$R_V = 1.65/(2.31 - 0.41\ln(\beta_{eff})) \quad (2)$$

These equations are based on the formulas given in Table 2 of Newmark and Hall (1982) for construction of elastic response spectra at different damping levels (expressed as a percentage of critical damping). The factors of Newmark and Hall represent all site classes (soil profile types), but distinguish between domains of constant acceleration and constant velocity. For either domain, the reduction factor is the ratio of 5%-damped response to response of the system with β_{eff} damping. Equations (1) and (2) yield reduction values of R_A = 1.0 and R_V = 1.0, respectively, for a value of β_{eff} = 5% of critical.

Effective damping, β_{eff}, is defined as the total energy dissipated by the building during peak earthquake response and is the sum of an elastic damping term, β_E, and a hysteretic damping term, β_H, associated with post-yield, inelastic response:

$$\beta_{eff} = \beta_E + \beta_H \tag{3}$$

The elastic damping term, β_E, is assumed to be a constant (i.e., amplitude independent) and follows the recommendations of Table 3 of Newmark & Hall for materials at or just below their yield points. Example values of the elastic damping term are given in Table 6.

The hysteretic damping term, β_H, is dependent on the amplitude of post-yield response and is based on the area enclosed by the hysteresis loop at peak response displacement, D, and acceleration, A, as shown in Figure 5. Hysteretic damping, β_H, is defined in Equation (4):

$$\beta_H = \kappa \left(\frac{\text{Area}}{2\pi D A} \right) \tag{4}$$

where:

- Area is the area enclosed by the hysteresis loop, as defined by a symmetrical push-pull of the building capacity curve up to peak positive and negative displacements, ± D
- D is the peak displacement response of the capacity curve,
- A is the peak acceleration response at peak displacement, D
- κ is a degradation factor that defines the fraction of the Area used to determine hysteretic damping (see Table 6 examples).

For a value of $\kappa = 1.0$, Equation (4) may be recognized as the definition of equivalent viscous damping, found in modern vibration textbooks (e.g., Chopra, 1995) and traceable to the early work by Jacobsen (1930) and others. The κ factor in Equation (4) reduces the amount of hysteretic damping as a function of model building type, seismic design level and shaking duration to simulate degradation (e.g., pinching) of the hysteresis loop during cyclic response. Shaking duration is described qualitatively as either short, moderate or long, and is assumed to be primarily a function of earthquake magnitude, although proximity to fault rupture can also influence the duration of the level of shaking that is most important to building damage. Example values of the degradation factor, κ, are given in Table 6.

Table 6. Example values of elastic damping and degradation factors (κ)

Building Type	Elastic Damping (β_E)	High-Code Design			Low-Code Design			Pre-Code Design		
		Duration of Strong Ground Shaking (Short, Moderate or Long)								
		Short	Mod.	Long	Short	Mod.	Long	Short	Mod.	Long
W1	15%	1.0	0.8	0.5	0.7	0.4	0.2	0.5	0.3	0.1
S1L	5%	0.9	0.6	0.4	0.6	0.3	0.1	0.4	0.2	0.0
S2L	7%	0.7	0.5	0.3	0.5	0.3	0.1	0.4	0.2	0.0
C2L	7%	0.9	0.6	0.4	0.6	0.3	0.1	0.4	0.2	0.0
URML	10%	N/A	N/A	N/A	0.5	0.3	0.1	0.4	0.2	0.0

Figure 6 shows a typical capacity curve and three example demand spectra for damping levels corresponding to short (κ = 0.9), moderate (κ = 0.6) and long (κ = 0.4) duration ground shaking, respectively. In this example, building displacement due to long-duration ground shaking is more than twice that due to short-duration ground shaking (although building acceleration does not increase). Damage to the structural system and nonstructural, drift-sensitive components and related losses increase significantly with increase in the duration of ground shaking for buildings that have reached yield.

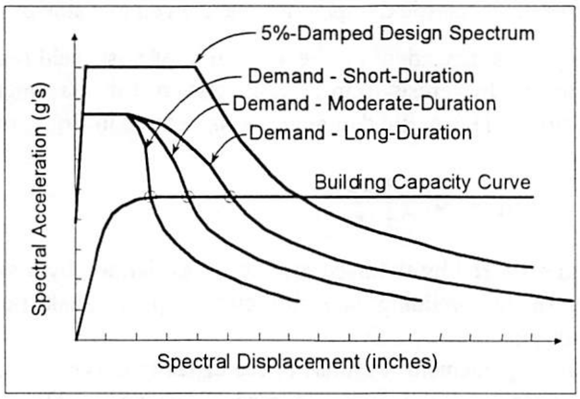


Figure 6. Example demand spectra – strong ground shaking of short, moderate and long-duration

BUILDING FRAGILITY CURVES

Building fragility curves are lognormal functions that describe the probability of reaching, or exceeding, structural and nonstructural damage states, given deterministic (median) estimates of spectral response, for example spectral displacement. These curves take into account the variability and uncertainty associated with capacity curve properties, damage states and ground shaking.

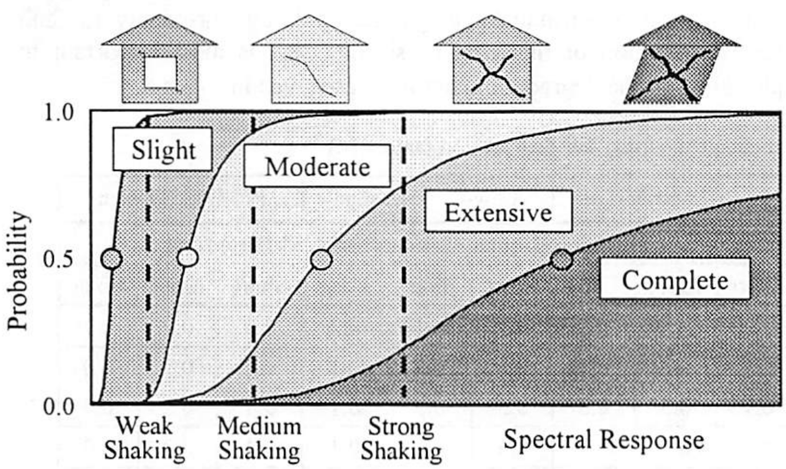


Figure 7. Example fragility curves for Slight, Moderate, Extensive and Complete damage

Figure 7 provides an example of fragility curves for the four damage states used in the FEMA/NIBS methodology and illustrates differences in damage-state probabilities for three levels of spectral response corresponding to weak, medium, and strong earthquake ground shaking, respectively. The terms "weak," "medium," and "strong" are used here for simplicity; in the actual methodology, only quantitative values of spectral response are used.

The fragility curves distribute damage among Slight, Moderate, Extensive and Complete damage states. For any given value of spectral response, discrete damage-state probabilities are calculated as the difference of the cumulative probabilities of reaching, or exceeding successive damage states. Discrete damage-state probabilities are used as inputs to the calculation of various types of building-related loss. Figure 8 provides an example of discrete damage state probabilities for the three levels of earthquake ground shaking.

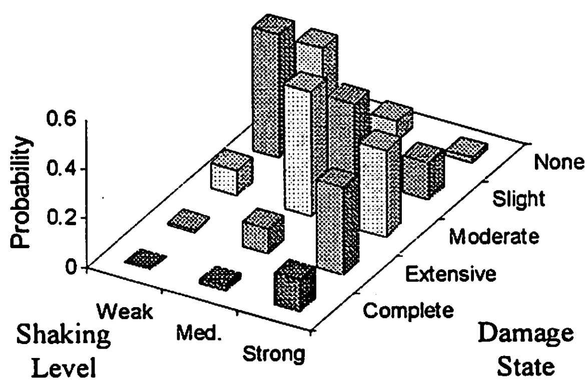


Figure 8. Example damage-state probabilities for weak, medium and strong shaking levels

Each fragility curve is defined by a median value of the demand parameter (e.g., spectral displacement) that corresponds to the threshold of that damage state and by the variability associated with that damage state. For example, the spectral displacement, S_d, that defines the threshold of a particular damage state (ds) is given by Equation (5):

$$S_d = \overline{S}_{d,ds}\,\varepsilon_{ds} \qquad (5)$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement of damage state, ds,

ε_{ds} is a lognormal random variable with a unit median value and a logarithmic standard deviation, β_{ds}.

In a more general formulation of fragility curves, the lognormal standard deviation, β, has been expressed in terms of the randomness and uncertainty components of variability, β_R and β_U, respectively [Kennedy, et. al., 1980]. In the Kennedy formulation, uncertainty represents the component of the variability that could theoretically be reduced with improved knowledge, whereas randomness represents the inherent variability (in response) that cannot be eliminated, even with perfect knowledge. Since it is not considered practical to separate uncertainty from randomness, the combined variability, β, is used to develop a composite "best-estimate" fragility curve. This approach is similar to that used to develop fragility curves for the FEMA-sponsored study of consequences of a large earthquake on six cities of the Mississippi Valley region (Kircher and McCann, 1983).

The conditional probability of being in, or exceeding, a particular damage state, ds, given the spectral displacement, S_d, (or other seismic demand parameter) is defined by Equation (6):

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \tag{6}$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state, ds,
β_{ds} is the standard deviation of the natural logarithm of spectral displacement for damage state, ds, and
Φ is the standard normal cumulative distribution function.

DAMAGE-STATE MEDIANS

Median values of fragility curves are developed for each damage state (i.e., Slight, Moderate, Extensive and Complete) of each of the three types of building systems: structural, nonstructural drift-sensitive components and nonstructural acceleration-sensitive components. In general, median fragility values are also different for each seismic design and performance level.

Structural fragility is expressed in terms of spectral displacement, except for lifeline buildings whose fragility functions are expressed in terms of peak ground acceleration for compatibility with lifeline equipment fragility. Median values of structural component fragility are based on inter-story drift ratios that describe the threshold of damage states. Damage-state drift ratios are converted to spectral displacement using Equation (7):

$$\overline{S}_{d,ds} = \delta_{ds}\,\alpha_2\,H \tag{7}$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement for damage state, ds,
δ_{ds} is the drift ratio at the threshold of structural damage state, ds,
α_2 is the fraction of the building (roof) height at the elevation where pushover-mode displacement equals spectral displacement, and
H is the typical roof height of the model building type of interest.

Values of damage-state drift ratios included in the FEMA/NIBS methodology are based, in part, on available damage data from a number of published sources, including Kustu et al. (1982), Ferritto (1982 and 1983), Czarnecki (1973), Hasselman et al. (1980), Whitman et al. (1977) and Wong (1975). Drift ratios are different for each model building type (including height-defined sub-types) and seismic design level. Table 7 summarizes typical drift ratios used to define structural damage for various building types. In Table 7, drift ratios decrease with building height to account for anticipated non-uniform distribution of drift over the height of the building (i.e., the taller the building, the more likely some floors will have higher than average drifts).

Table 7. Typical drift ratios used to define structural damage states

Design Level	Model Building Type	Drift Ratio at the Threshold of Structural Damage			
		Slight	Moderate	Extensive	Complete
High-Code	W1	0.004	0.012	0.040	0.100
	S1L	0.006	0.012	0.030	0.080
	S1M	0.004	0.008	0.020	0.053
	S1H	0.003	0.006	0.015	0.040
	C2L	0.004	0.010	0.030	0.080
Moderate-Code	W1	0.004	0.010	0.031	0.075
	S1L	0.006	0.010	0.024	0.060
	C2L	0.004	0.008	0.023	0.060
Low-Code	W1	0.004	0.010	0.031	0.075
	S1L	0.006	0.010	0.020	0.050
	C2L	0.004	0.008	0.020	0.050
	URML	0.003	0.006	0.015	0.035
Pre-Code	W1	0.003	0.008	0.025	0.060
	S1L	0.005	0.008	0.016	0.040
	C2L	0.003	0.006	0.016	0.040
	URML	0.002	0.005	0.012	0.028

Nonstructural drift-sensitive component fragility is based on spectral displacement, as is structural system fragility. As in Equation (7), median values of spectral displacement are expressed in terms of the product of (1) damage-state drift ratios, (2) the fraction of building height at the elevation where pushover mode equals spectral displacement (α_2), and (3) typical roof height of the model building type.

Damage-state drift ratios are based, in part, on the work of Ferritto (1982 and 1983) and on a recent update of this data included in a California Division of the State Architect report (DSA, 1996). Table 8 summarizes the drift ratios used to develop median values of fragility curves for drift-sensitive nonstructural components of buildings. Nonstructural damage drift ratios are assumed independent of model building type and seismic design level.

Table 8. Drift ratios used to define median values of fragility curves for nonstructural drift-sensitive components

Drift Ratio at the Threshold of Nonstructural Damage			
Slight	Moderate	Extensive	Complete
0.004	0.008	0.025	0.050

Nonstructural acceleration-sensitive component fragility is based on peak floor acceleration, taken as either peak ground acceleration for evaluation of components located at or near the base of the building, or average upper-floor peak acceleration for evaluation of components located in the upper stories of the building. Average upper-floor acceleration is assumed to be equal to the spectral acceleration defined by the capacity curve.

Median values of damage-state spectral acceleration are based, in part, on the work of Ferritto (1982 and 1983) and on a recent update of this data included in a DSA report (1996). Table 9 summarizes the peak floor accelerations used to define median values of fragility curves for acceleration-sensitive nonstructural components of buildings. Nonstructural damage acceleration values are the same for each model building type, but vary by seismic design level to account for different levels of seismic restraint and/or anchorage.

Table 9. Peak floor accelerations used to define median values of fragility curves for nonstructural acceleration-sensitive components

Seismic Design Level	Peak Floor Acceleration at the Threshold of Nonstructural Damage (g)			
	Slight	Moderate	Extensive	Complete
High-Code	0.30	0.60	1.20	2.40
Moderate-Code	0.25	0.50	1.00	2.00
Low-Code	0.20	0.40	0.80	1.60
Pre-Code	0.20	0.40	0.80	1.60

DAMAGE-STATE VARIABILITY

Lognormal standard deviation values (β) describe the total variability of fragility-curve damage states. Three primary sources contribute to the total variability of any given state, namely, the variability associated with the capacity curve, β_C, the variability associated with the demand spectrum, β_D, and the variability associated with the discrete threshold of each damage state, $\beta_{T,ds}$, as described in Equation (8):

$$\beta_{ds} = \sqrt{(\mathrm{CONV}[\beta_C, \beta_D])^2 + (\beta_{T,ds})^2} \tag{8}$$

where:

- β_{ds} is the lognormal standard deviation parameter that describes the total variability of damage state, ds,
- β_C is the lognormal standard deviation parameter that describes the variability of the capacity curve,
- β_D is the lognormal standard deviation parameter that describes the variability of the demand spectrum,
- $\beta_{T,ds}$ is the lognormal standard deviation parameter that describes the variability of the threshold of damage state, ds.

Since the demand spectrum is dependent on building capacity, a convolution process is required to combine their respective contributions to total variability. This is referred to as "CONV" in Equation (8) and is described below. The third contributor to total variability, $\beta_{T,ds}$, is assumed mutually independent of the first two variables and is combined with the results of the CONV process using the square-root-sum-of-the squares (SRSS) method.

The convolution process is graphically illustrated by a three-dimensional (3D) surface as shown in Figure 11. This surface defines the joint probability function of intersection points of capacity and demand in the spectral displacement-spectral acceleration (S_d-S_a) domain. For any given building type, a unique median capacity curve is defined as described in the previous section. A suite of curves representing other (non-median) probability levels characterizes capacity variability in the S_d-S_a domain. Each of these curves has a probability defined by the lognormal standard deviation parameter, β_C, and a shape that maintains the relationship between yield and ultimate points, as shown in Figure 2. In 3D space, the distribution of possible capacity curves looks like a bell curve moving along the median.

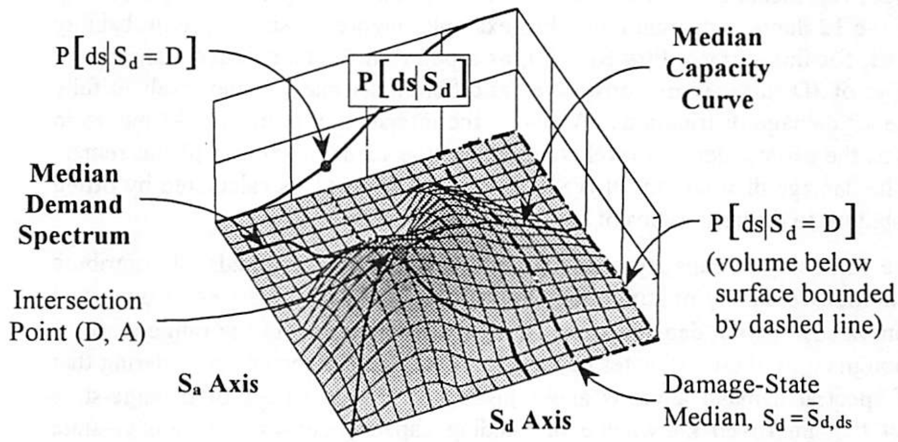


Figure 11. Example joint probability surface of demand and capacity intersection points. *In color:* see plates following p. 738.

The median demand spectrum is defined by a generic shape scaled to represent different levels of ground shaking (i.e., different distances from the source). In general, the shape of the median demand spectrum is a function of a number of factors, including source magnitude and type, and site conditions. For the purpose of defining demand variability, the shape of the median demand spectrum is assumed to be the same for all source and site conditions. A suite of demand curves representing other (non-median) probability levels characterizes demand variability in the S_d-S_a domain. Each of these curves has a probability defined by the lognormal standard deviation parameter, β_D, and the same shape as median spectral demand.

The joint probability surface shown in Figure 11 is the cross-product of demand and capacity probability functions, discretely characterized by the suites of demand and capacity curves described above. The shape of surface is an indicator of response variability; the greater the variability of capacity and demand, the flatter the surface. On the other hand, if capacity and demand were known exactly (which is not realistic), the surface would converge to a spike at the intersection point of median demand and capacity (D, A).

Vertical planes in 3D space are used to calculate damage distributions for each of the three building systems: structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive components. Planes normal to the S_d axis represent the first two systems, while planes normal to the S_a axis represent the latter system. Each plane is defined by the median value of the damage state. There are 12 vertical planes in total, representing four damage states for each of the three building systems.

The volume under the entire 3D surface shown in Figure 11 is 100%, representing all possible intersections of demand and capacity in the S_d-S_a domain. The probability of reaching or exceeding a given damage state, ds, for a given building system is the volume under the 3D surface for values of S_d (or S_a) greater than median value of S_d (or S_a) that defines the plane representing the damage state. For example, a dashed line in Figure 11 bounds the portion of the 3D surface used to calculate the probability of damage state, ds, given spectral displacement, $S_d = D$.

Each 3D surface represents a specific level of seismic demand and yields one probability value for each of the 12 damage distributions. For example, Figure 11 shows the probability of damage state, ds, for this surface, $P[ds|S_d = D]$, as a point on the cumulative distribution, $P[ds|S_d]$. A number of 3D surfaces are constructed at different seismic demand levels to fully define each of the 12 damage distributions. Visually, the intersection point (D, A) moves in the S_d-S_a domain as the seismic demand level changes, but the 12 damage-state planes remain fixed in space. The damage distribution, $P[ds|S_d]$, shown in Figure 11, is calculated by fitting a lognormal distribution to discrete values of cumulative probability.

In general, the variability of capacity, demand and damage-state thresholds all contribute significantly to the total variability of structural and nonstructural damage states. Lognormal standard deviation values of total damage-state variability are generally in the range of β_{ds} = 0.65 to 1.2. Although large, these estimates of total variability are reasonable considering that the variability of spectral demand alone is about $\beta_D = 0.5$. Large values of damage-state variability suggest that improved knowledge of building capacity curves and damage-state thresholds could appreciably reduce uncertainty in damage estimates. However, damage-state variability can never be less than the variability of spectral demand, and damage estimates will always have uncertainty due to the inherent variability of earthquake ground shaking.

Reducing damage-state variability would have a limited effect on the probability of damage for demand levels at or near the median value of the damage state of interest. On the other hand, reducing variability would significantly change the probability of damage for demand levels that are much smaller than the median of the given damage state. The latter condition is typical of estimates of Extensive or Complete damage, which tend to have small probabilities (i.e., less than 0.10) even for strong ground shaking. Improved knowledge of building capacity and damage states would be most useful for better estimation of the probabilities of Extensive or Complete damage, and those losses, such as fatalities or loss of function, that are most dependent on these states of damage. In contrast, economic loss is less sensitive to damage-state variability, since all damage states contribute significantly to this type of loss.

CONCLUSION

This paper has described building damage functions of the FEMA/NIBS earthquake loss estimation methodology. These functions estimate probabilities of building damage states based on quantitative measures of ground shaking (response spectra). Damage-state probabilities are used by the FEMA/NIBS methodology as inputs to the estimation of building losses, including economic loss, casualties and loss of function.

Building damage functions are of a new form and represent a significant step forward in the prediction of earthquake impacts. These functions now permit loss estimation to incorporate important ground shaking characteristics, including site/soil amplification effects and shaking duration. Further, these functions explicitly consider the differences among buildings based on their seismic design level and vintage, and anticipated performance, explicitly considering nonlinear inelastic response, and its effects on the structural system, nonstructural components, and contents of the building.

FEMA/NIBS building damage functions provide rational tools for quantitative evaluation of building losses and mitigation alternatives that previously could only be judged in a qualitative manner. With these tools, engineers and planners can begin to develop strategies for earthquake hazard mitigation that combine both elements of pre-event action and post-event response and recovery using more reliable engineering data.

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8.

Estimation of Earthquake Losses to Buildings

Charles A. Kircher, M.EERI, Robert K. Reitherman, M.EERI,
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This paper describes methods for estimating building losses that were developed for the FEMA/NIBS earthquake loss estimation methodology (Whitman et al., 1997). These methods are of a new form and represent a significant step forward in the prediction of earthquake impacts. Unlike previous building loss models that are based on Modified Mercalli Intensity, the new methods use quantitative measures of ground shaking (and ground failure) and analyze model building types in a similar manner to the engineering analysis of a single structure. Direct economic losses predicted by these new methods for typical single-family homes compare well with observed losses to Los Angeles County residences damaged by the 1994 Northridge Earthquake.

INTRODUCTION

Past earthquakes have shown that economic and social losses are primarily a function of damage to buildings. This is true for two very basic reasons: (1) buildings are the predominant kind of facility in the built environment and (2) buildings are vulnerable to earthquake damage. Buildings meet a variety of needs of society: providing shelter for people, whether at home or at work, housing commercial and industrial operations, and serving as essential facilities, such as schools and hospitals. Accurate prediction of building damage and loss is at the heart of reliable estimates of earthquake impacts.

This paper describes building loss functions developed as part of the FEMA/NIBS earthquake loss estimation methodology. This methodology has many components, or modules, as described in the paper by Whitman, et al. (1997) in this *Spectra* issue. The flow of the methodology between those modules related to building damage and loss is illustrated in Figure 1. Inputs to the estimation of building damage include ground failure, characterized

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by permanent ground deformation (PGD) due to settlement or lateral spreading, and ground shaking, typically characterized by response spectra, or, for those few buildings that are components of lifeline systems, by peak ground acceleration (PGA).

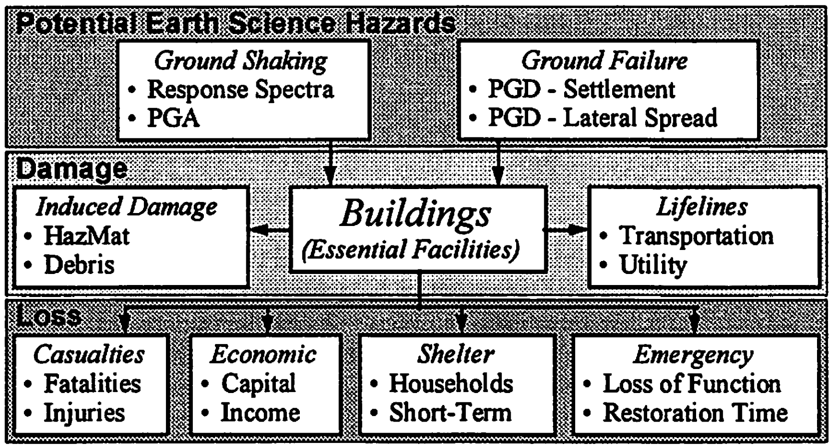

Figure 1. Building-related modules of the FEMA/NIBS methodology

Estimates of building damage are used as inputs to other damage modules (e.g., debris generation), and as inputs to transportation and utility lifelines that have buildings as a part of the system (e.g., airport control tower). Most importantly, building damage is used as an input to a number of loss modules, including the estimation of casualties, direct economic losses, displaced households and short-term shelter needs, loss of emergency facility function and the time required to restore functionality.

The FEMA/NIBS building damage functions have two basic components: (1) capacity curves and (2) fragility curves. The capacity curves are based on engineering parameters (e.g., yield and ultimate levels of structural strength) that characterize the nonlinear (pushover) behavior of 36 different model building types. For each of these building types, capacity parameters distinguish between different levels of seismic design and anticipated seismic performance. The fragility curves describe the probability of damage to a model building's (1) structural system, (2) nonstructural components sensitive to drift and (3) nonstructural components (and contents) sensitive to acceleration. For a given level of building response, fragility curves distribute damage between four physical damage states: Slight, Moderate, Extensive and Complete. A companion paper by Kircher et al. (1997) in this *Spectra* issue provides a more thorough description of the FEMA/NIBS building damage functions.

Earthquake loss due to building damage is based on the physical damage states that are the most appropriate and significant contributors to that particular type of loss. Deaths are heavily influenced by the number of buildings in the Complete damage state, which includes the kind of partial and complete collapse most likely to cause fatalities. In contrast, direct economic loss (e.g., repair/replacement cost) is accumulated from significant loss contributions in all states of structural and nonstructural damage.

The balance of this paper begins with a historical perspective on building loss estimates and its importance to the FEMA/NIBS methodology. The paper then summarizes methods for the estimation of direct economic loss to buildings (assuming that estimates of building damage have already been made). Methods for calculating other types of loss and detailed documentation of all of the topics covered in this paper may be found in the *Technical Manual* (NIBS, 1997). The paper closes with a comparison of predicted and observed economic loss to buildings using data for Los Angeles County residences damaged by the 1994 Northridge Earthquake.

HISTORICAL BACKGROUND

When considered in historical context, it is clear that in some ways the FEMA/NIBS methodology draws on previous work and represents a gradual evolutionary development, while in other respects it introduces major innovations that depart from past work.

INTENSITY AS A DAMAGE PREDICTOR

The FEMA/NIBS methodology uses quantitative definitions of ground motions rather than intensity. This is perhaps the single most useful topic to discuss in this historical context for three reasons. First, in and of itself, the way in which a loss estimation method incorporates a strong motion seismology module and defines and predicts ground shaking is of obvious importance. Second, the concept of intensity, with its long history, provides a convenient means of framing a very condensed review of some previous loss estimation methods. Third, knowing that the FEMA/NIBS methodology does not rely on intensity provides a subtle foreshadowing of the fact that damage is not predicted by graphs that relate loss to an intensity scale, but rather by means of a set of calculations that closely mimic the quantitative engineering evaluation of a single building.

If one were to update Charles Davison's 1927 book, *The Founders of Seismology* (Davison, 1927), in which he reviewed intensity scales developed since the 1780s, one would need only add to his lists the current versions of the Modified Mercalli Intensity (MMI), Japanese Meteorological Agency (JMA), Medvedev-Sponheur-Karnik (MSK) and a few others. It would not be necessary to describe the present generation of scales as a separate breed, that is, definitions have been tightened up, but the essential concept, for loss estimation purposes, of a graph or table relating damage to the number on an intensity scale still pertains. Hugo Benioff (1934) tantalizingly suggested the goal of characterizing ground motion in the title of his paper, "The Physical Evaluation of Seismic Destructiveness." This paper describes the basic approach of relating destructiveness to the "pendular spectrum" (or the response spectrum, constructed by calculating "the maximum deflections of a small finite number of pendulums"). Intensity scales have in some instances (e.g., the MSK Scale) incorporated parallel cross-referenced quantitative scales for peak ground acceleration or peak ground velocity, but incorporation of response spectra has remained elusive.

PREVIOUS LOSS ESTIMATION METHODS

John Freeman (1932) discusses early twentieth century loss estimation in the classic book, *Earthquake Damage and Earthquake Insurance*, whose title indicates the primary use of loss estimation at that time. Further developments in loss estimation in this country until about the 1970s remained largely confined within the insurance industry. The work of the Insurance Services Office (ISO) was especially influential, as discussed in Steinbrugge (1982). For insurance purposes, the prediction of physical damage is not of interest in itself; only the dollar cost of repairing the damage is desired.

With the publication in 1972 of *A Study of Earthquake Losses in the San Francisco Bay Area* (Algermissen et al., 1972), the federal government began to produce comprehensive estimates of the effects of major earthquakes on large urban regions. Direct economic losses, casualties, essential facilities' functionality, and some lifeline impacts were estimated. By the mid-1980's, these studies, produced by teams assembled by the National Oceanic and Atmospheric Administration and later the United States Geological Survey, had forecast losses for about a dozen metropolitan areas in the United States. (See NRC, 1989 and FEMA, 1994).

A program of studies at MIT, Seismic Design Decision Analysis, was begun after the 1971 San Fernando Earthquake and was directed by Robert Whitman (Whitman et al., 1974). This work popularized a new way to relate ground motion to loss, the damage probability matrix (Whitman, Reed, and Hong, 1973). Explicit recognition of the probabilistic nature of the underlying loss phenomenon became a reality that subsequent loss estimation methods could no longer overlook.

An influential study in 1985, *Earthquake Damage Evaluation Data for California*, (Applied Technology Council, 1985), commonly called ATC-13, used the Whitman damage probability matrix as its central framework. It also introduced several other notable advances in large-scale loss estimation, such as using expert opinion in a well-documented and systematic way, devising intensity-damage relations for a large number of buildings and structure types, predicting a greater variety of losses than had been previously done, and developing what might be called synthetic inventories by inferences relating structural type to building occupancy.

When the National Research Council's Panel on Earthquake Loss Estimation convened in the mid-80's, it noted that "more complex representations of ground shaking, for example, through a filtered 'effective' peak motion, a single-degree-of-freedom linear response spectrum, a nonlinear spectrum, a time history of motion, and the duration of strong shaking, have the ability to be more accurate predictors of damage and loss. There is less agreement, however, on how to estimate these functions for a future earthquake, how to quantify the single or multi-dimensional hazard associated with them, and how to derive an accurate predictor of damage from them." (NRC, 1989).

It is precisely the challenges defined by the Panel's 1989 report that the FEMA/NIBS methodology addresses, by using spectral response curves, capacity curves, and push-over analyses that parallel procedures used in the engineering design and evaluation of actual buildings to predict damage and loss. In this sense, these new methods follow the spirit of the recommendations of the National Research Council's Panel on Earthquake Loss Estimation and accomplishes in the field of large-scale loss estimation what Hugo Benioff and others of the 1930s could envision but not yet produce.

BUILDING LOSS FUNCTIONS

Building loss functions of the FEMA/NIBS methodology may be thought of as the second part of an integral two-step process in which estimates of building damage (i.e., probability of damage state) are transformed into estimates of various types of loss. The companion paper by Kircher, et al. (1997) in this *Spectra* issue describes the first step of this process and should be referred to for estimation of building damage and description of model building types, design levels, and other building parameters.

The building loss functions are typically complex and a full description of the background and theory is beyond the scope of this paper. The reader is directed to the *Technical Manual* (NIBS, 1997) for additional information. The balance of this section provides a summary description of direct economic loss functions for buildings.

DIRECT ECONOMIC LOSS FUNCTIONS

Direct dollar loss is defined in the FEMA/NIBS methodology as either capital-related or income-related. Capital-related losses for buildings include costs for repair and replacement of damage to the structural system, nonstructural components and building contents (including business inventory for commercial facilities). Income-related losses for a building include rental income loss, relocation expenses, and other losses directly caused by damage to the building, and while these losses are included in the methodology, they are not within the scope of this paper.

Direct economic losses depend on both building occupancy class (e.g., single-family residences) and model building type (e.g., light-frame wood, W1). Inventory information defines the floor area of each model building type used for each occupancy class in each area (i.e., census tract or group of census tracts) of the region being studied.

The FEMA/NIBS methodology provides default values for building repair and replacement cost (expressed in terms of dollars per square foot) for each combination of model building type and occupancy class. While it can be argued that the true cost of buildings damaged or destroyed is their loss of market value, replacement cost provides an immediately understandable picture of the community building loss. Furthermore, disaster assistance and most insurance is based on replacement cost. Market value is by no means constant in relation to replacement cost. For example, typical estimates of market value include lot value, which is not included in the replacement cost of a building and may cause market value to greatly exceed replacement cost.

Default values of repair and replacement costs are specified separately for the structural system, nonstructural drift-sensitive components and nonstructural acceleration-sensitive components of the building. The relative percentage of total building cost allocated to structural and nonstructural systems is derived from *Means* (Jackson, 1994) component data for each building occupancy class. For most classes, the nonstructural portion of the cost is about 75% of the total. In addition, adjustment factors based on *Means* data are used to reflect differences in construction cost for different regions of the United States. Contents value is expressed as a percentage of structural and nonstructural replacement cost for each occupancy class in a manner similar to that of *ATC-13* (ATC, 1985), but with different (lower) rates.

The costs of Slight, Moderate, Extensive and Complete structural and nonstructural damage are defined as fractions of full replacement cost of the building. These fractions are similar in concept to the central damage factors of ATC-13 (ATC, 1985), but are calibrated to better reflect observed earthquake losses. Damage to contents follows the same approach as that of the building, except that only 50% of all contents are assumed to be susceptible to earthquake damage, even in the case of Complete damage. The relationship between damage state and replacement cost is summarized in Table 1 for the structural system, nonstructural components, and contents.

Table 1. Direct economic loss as a percentage of building replacement cost by damage state

Damage State	Structural System	Nonstructural (Drift Sensitive)	Nonstructural (Acceleration Sensitive)	Contents
Slight	2%	2%	2%	1%
Moderate	10%	10%	10%	5%
Extensive	50%	50%	50%	25%
Complete	100%	100%	100%	50%

The process for determining direct economic capital-related loss to all buildings in a given study region is illustrated by the logic tree shown in Figure 2.

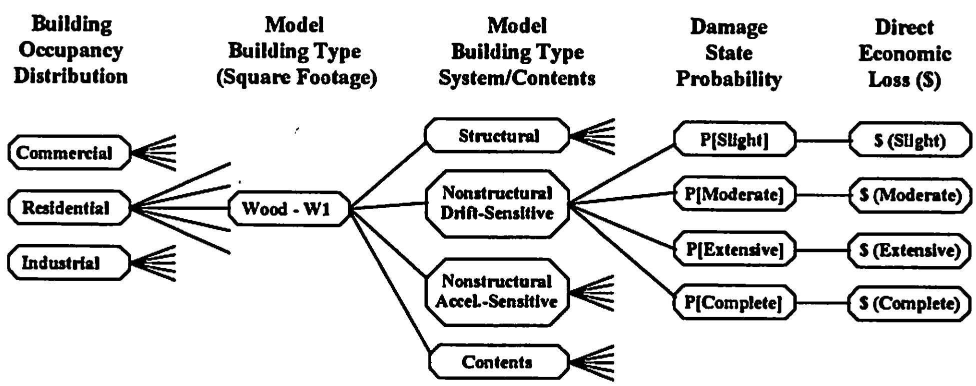

Figure 2. Logic tree for calculation of direct economic loss to buildings

Equation (1) illustrates the calculation of direct economic loss due to structural damage for a given model building type (e.g., single-family residential, light-frame wood building):

$$\$\text{Loss (Structural)} = \text{Square Footage}\left(\sum_{i}^{\text{damage-states}} P_i[SD]\,\$R_i[SD]\right) \quad (1)$$

Structural system loss rates, $\$R_i[SD]$, and nonstructural component and contents loss rates are given in Table 2 for a typical California, single-family residence. The term, $P_i[SD]$, in Equation (1) represents the probability of structural damage of damage state i. Similar equations are used to calculate losses due to damage to nonstructural drift-sensitive components, nonstructural acceleration-sensitive components, and contents.

Table 2. Typical loss rates for single-family residences of light-frame wood construction located in California (dollars per square foot)

Damage State	Structural System	Nonstructural (Drift Sensitive)	Nonstructural (Acceleration Sensitive)	Total Building	Contents	Building Plus Contents
Slight	$0.38	$0.80	$0.43	$1.60	$0.40	$2.00
Moderate	$1.88	$2.00	$2.13	$8.00	$2.00	$10.00
Extensive	$9.38	$20.00	$10.63	$40.00	$10.00	$50.00
Complete	$18.75	$40.00	$21.25	$80.00	$20.00	$100.00

Total loss to this particular building type and occupancy class is the sum of structural, nonstructural and contents losses. The total loss to all residences is the sum of the individual losses to each type of building used for residential construction. Total loss to all buildings is the sum over all occupancy classes.

PREDICTED AND OBSERVED LOSS - 1994 NORTHRIDGE EARTHQUAKE

As part of the development of the FEMA/NIBS methodology, loss functions were calibrated by comparing predicted loss with observed loss due to previous earthquakes, including the 1994 Northridge Earthquake. For the 1994 Northridge Earthquake, predictions of damage and loss were based on response spectra of ground shaking records. These comparisons either verified that building loss functions could reasonably replicate observed impacts, or in certain cases, loss functions were revised to achieve better correlation between predicted and observed losses.

Los Angeles County was selected as the study area for comparison of predicted and observed losses of the 1994 Northridge Earthquake. Los Angeles County is large (over 1,600 census tracts) and includes most of the populated areas that felt strong ground shaking. Losses were evaluated for individual census tracts, and aggregated results were used for calibration of loss functions.

To permit comparison with other loss estimation methods (and to simplify results for this paper), Los Angeles County census tracts are grouped into five regions of common Modified Mercalli Intensity (MMI). Intensity data was taken from the MMI map of Dewey (reproduced in the California Governor's Office of Emergency Services report on the 1994 Northridge Earthquake, OES, 1995). Figure 3 shows MMI shaking regions superimposed on top of the distribution of building value (i.e., replacement cost per square mile) of Los Angeles County residences.

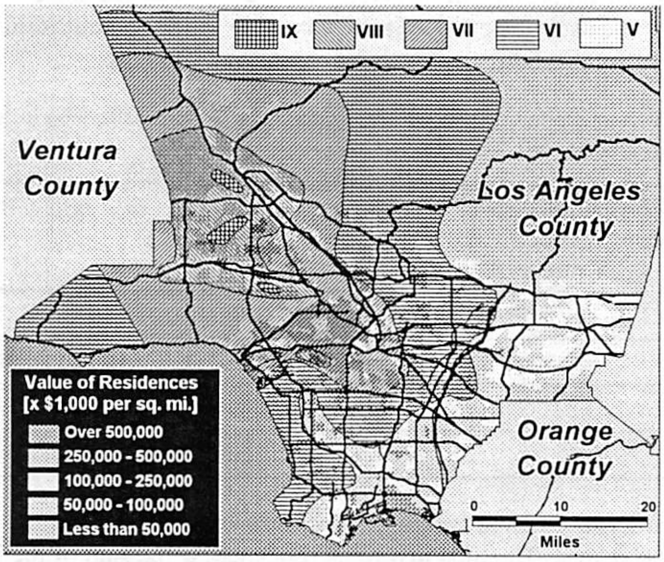

Figure 3. Map of Los Angeles County residential building value and MMI shaking regions of the 1994 Northridge Earthquake. *In color:* see plates following p. 738.

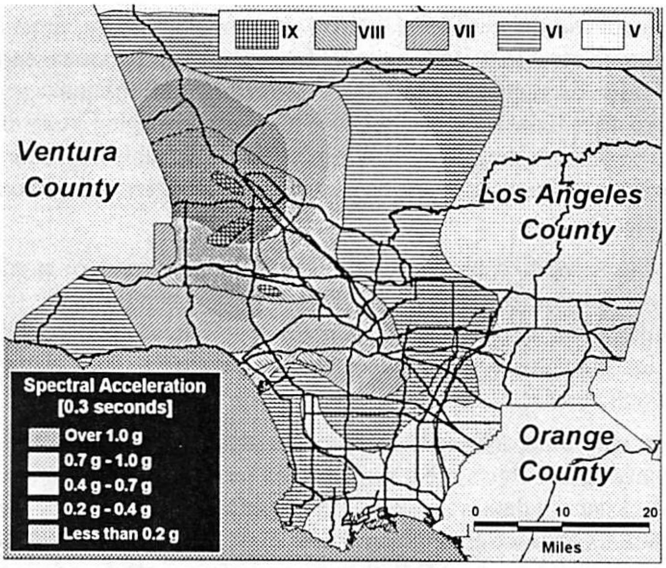

Figure 4. Map of Los Angeles County comparing 0.3-second spectral acceleration response and MMI shaking regions of the 1994 Northridge Earthquake. *In color:* see plates following p. 738.

Representative ground response spectra (5% damping) are developed for each of the five regions of MMI shaking intensity. These spectra are based on weighted averages of individual census tract spectra of each MMI shaking region. Spectra are weighted by building floor area (since all census tracts do not have the same quantity of buildings). Individual census tract spectra are based on the spectral contour data developed by Somerville for the SAC Joint Venture investigation of steel moment frame structures (SAC 95-03, 1995). Figure 4 shows MMI shaking regions superimposed on top of 0.3-second spectral acceleration data used to define short-period earthquake demand.

The spectral contour data are based on recorded ground motion smoothed to eliminate local effects. Spectral demand (and corresponding loss predictions) for an individual census tract may not be valid, since smoothed spectral contour data may overpredict (or underpredict) actual ground shaking at an individual tract. Average spectral demand produces valid results, provided there are a sufficient number of census tracts in each group to determine a reliable estimate of ground shaking. All MMI shaking regions have a large number of census tracts, except MMI IX which does not contain a sufficient number of census tracts to produce a reliable estimate of typical ground shaking. Ground shaking for the MMI IX shaking region is estimated as 1.5 times the shaking for MMI VIII. This level of ground shaking is slightly above the calculated average, but well within the scatter of spectral contour values for census tracts of the MMI IX shaking region.

Figure 5 shows a plot of the ground response spectra (5% damping) developed for each of the five MMI shaking regions. The response spectrum for the MMI VIII shaking region is about 80% of the response spectrum required by the *Uniform Building Code* (ICBO, 1997) for design of buildings located in Seismic Zone 4 on stiff soil (Site Class D) at least 10 km from active sources. This level of ground shaking is not expected to cause life-threatening damage to modern buildings designed for earthquakes, but is sufficiently strong to cause some amount of structural and nonstructural damage.

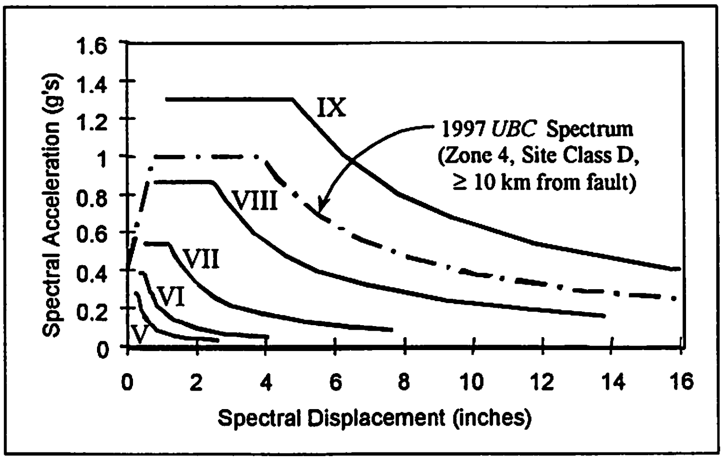

Figure 5. Average 5%-damped response spectra of the 1994 Northridge Earthquake for MMI shaking regions V - IX

LOS ANGELES COUNTY STUDY REGION

Population and building inventory data for Los Angeles County are based on census data provided with the FEMA/NIBS methodology, and on tax assessor data. Key information on population and building inventory, including the number, value (replacement cost), age, and construction of residences, is summarized in Table 3 for Los Angeles County as a whole, and as distributed among each of the five MMI shaking regions.

Table 3. Los Angeles County population and building inventory data by MMI shaking region

Population or Building Inventory Item	MMI Shaking Region - Los Angeles County					
	All	V	VI	VII	VIII	IX
Population ($x10^3$)	8,863	2,628	2,545	2,590	1,007	92
Number of Buildings ($x 10^3$)	2,254	745	682	526	272	28
Number of Residential Buildings and Living Units						
All Residences ($x 10^3$)	2,023	670	614	460	254	26
Single-Family Units ($x 10^3$)	1,740	578	548	386	206	23
Multi-Family Units ($x 10^3$)	1,334	288	301	555	180	10
Mobile Homes ($x 10^3$)	55.4	31.1	13.7	5.0	5.6	0.0
Replacement Cost of Residential Buildings - Dollars in Billions						
Building without Contents	$340B	$99B	$95B	$102B	$40.5B	$3.5B
Contents (50% of Building)	$170B	$49B	$48B	$51B	$20.5B	$1.5B
Building plus Contents	$510B	$148B	$143B	$153B	$61B	$5B
Building plus Contents (%)	100%	29%	28%	30%	12%	1%
Age and Construction of Residential Buildings						
Pre-1941 Residences (%)	29%	17%	32%	50%	14%	22%
1941-1976 Residences (%)	65%	62%	56%	36%	68%	68%
Post-1976 Residences (%)	16%	21%	12%	14%	18%	10%
Wood Residences (%)	99.2%	99.5%	98.4%	98.4%	99.3%	99.6%
Brick Residences (%)	0.5%	0.4%	0.4%	0.7%	0.4%	0.3%

Based on building value (defined as the replacement cost of the building, excluding land value), only about 12% of all residential construction is located in the MMI VIII shaking region, and just over 1% of all residential construction is located in the MMI IX shaking region. This distribution of building value is illustrated in Figure 6, which also shows the relative amount of replacement cost for the structural system, nonstructural drift-sensitive and acceleration-sensitive components, and building contents. Direct economic loss to residences due to damage in the MMI IX shaking region was not a significant portion of total residential loss, simply because only a small fraction of all residences are located in this region of shaking intensity.

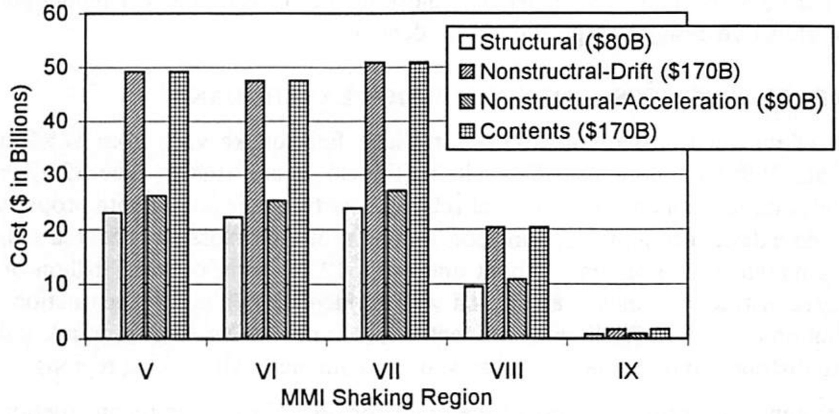

Figure 6. Replacement cost of Los Angeles County residences by MMI shaking region

Los Angeles County has a total population of 8.86 million people and an inventory of 2.25 million buildings. About 90% (over 2 million) of all buildings are residential. In terms of the replacement cost (based on floor area), residences represent about 75% of the total value of all buildings. Residences in Los Angeles County have a replacement cost (without contents) of $340 billion, or about $510 billion with contents.

Over 99% of all residences are wood construction (excluding mobile homes). This percentage applies to single-family residences, which are the most common type of residence. Multi-family residences are primarily wood construction, but also include about 5% steel, concrete or masonry buildings. There are 1.74 million single-family living units (residences) and 1.33 million multi-family living units (in about 230,000 buildings). In rough numbers, single-family residences represent about 75% of the total residential value. These data indicate that light-frame wood buildings (i.e., model building type W1 of the FEMA/NIBS methodology) are by far the most common type of residential building.

By age, about 29% of all residences in Los Angeles were built before 1941, about 65% were built between 1941 and 1976 and about 16% were built after 1976. These data indicate that residences were typically built to the seismic requirements of the *Uniform Building Code*, but before modern seismic-code criteria were adopted (i.e., Moderate-Code design level of the FEMA/NIBS methodology). In general, damage to residences built before 1941 (i.e., Pre-Code design level), such as wood buildings with cripple walls without bracing, or unreinforced masonry (URM) buildings, is expected to be much higher than that predicted by Moderate-Code buildings. However, the number of particularly vulnerable buildings is relatively small, and hazard reduction programs, such as Los Angeles City's Division 88 program to retrofit URM buildings, have helped reduce losses in these types of buildings (SSC, 1995).

To illustrate the loss estimation process, this paper predicts economic loss to residences based on a single model building type and design level (i.e., W1 buildings of Moderate-Code design). If a more realistic mix of residential building type and design vintage was used, then higher losses would be predicted. Since most residences are light-frame wood (W1) buildings of 1941 – 1973 (Moderate-Code) design vintage, losses predicted using a more realistic mix would likely not be more than 50% higher than those predicted using the W1 model building type of Moderate-Code design as typical of all residences.

OBSERVED ECONOMIC LOSS - 1994 NORTHRIDGE EARTHQUAKE

Estimates of the total cost of the 1994 Northridge Earthquake vary from $25.7 billion (Comerio et al., 1996) to more than $40 billion (Eguchi et al., 1996). The $25.7 billion estimate includes direct economic (i.e., capital-related) loss to public and private property, but does not include indirect economic loss and some amount of direct loss not covered either by insurance or governmental programs. About one-half, $12.7 billion, of $25.7 billion of total recovery and reconstruction funds is associated with residential building reconstruction. The spatial distribution of the $12.7 billion of residential loss is not known and insurance industry data is used to distribute this estimate of "observed" loss among MMI shaking regions.

Private insurance has provided most of the funds for post-Northridge reconstruction. As of June 1996, the California Department of Insurance estimates that the state's private insurance companies have paid a total of about $12.3 billion for Northridge-related claims, of which approximately $9.5 billion, or 78%, has been for residential claims. Insurance claims include four types of coverage: (1) primary structures (Type A), (2) appurtenances (Type B), (3) contents (Type C) and (4) loss of use (Type D). Loss of use (Type D) is not considered a capital-related loss by the FEMA/NIBS methodology. Type D losses account for only 5.6% of insurance claims and are not a dominant portion of observed loss.

The spatial distribution of observed residential loss by MMI shaking region is estimated based on a sample of insurance coverage and claims paid (RMS, 1996). Information on about 85,000 claims was sorted by MMI shaking region to establish the distribution of exposure (policy limits), the number of claims and the amount of "ground-up" losses. Ground-up loss reflects actual claims paid, plus an estimate of losses not covered by policy deductibles. Dividing ground-up loss by exposure provides an estimate of the insured loss ratio for each MMI shaking region. This information is summarized in Table 4.

The $12.7 billion of residential building loss appears to be low, considering that insurance companies paid about $9 billion for residential claims (excluding deductible losses) and that only about one-half of all residences were covered by insurance. The $12.7 billion amount for residential recovery and reconstruction should be considered a lower bound on direct economic loss. If the insured loss ratios of Table 4 were applied to all residences in Los Angeles County, then the estimate of residential loss would be over $20 billion (if all damage was repaired and all uncompensated out-of-pocket expenses were paid).

The $12.7 billion estimate of observed residential loss (building plus contents) is distributed by MMI shaking region in proportion to insured loss ratios. Observed loss ratios are calculated for each MMI shaking region by dividing observed loss by residential value (i.e., the replacement cost of residential buildings and their contents). Observed losses and the corresponding loss ratios are summarized in Table 4.

A total of about $10.5 billion, over 80% all residential loss, is attributed to MMI shaking regions VII and VIII. These shaking regions have both relatively large inventories of buildings and damaging levels of shaking intensity. In contrast, only about $740 million, less than 6% of all residential loss, is attributed to MMI shaking region IX. Although the loss ratio is high for this region, the inventory of buildings is relatively small.

Table 4. Insured and observed economic loss to residences by MMI shaking region – 1994 Northridge Earthquake

Insurance/Observed Loss Item	MMI Shaking Region - Los Angeles County Study Area					
	All	V	VI	VII	VIII	IX
Insurance Loss Data – Dollars in Billions (RMS, 1996)						
Number of Claims	84,983	164	5,288	22,625	32,214	4,692
Exposure (Policy Limits)	$52B	$1.35B	$17.0B	$19.6B	$12.2B	$1.62B
Ground-Up Loss	$3.7B	$0.006B	$0.21B	$1.05B	$2.03B	$0.41B
Insured Loss Ratio		0.41%	1.25%	5.4%	16.6%	25%
Observed Loss Data – Dollars in Billions						
Replacement Cost	$510B	$148B	$143B	$153B	$61B	$5B
Observed Loss	$12.7B	$0.35B	$1.03B	$4.72B	$5.81B	$0.74B
Observed Loss Ratio		0.23%	0.72%	3.1%	9.5%	15%

PREDICTED ECONOMIC LOSS

Predictions of damage and direct economic loss are made for single-family residences of light-frame wood (W1) construction and older (Moderate-Code) design vintage using the response spectra shown in Figure 5. Peak earthquake response of the structure, the corresponding probability of structural damage, and the resulting losses to the structural system and the building as a whole, are summarized in Table 5 for each MMI shaking region. Predicted losses for the Los Angeles County study area assume all residences to be the same model building type (i.e., W1 buildings of Moderate-Code design). Figure 7 illustrates the distribution of predicted residential losses between MMI shaking regions for the structural system, nonstructural components and contents, respectively.

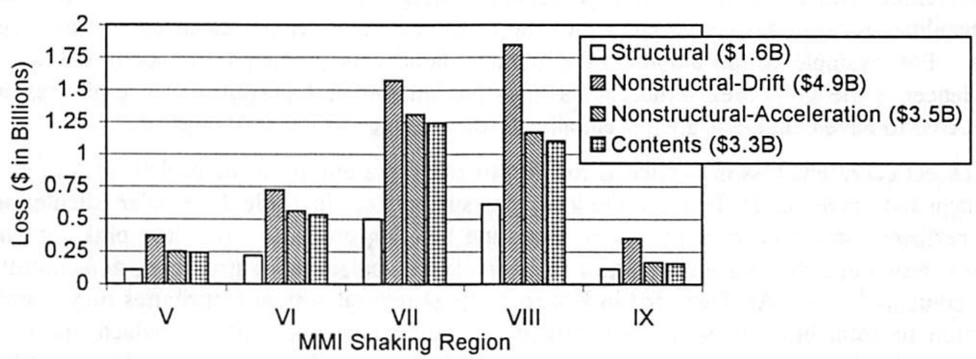

Figure 7. Direct economic loss predicted by the FEMA/NIBS methodology for Los Angeles County residences by MMI shaking region - 1994 Northridge Earthquake

Table 5. Damage and direct economic loss predicted by the FEMA/NIBS methodology for Los Angeles County residences by MMI shaking region - 1994 Northridge Earthquake

Peak Response, Damage or Loss Parameter	MMI Shaking Region - Los Angeles County Study Area					
	All	V	VI	VII	VIII	IX
Peak Response of W1 Buildings (Moderate-Code Design)						
Peak Displacement (in.)		0.21	0.29	0.42	0.70	1.25
Peak Acceleration (g)		0.17	0.25	0.35	0.54	0.70
Probability of Structural Damage to W1 Buildings (Moderate-Code Design)						
P[No Damage]	65.9%	85.3%	73.9%	57.3%	26.7%	8.9%
P[Slight Damage]	24.5%	12.8%	21.4%	31.9%	40.7%	31.0%
P[Moderate Damage]	8.7%	1.83%	4.5%	10.2%	28.2%	44.7%
P[Extensive Damage]	0.74%	0.04%	0.15%	0.55%	3.4%	11.3%
P[Complete Damage]	0.23%	0.01%	0.04%	0.15%	1.0%	4.2%
Predicted Loss to Residences – Dollars in Billions						
Replacement Cost	$510B	$148B	$143B	$153B	$61B	$5B
Structural System Loss	$1.56B	$0.11B	$0.22B	$0.50B	$0.61B	$0.12B
Building plus Contents Loss	$13.1B	$0.96B	$2.03B	$4.61B	$4.72B	$0.79B
Predicted Loss Ratio		0.65%	1.4%	3.0%	7.8%	16%

Peak displacement and acceleration response of single-family residences (i.e., W1 buildings of Moderate-Code design) and the corresponding probabilities of structural damage are calculated using the building damage functions described in the companion paper by Kircher et al. (1997) in this *Spectra* issue. Peak displacement and acceleration values represent average response within each MMI shaking region, since they are based on the average 5%-damped response spectra of each MMI shaking region (Figure 5).

Damage state probabilities shown for "All" MMI shaking regions reflect the combination of individual MMI shaking region probabilities weighted by building value. The "All" probabilities provide an overall picture of the earthquake's effect on residences of the study area. For example, some amount of structural damage is predicted for about 1/3 of all residences in the study area, although less than one-quarter of 1 percent of all residences are predicted to have Complete, and potentially life-threatening, structural damage.

Direct economic loss is calculated for the structural system using the probabilities of each damage state given in Table 5 and the loss rates summarized in Table 2. Similar calculations are performed for nonstructural components and building contents. Building plus contents losses shown in Table 5 are the sum of the individual calculations of structural, nonstructural and contents losses. As illustrated in Figure 7, the structural system contributes only a small fraction to total building loss. Nonstructural components and contents, which are more valuable, dominate the calculation of direct economic loss. Predicted loss ratios for each MMI region are calculated by dividing buildings plus contents loss by residential value (i.e., the replacement cost of residential buildings and their contents).

COMPARISON OF PREDICTED AND OBSERVED ECONOMIC LOSS

FEMA/NIBS predictions of residential loss ratios for MMI shaking regions are compared in Figure 8 with ratios derived from observed residential losses (distributed by MMI based on insurance claims data). Also shown in Figure 8 are loss ratios taken from Steinbrugge (1982) for Class 1D buildings and loss ratios derived from ATC-13 damage probability matrices (ATC, 1985) for low-rise wood buildings.

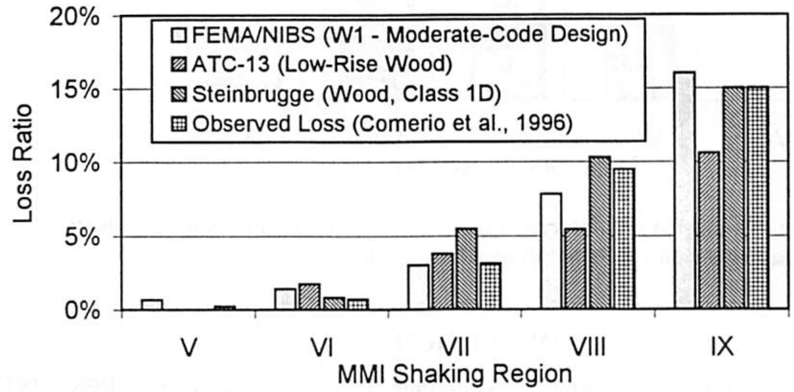

Figure 8. Comparison of loss ratios of various predictive methods and observed loss ratios for Los Angeles County Residences by MMI shaking region - 1994 Northridge Earthquake

FEMA/NIBS predictions of residential losses for MMI shaking regions are compared in Figure 9 with losses derived from observed residential losses (distributed by MMI based on insurance claims data) and with predictions based on the loss ratios of Steinbrugge and ATC-13, shown in Figure 8. To permit uniform comparison of losses predicted by different methods, Steinbrugge and ATC-13 predictions are based on the same replacement cost of residential buildings and their contents as those of the FEMA/NIBS methodology (i.e., $510 billion for the Los Angeles County study area). This approach is not entirely consistent with the definition of ATC-13 and Steinbrugge loss ratios, which apply to residences whose replacement cost does not include an additional 50% increase for contents. If contents were excluded, the predictions of ATC-13 and Steinbrugge would be 33% lower.

Figure 9 indicates a good comparison between residential losses predicted by the FEMA/NIBS methodology and observed losses for MMI shaking regions VII and VIII, the two regions that dominate direct economic loss for the 1994 Northridge Earthquake. The ATC-13 method tends to underpredict observed loss in the MMI VIII shaking region, and the Steinbrugge method tends to overpredict observed loss in the MMI VII shaking region. However, all three predictive methods provide reasonable estimates of observed loss to residential buildings of Los Angeles County damaged by the 1994 Northridge Earthquake.

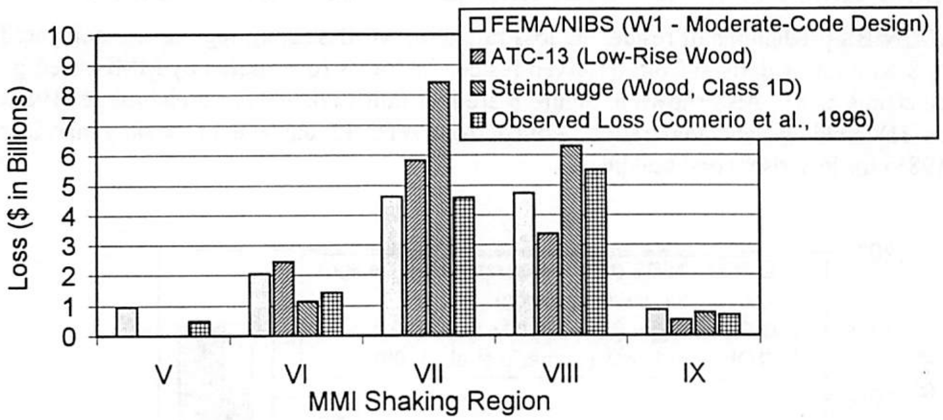

Figure 9. Comparison of predicted and observed direct economic loss for Los Angeles County residences by MMI shaking region - 1994 Northridge Earthquake

CONCLUSION

This paper has described the building economic loss methods of the FEMA/NIBS earthquake loss estimation methodology and compared predicted losses to residences using these methods with those observed for the 1994 Northridge Earthquake as well as with losses predicted by the methods of ATC-13 and Steinbrugge.

Building loss functions (and related damage functions) are of a new form and represent a significant step forward in the prediction of earthquake impacts. Previous methods, such as those of ATC-13 and Steinbrugge, are based on MMI. The new functions are based on quantitative measures of ground shaking (and ground failure) that analyze groups of buildings in urban regions in a manner similar to that used for the seismic design of new buildings and rehabilitation of existing ones.

The FEMA/NIBS methodology now permits loss estimation to incorporate important ground shaking characteristics, including site/soil amplification effects and shaking duration. Further, the methodology explicitly considers differences among buildings based on their seismic design level and vintage, and anticipated performance, explicitly considering nonlinear inelastic response, and its effects on the structural system, nonstructural components, and contents of the building.

Direct economic losses predicted for Los Angeles County residences compare well with those observed for the 1994 Northridge Earthquake and are consistent with existing MMI-based predictions based on ATC-13 and Steinbrugge methods. In future studies of earthquake loss, the FEMA/NIBS methodology would be expected to provide more reliable estimates of building loss, since quantitative measures (response spectra) provide a more meaningful description of ground shaking than MMI intensity. Improvements in the prediction of ground shaking (response spectra) can be incorporated directly into the estimation of building losses.

The FEMA/NIBS methodology opens the way for quantitative evaluation of building losses and mitigation alternatives that previously could only be judged in a qualitative manner. With these tools, engineers and planners can now develop strategies for earthquake hazard mitigation that combine both elements of pre-event action and post-event response and recovery in a more rational manner.

ACKNOWLEDGMENTS

Dr. Jawhar Bouabid of RMS Inc., Menlo Park, California, created the GIS figures of the Los Angeles County study area data and assisted with compilation of insurance industry data on residential losses.

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Seismic Risk: An Owner's Perspective

Presenter: LLOYD S. CLUFF
Pacific Gas and Electric Co., Geosciences Department

Structural Engineers Association of Northern California
1999 Spring Seminar
"Seismic Risk Analysis: Probable Maximum Loss and Related Topics"
March 11, 1999

Seismic Risk: An Owner's Perspective

Lloyd S. Cluff
Manager of PG&E's Earthquake Risk Management Program

The attached published papers are relevant to Mr. Cluff's presentation:

1. Long-Term Risk-Management Strategy for Reducing Earthquake Vulnerability of Gas and Electric Systems

2. Policy on Acceptable Levels of Earthquake Risk for California Gas and Electric Utilities

3. Using Earthquake Scenarios to Guide Urban Development Policies and Practices Toward Significant Earthquake Loss Reduction

4. Program for the Post-Earthquake Inspection of Essential Buildings for a Major Utility

Proceedings of the Fifth International Conference on Seismic Zonation,
October 17-19, 1995, Nice, France, Pages 208-214

APPLICATIONS TO DIFFERENT SYSTEMS: UTILITIES

LONG-TERM RISK-MANAGEMENT STRATEGY FOR REDUCING EARTHQUAKE VULNERABILITY OF GAS AND ELECTRIC SYSTEMS

William SAVAGE*, Edward MATSUDA**, and Lloyd CLUFF***

Abstract: The potential for future earthquake-caused damage to gas and electric utilities is dominated by the vulnerabilities of the older parts of the existing system, which were built under less stringent seismic codes and construction practices. Addressing earthquake safety is complicated, because utility facilities are spatially distributed and face differing earthquake effects, the operation of a utility system has complex aspects requiring various response strategies, and there is increasing competition for available resources. An approach for a utility to effect appropriate and cost-effective risk reduction should include identifying the earthquake hazards and selecting scenario earthquakes, systematically classifying the importance and vulnerability of components of the system, predicting potential damage due to the scenario earthquakes, prioritizing alternative mitigation measures according to threat to life safety and likelihood and severity of post-earthquake disruption, and establishing a long-term plan and annual budget to support the risk management activities.

Introduction

A practical and cost-effective approach has been developed to objectively understand the specific nature and implications of the earthquake threat faced by gas and electric power utilities, and then strategically manage that threat to reach a level of earthquake risk that is acceptable to the utility customers, regulators, and owners. This approach has been implemented for the utility systems of the Pacific Gas and Electric Company in northern and central California. We believe other gas and electric power utilities can customize and apply this approach to effect appropriate and cost-effective seismic risk reduction. In fact, some West Coast gas and electric utilities are also using generally similar approaches, and have been collaborating in exchanging earthquake mitigation information.

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The Problem

For many areas in the United States, and other parts of the world, gas and electric utility systems are vulnerable to significant earthquake damage that can cause threats to life safety and unacceptable disruptions of customer service, and can threaten the business stability of the utility companies. Yet many utilities have not taken effective mitigative action to manage the risks presented by earthquakes. This risk-management problem has four primary components:

- Earthquake hazards vary regionally. An individual utility's exposure to earthquake hazards is a function of where and how often earthquakes of various sizes occur, and the severity of the effects of ground shaking, ground failure, and surface faulting. Because gas and electric utility systems comprise spatially distributed components, their seismic hazard exposure typically varies significantly throughout the service territory. Different specific actions are needed to address high-hazard areas, where large earthquakes or hazardous earthquake effects occur relatively often with respect to the operational life of the facilities, versus low-hazard areas, where the probability of significant earthquake effects is low.

- Utility systems as they exist today have grown during this century to provide the supply, transmission, and distribution capacities needed to serve present-day customer bases. Thus such systems have seismic performance capabilities that are a function of the many different design criteria, materials, and fabrication and construction practices that have been applied over succeeding decades. As a result, the current seismic vulnerability of a given utility system is not measured by the seismic design criteria used today by the utility, but is a product of the vulnerabilities of the older parts of the system.

- The effect of earthquake damage to utility system components on the operation of a utility system has complex aspects. Gas and electric systems are built to have significant redundancies and operational flexibility to provide reliable customer service while meeting maintenance needs and in case of unexpected system damage or disruption. Although much experience has been gained in addressing routine maintenance and in such emergencies as pipeline damage by third-party excavation, vehicle collisions with power poles or towers, or damage due to major storms, significant earthquake damage is rare. The usual response strategies to restore service can be severely compromised in an earthquake by the nature of the damage, the amount of damage, the spatial extent of the damage, and the disruption in other aspects of the infrastructure that delay prompt utility action. Significant penalties, including loss of investment, loss of business, and regulatory agency actions, can result from utility system damage and unacceptably slow service restoration.

- The changing business and regulatory climate in the United States is creating an increasingly competitive financial environment for gas and electric utilities. Thus utility managers are under increasing constraints to limit capital expenditures, stretch maintenance and operations budgets, and take more risks. At the same time, however, society is increasingly dependent on highly reliable gas and electric power service for business, residential, and health and safety purposes. The successful utility organization needs to find its own balance of acceptable risk in the face of such conflicting priorities.

Approach

Earthquake risk management for a utility should be systematically planned and conducted in a cost-effective manner, so that every dollar spent to address risk obtains the most earthquake protection possible. Whether the mitigation be earthquake insurance or retrofitting components or emergency response preparations, an objective analysis is needed to determine what action to take. At every stage, from initial planning onward, several key perspectives should be kept in mind.

Long-term Process: Earthquake risk management is a long-term process, not a short-term action. Although some activities, such as retrofitting a transformer bushing to a higher seismic level, can be specified, scheduled, and fully completed, the overall approach involves an ongoing, systematic program that is intended to reach and then maintain an acceptable level of earthquake risk.

Annual Priorities: Each annual budget of the utility should have a set of seismic mitigation actions that are the best use of available money at that time. The objective analysis should enable setting such annual priorities.

Goal is acceptable risk, not no risk: The cost of achieving no seismic risk, if even possible, is economically unwarranted and should not be viewed as a desirable accomplishment. Risk reduction and maintaining acceptable risk are the proper goals of a utility's long-term seismic safety program.

The comprehensive approach we describe to reduce the earthquake vulnerability of gas and electric utility systems comprises five elements. These elements can be individualized and made applicable to utility systems of widely differing sizes that operate in the wide spectrum of seismic hazards settings.

Element 1: Identify earthquake sources and hazards, and select scenario earthquakes

The process of mitigating earthquake hazards begins with an accurate, realistic, and quantitative understanding of the earthquake hazards to which the utility system is exposed. For the utility service territory and adjacent areas, the seismic sources (active faults or earthquake source areas) are identified using available scientific studies or special utility-directed investigations. Each source is characterized by its location, style of faulting, recurrence rate of earthquakes as a function of earthquake magnitude, and potential for surface fault rupture or tectonic ground warping or tilting.

Although these earthquake source data can be used to compute probabilistic seismic hazard maps for the service territory or utility corridors, it should be noted that such probabilistic maps of ground motions are not appropriate for the seismic analysis of a utility network as discussed herein. Because a utility system is spatially distributed, the potential effects of an earthquake on the system must be evaluated using individual earthquake events, each one of which could produce a different distribution of ground motions and other effects across the service territory. The mixing of multiple earthquakes in a probabilistic map produces a physically impossible suite of earthquake effects on a utility system.

From these individual earthquake sources, a subset is selected, called scenario earthquakes, that have a relatively high probability of occurrence, such as once every 500 years or less. The scenario events are also chosen to be of sufficient magnitude to be capable of causing significant damage, which depends on the size of the service territory, the location of the utility facilities, and the vulnerability of the utility system to damage. The scenario events are chosen to occur in locations that expose relatively large numbers of customers and utility facilities to potentially damaging earthquake effects. A few to about a dozen scenario earthquakes are appropriate for small to very large utilities, respectively. For a utility located in a relatively low seismicity area, there may be no scenario earthquakes that fit these magnitude and recurrence criteria. In such a case, longer recurrence times may be considered in selecting scenario earthquakes for further analysis, but appropriate decreases in risk reduction priority may be warranted, as discussed below.

Three additional sets of earth-science data are needed for scenario earthquake analyses:

- Estimates of peak and spectral ground motion values at a range of distances from a seismic source, including corrections for site response

- Maps of the susceptibility of facility sites or pipeline or power-line corridors to ground failure due to liquefaction, including the potential for lateral spreading

- Maps of the susceptibility of facility sites or pipeline or power-line corridors to landsliding

Element 2: Classify importance and seismic vulnerability of utility system facilities and components

Each utility system facility and component is classified in terms of three factors:

- Potential to threaten life safety of utility employees or the general public due to earthquake damage or collapse. Occupied buildings are usually the most significant source of risk to life in the utility system.

- Criticality in maintaining or restoring earthquake service to customers following an earthquake. High-voltage circuit breakers and transformers, and gas transmission pipelines and regulator valves are typical critical components in post-earthquake service. Other electric power and gas components are less critical, and the system could be operated on an emergency and temporary basis without them. Facilities such as emergency response centers, warehouses, and customer service facilities are also critical in service restoration.

- Vulnerability to earthquake damage due to strong ground shaking, ground failure (landsliding or liquefaction), or tectonic surface faulting or warping. Certain types and vintages of high-voltage substation equipment have demonstrated vulnerability to even moderate levels of strong ground shaking, while others have performed well under the most severe shaking. Similarly, oxy-acetylene welds in high-pressure gas pipelines dating from early this century have been prone to failure in areas of permanent ground deformation in earthquakes, while pipelines in the same localities that had more modern welding and inspection procedures have not been damaged. Component vulnerabilities are increasingly being expressed by functions relating probability of damage and ground motion or ground deformation level.

Experience in past earthquakes shows that most gas and electric system components perform well in earthquakes. Also, utility systems can absorb some amount of damage to both critical and non-critical components before the system functionality is significantly affected. The classification of the many hundreds or thousands of elements in a utility system should take advantage of this experience to focus in detail on the known vulnerabilities of the most critical components.

Element 3: Evaluate potential damage and system operability in scenario earthquakes

For each scenario earthquake, the ground shaking and ground failure at facility sites and along utility corridors is predicted. The expected response of the critical system facilities and components to these earthquake effects is then assessed. Application of the component vulnerability functions leads to a best estimate of the amount of damage the scenario earthquake produces, and where in the utility system the damage is located. From this damage state, the operability of the system is assessed. Finally, alternative response and recovery schemes, such as bypassing the damage or rapid replacement and repair, are evaluated in consideration of availability of transportation, parts, and repair personnel. In this manner, the overall impact of the damage can be evaluated. These evaluations thus identify the problems in or barriers to rapid and economical restoration of service to customers, and resumption of the normal business of the utility.

Element 4: Evaluate and prioritize alternative mitigations

Using the scenario earthquake analyses from Element 3, the engineering, operations, and business staffs can objectively and quantitatively consider alternative mitigation measures that could systematically reduce predicted earthquake effects that are judged to be unacceptable to the utility. Mitigation measures could include physical changes in the system, such as replacing or upgrading components or facilities to meet higher earthquake performance levels, increasing system redundancy, preplanning bypasses to accommodate anticipated damage, and stockpiling spare parts to facilitate rapid replacement of vulnerable components. Additional alternative measures include assisting customers to preplan the emergency replacement of service, establishing mutual aid agreements with other utilities to provide field service personnel and materiel, encouraging customers to undertake earthquake vulnerability reduction programs so they can rapidly resume use of utility service following an earthquake, and obtaining insurance protection against very large capital or revenue losses or liability claims. These and other mitigation alternatives can be analyzed in terms of likelihood and effectiveness in reducing earthquake losses. Simply put, the highest priority mitigations are those that reduce the most likely losses in the most rapid and lowest-cost manner.

Element 5: Implement a long-term earthquake safety program

The final element consists of establishing a program within the utility organization and culture that systematically carries out earthquake mitigations. Even in the face of severe economic limitations, many low-cost actions can be highly effective in reducing earthquake damage. Chief among these are simple bracing and anchoring of components. Many utilities have low to moderate earthquake risk on a time scale of a decade, but need to address infrequent catastrophic events. Use of industry-accepted seismic performance criteria for new and routine replacement equipment, when coupled with good anchorage and bracing, will deliver improved earthquake resistance in the long term at little or no added cost.

For utilities having a high probability of facing multiple major earthquakes in the near future, more extensive seismic retrofitting of the existing systems is necessary to reduce seismic risk at an adequately rapid rate. The increase in the number of strong earthquakes in California during the past decade has greatly accelerated the upgrading process for the affected utilities by damaging or destroying numerous vulnerable gas and system components. However, it is not necessary or desirable to suffer earthquake damage before taking effective action to mitigate it.

The best of intentions to develop and implement a long-term seismic safety program can be confounded by inappropriate short-term priorities and management perspectives. An increasing number of utilities have found that one of the most helpful sources of encouragement and support in this area is inter-utility collaboration. The major California gas and electric utilities have participated in an ad hoc Inter-Utility Seismic Working Group to exchange information on earthquake risk reduction for more than the past five years. Other West Coast electric power utilities have started to participate, and a similar exchange has begun in the Central United States. State agencies have supported these efforts in California and elsewhere to effectively and efficiently improve seismic safety for utilities and their customers.

Acknowledgments

We have benefited from many discussions on the ideas of this paper with valued colleagues in Southern California Edison Company, Southern California Gas Company, Los Angeles Department of Water and Power, San Diego Gas and Electric Company, Southwest Gas, British Columbia Hydro and Power Authority, the California Seismic Safety Commission, the California Public Utilities Commission, and especially Pacific Gas and Electric Company.

Proceedings of the Fourth U.S. Conference on Lifeline Earthquake Engineering, ASCE, July 1995

Policy on Acceptable Levels of Earthquake Risk for California Gas and Electric Utilities

Inter-Utility Seismic Working Group[1]

Abstract

Earthquake specialists from the major California gas and electric power utilities have prepared a policy statement and associated implementation program as a framework for assessing and achieving acceptable levels of earthquake risk. The policy states:

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Each California gas and electric power utility system shall withstand earthquakes to provide reasonable protection of life, to limit damage to property, and to provide for resumption of utility system functions in a reasonable and timely manner.

The policy scope is broad, to permit its application to utilities in the differing seismic hazard regions of the State. Because each utility also has its own unique earthquake vulnerabilities, it also has its own long-term seismic safety implementation plan. It is the goal of this policy that each utility meet its responsibilities to provide reasonable public safety and customer service. Compliance will not prevent all loss of life, property damage, or loss of utility function. Experience with recent earthquakes in California suggests that implementing this policy through long-term implementation plans is an effective and practical means of reducing earthquake vulnerability to acceptable levels.

Introduction

The California Public Utilities Commission (CPUC) has been identified by the California Seismic Safety Commission as the lead state agency having oversight responsibility for the seismic safety of the regulated utilities. As part of its five-year earthquake hazards reduction report, *California at Risk, 1993-1997*, the Seismic Safety Commission has outlined a seismic safety program to improve the earthquake performance of electric power and gas systems. The CPUC has adopted this program, and requested the regulated utilities in the State to work with the Commission's Utility Safety Branch to accomplish the seven milestones of the program by the end of 1995. This paper addresses the third milestone:

Develop and adopt a comprehensive policy on acceptable levels of earthquake risk with long term priorities and schedules for the reduction of unacceptable hazards.

The following policy statement was prepared by the Inter-Utility Seismic Working Group, an ad hoc committee initially formed of earthquake specialists from the larger California utilities, and now including utility representatives from the Pacific Northwest and elsewhere. The policy sets a framework for earthquake vulnerability reduction, which has as its goal reaching and maintaining an acceptable level of earthquake risk.

Policy Statement

Each California gas and electric power utility system shall withstand earthquakes to provide reasonable protection of life, to limit damage to property, and to provide for resumption of utility system functions in a reasonable and timely manner. An acceptable level of earthquake risk is the residual risk that remains when this policy has been fully implemented.

It is the goal of this policy that each utility satisfy its responsibilities to protect the public and to provide reliable customer service in the face of possible earthquake effects. Although compliance with this policy will provide reasonable public safety and customer service, it will not prevent all loss of life, property damage, or loss of utility function.

Each utility is responsible for its own compliance with this policy by preparing and carrying out a long-term seismic safety implementation plan. The plan should be based on the current understanding of earthquake hazards and risk, and the current technical capabilities and practices of the industry.

Policy Implementation

The policy is broad in scope to allow it to apply to utilities in all parts of California, and other areas if desired. Each utility is unique in its exposure to earthquake hazards, in the seismic vulnerability of its facilities, in its operational redundancy, and thus in its ability to accommodate damage and avoid significant loss of service. Implementation of the policy will be specific to individual utilities.

To develop its implementation plan, each utility shall identify performance objectives for its utility functions and the time frames for their restoration after earthquakes to meet the goals of the policy. Each utility shall then establish priorities and schedules for reducing or eliminating significant hazards to life, property, and utility system functions that it has identified as unacceptable, and shall develop strategies and programs to manage the residual earthquake risk that remains.

To satisfy the intent of the policy and achieve an acceptable level of earthquake risk, each utility's implementation plan must address the following elements to demonstrate an effective seismic risk management plan. This list may serve as a check-list for assessing compliance with the policy.

1. Seismic Safety Program. A plan and process will be prepared that includes the following steps:

   1A. Identify earthquake hazards that may place people and utility functions at significant risk
   1B. Assess the seismic vulnerability of essential facilities and utility functions (considering redundancy)
   1C. Prioritize, schedule, and verify completion of mitigations of significant hazards to life safety, property, and extended loss of customer service
   1D. Prepare and practice emergency response plans
   1E. Establish seismic criteria for the design and construction of new facilities and equipment that will maintain acceptable levels of risk for the utility system.

2. Responsible Staff. A utility official having the clear responsibility for meeting the goals in the policy statement, and an appropriate staff, will carry out the program.

3. Adequate Funds. Adequate financial resources will be budgeted to carry out the program.

4. Accountability. A procedure will be established within each utility to measure and verify progress in the program.

<u>Discussion</u>

Most components of utility gas and electric systems within California are seismically rugged, and the utility component networks provide many redundant service paths. However, potential earthquake damage to more vulnerable parts of the systems, if proper mitigation measures were not taken, could create safety hazards, such as collapsed utility buildings, and long-duration, widespread interruptions of customer service that would be generally unacceptable. Many of the vulnerable system components and facilities were designed and constructed many decades ago, when lower seismic standards were in effect, and when accurate information about earthquake hazards and the performance of engineered structures and components was not available. It is the intent of this policy to guide both the mitigation of hazards to existing facilities, and the design and construction of new facilities.

Certain terms and phrases in the policy statement and policy implementation need to be clearly understood in producing an effective and worthwhile seismic program for each utility. These terms are discussed in the following paragraphs.

"Provide reasonable protection of life, and limit damage to property" acknowledges that it is not feasible to improve existing facilities or design new utility facilities to prevent all losses of life or all property damage. The utilities should use sound judgment and take prudent actions to protect lives and maintain functionality, consistent with the intent of current California codes and building performance standards for other kinds of facilities. This policy is not intended to require extreme, excessive, or every possible action.

"Resumption of utility system functions in a reasonable and timely manner" is the restoration, in a prudent manner under the conditions that prevail in the affected area, of the utility's ability to produce, transport, and deliver service to its customers who require the service. Such resumption of service should be consistent with other earthquake recovery and response plans in the affected areas. It is recognized that service disruptions will occur due to customer facility damage, fire hazards, transportation and other infrastructure damage, and other circumstances beyond utility control, as well as due to utility system damage and system imbalances. Priorities for service restoration will be consistent with societal needs.

"Long-term seismic safety implementation plan" means that the implementation of the policy is expected to extend over a period of years. As such, the plan should include the potential for future revision and updating as necessary, and thus allow for changes in approach or schedule.

"Manage the earthquake risk that remains" acknowledges that all risk cannot be eliminated. The utility will maintain a state of readiness for earthquakes, including emergency-response planning, staffing, funding, and maintaining emergency stocks of spare parts, and will apply appropriate seismic criteria to new facilities and equipment.

The focus of the policy is on gas and electric utility lifeline systems, not other utility facilities or facilities for which earthquake safety is otherwise specifically regulated. It is meant to be comprehensive and appropriately consider such topics as utility facilities, suppliers, and customers, other lifelines, emergency response plans, emergency stock, contingency plans, critical facilities, high-hazard areas, and mutual aid agreements.

It is virtually impossible for a utility to guarantee meeting a rigid goal of reestablishing service to a large percentage of customers within a short time period, such as 72 hours, because the extent and severity of the damage due to an earthquake can vary greatly from pre-earthquake expectations. The utility response would consider such variables as customer recovery and readiness for service, the ability of other lifelines and infrastructure to safely support the customer base, and the regional extent of damage. Civil defense and government emergency response personnel also have important input to establishing the priority of service restoration.

In taking actions to mitigate the risk of unacceptable earthquake performance of components or systems, the most beneficial actions should be undertaken first to most expeditiously improve seismic performance. Consistent with past regulatory approvals, utilities will weigh an appropriate level of economic risk in balance with the potential costs associated with the various levels of hazards. In general, seismic upgrades are expected to be accomplished within the budgets of the long-term maintenance and operation of the utility system, consistent with providing utility services at prices commensurate with public expectations.

Evaluation of Performance During Recent Earthquakes

The electric power and gas utilities in California have established a progressive record of preparing for and responding to earthquakes in an acceptable manner. In large part, the above policy formalizes the ongoing practices of the California utilities, for whom the importance of seismic safety is comparable to that of other safety issues.

It is instructive, nonetheless, to ask the question, "Has the performance of gas and electric utility systems in recent California earthquakes been acceptable in terms of protecting life safety, limiting property damage, and resuming service in a reasonable and timely fashion?" We find the answer to this question, with respect to such recent significant earthquakes as the 1989 Loma Prieta, the 1992 Landers, and the 1994 Northridge events, is generally, "Yes." Service to the vast majority of affected customers was quickly and safely restored. There were notable specific exceptions, however, including the following:

- In the Loma Prieta earthquake, vulnerable gas pipelines failed due to extensive liquefaction-induced ground failure in the Marina District of San Francisco, leading to weeks of lost gas service to the residents. The local customers were understanding, because they were also affected by substantial building and other utility damage, but the seismic performance of the gas distribution system did not meet the standard of the policy.

- In the Northridge earthquake, although there were relatively few pipeline breaks overall and those were repaired rapidly, the failure and ignition of the high-pressure transmission pipeline in Balboa Boulevard in Granada Hills destroyed five homes and called up the specter of major, post-earthquake fires. It was unfortunate timing for the Balboa Boulevard pipeline; a new pipeline was awaiting tie-in when the earthquake occurred.

- In the Northridge earthquake, the electric power transmission systems in Los Angeles County were hit very hard at a number of substations, resulting in extensive damage to substation components. Customer service was quickly restored in all but the most severely damaged neighborhoods, in spite of the level of damage, but the high financial impact on the utilities meant the seismic performance of the power transmission systems did not meet the standard of the policy.

In each of these cases, the significant component vulnerabilities that led to local life-safety threats, significant property damage (both to the utility and to others), or delays in service restoration were previously identified and, for each of the utilities involved, were in the process of being mitigated. In our view, the policy implementation process, as described above and as implemented among the affected utilities prior to and following the recent significant earthquakes, is clearly an effective means of reducing future earthquake vulnerabilities. The earthquake mitigation process is systematically reducing earthquake risk at utilities, and progress needs to continue so all the State's gas and electric power systems are operating at acceptable levels of earthquake risk.

Proceedings of the Second U.S.-Japan Earthquake Policy Symposium
Kobe, Hyogo Prefecture
17-19 September 1997
FEMA-MARCH 1998
The Common Agenda for Cooperation in Global Perspective

THEME 6

USING EARTHQUAKE SCENARIOS TO GUIDE URBAN DEVELOPMENT POLICIES AND PRACTICES TOWARD SIGNIFICANT EARTHQUAKE LOSS REDUCTION

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EXECUTIVE SUMMARY

Destructive earthquakes can be viewed as opportunities, in that they motivate decision-makers to take swift and positive actions for the long-term improvement of seismic safety. However, other conditions also must be present to cause policy changes and achieve earthquake loss reduction measures. There must be seismic safety champions—people who plan in advance and are prepared to act when the opportunity presents itself. Seismic safety legislation that has followed California's recent destructive earthquakes is due to the existence of the Seismic Safety Commission, an advocacy group that has the technical information, abilities, and contacts to sponsor the draft legislation. To be most effective, the advocacy group must have a plan and be organized before the earthquake occurs, so that public policy changes can be fed rapidly into the legislative process immediately after the earthquake—while the door of opportunity is open.

Having a champion and a plan to achieve earthquake safety must be complemented by significant technical information about earthquake effects and their relation to losses. Scenario earthquakes are a powerful tool for managing that information, quantifying earthquake hazards and risks, and communicating with policy makers. By envisioning the effects of a credible earthquake at a specific location at a certain time of day, earthquake scenarios present a compelling portrayal of the seriousness of a destructive earthquake. Scenario earthquakes have been used effectively by the Earthquake Engineering Research Institute to describe a likely major urban earthquake, and by Pacific Gas and Electric Company for earthquake emergency exercises. Scenario earthquakes allow the consideration of all earthquake effects, provide a framework in which to include new data, enable all aspects of society to be informed and involved, and illuminate strengths and weaknesses at all levels. They can significantly impact urban development policies, and provide strategies for improved earthquake mitigation, emergency response, and quick recovery.

U.S.-Japan cooperative efforts toward improved earthquake safety can include formulating earthquake loss reduction commissions and action plans for Japan, participating in utility-to-utility programs for managing earthquake risk, and collaborating on earthquake scenarios.

INTRODUCTION

"Seismic safety is treated too casually and inconsistently for the public safety and the economic issues at stake," wrote California Governor Pete Wilson following the 1994 magnitude 6.7 Northridge earthquake (California Seismic Safety Commission, 1994). Complacency develops when there is a quiescent period between earthquakes; then disaster shakes us and we wonder how we could have known so much yet done so little to prepare.

As our urban concentrations grow, the life safety threats and economic costs are becoming prohibitively high. It is clear we need an improved approach to increased seismic safety, we need consistency, and we need credibility. There undoubtedly are many ways in which to gain these; however, I would like to discuss two that, in my experience, have been most effective. The first has to do with managing the political process, and the second has to do with managing the technical information.

TREATING DAMAGING EARTHQUAKES AS OPPORTUNITIES

The history of the development of earthquake safety measures in California begins with the great San Francisco earthquake of April 18, 1906. Shortly after the earthquake, the Governor of California appointed an Earthquake Commission, under the direction of geologist Andrew Lawson, to study the event. On May 31, 1906, only six weeks after the earthquake, the commission presented their preliminary report to the governor, recommending that a comprehensive investigation be undertaken to study the causes of earthquakes and their effects, and to assess what could be done to reduce the losses from future earthquakes. Although the Commission's work originally was not funded, funding was later provided by the Carnegie Institution of Washington, D.C., and the Earthquake Commission was able to complete its program as planned (Lawson, 1908).

There followed decades of quiescence. When the 1971 magnitude 6.5 San Fernando earthquake struck near Los Angeles, California realized the value of establishing a permanent state agency to manage its earthquake threat. In 1975, the State adopted legislation creating the California Seismic Safety Commission (SSC), a body of 17 outstanding interdisciplinary professionals charged with advising the governor and the legislature on policy issues with regard to the need for and ways to improve seismic safety.

In 1985, a legislative bill endorsed by the SSC to create a California Earthquake Hazards Reduction Act had been pending. When a destructive earthquake hit Mexico City in September, the California legislators quickly passed and the governor signed into law the Earthquake Hazards Reduction Act of 1986. The act mandated that the Seismic Safety Commission develop initiatives to meet earthquake loss reduction objectives. The resulting plan covers 5-year spans, and is updated annually. The first publication, called California At Risk—Reducing Earthquake Hazards 1987-1992 (California Seismic Safety Commission, 1986), presented a framework to organize, promote, and monitor needed improvements, provided cost estimates, and identified the responsible government and private entities.

Destructive earthquakes can have value in that they motivate decision-makers to take swift and positive action for the long-term improvement of seismic safety. They are opportunities for the political process to move forward, playing on emotions. However, although damaging earthquakes may open the door of opportunity, other conditions must be present to cause policy changes to come about and achieve earthquake loss reduction measures. There must be significant technical information about earthquake effects and their relation to losses, a receptive political climate, and significant press coverage. There must be seismic safety champions—people who plan in advance and are prepared to act when the opportunity presents itself. Much of the recent seismic safety legislation that has followed California's destructive earthquakes has been due to the existence of the Seismic Safety Commission, an advocacy group that has the technical information, abilities, and contacts to sponsor the draft legislation. To be most effective, the advocacy group must be organized before the earthquake occurs. Public policy changes must be prepared in advance, and fed rapidly into the legislative process immediately after the earthquake—while the door of opportunity is open.

In 1989, the California Seismic Safety Commission published its annual update of California at Risk (California Seismic Safety Commission, 1989) and delivered it to all legislators and the governor in September. The SSC had recommended 72 action-oriented initiatives that various state agencies could carry out to improve seismic safety. On October 17, 1989, the magnitude 7.1 Loma Prieta earthquake occurred. The door of opportunity was wide open, and California at Risk provided seismic safety improvement recommendations that policy makers were eager to adopt. The post Loma Prieta emergency session was the most prolific legislative session on seismic safety in the world's earthquake history. A total of 443 seismic safety bills were introduced. The legislature passed 164, and the governor signed most of them into law—the exceptions were bills that had large long-term financial impacts. California policy makers had at their fingertips a clear report that gave them the seismic safety issues that needed to be addressed, as well as the language with which to address them. The Commission, by being organized and well-prepared, was the seismic safety champion. They had developed the right information, it was available to the right people, and at the right time.

The most recent edition of the Commission's goals and priorities for seismic safety is called The California Earthquake Loss Reduction Plan (California Seismic Safety Commission, 1997). It is a new strategic plan, setting forth basic government policy and direction. It consists of a matrix of eleven elements, each addressing a distinct, but inter-related area of concern. Each element is both a stand-alone avenue to pursue improved levels of risk reduction and preparedness for that particular element, and a mechanism for interconnecting with the other elements. The goals, objectives, and strategies of the plan address California's most pressing seismic issues. The plan is based on the facts that mitigation works, and loss reduction is possible, practical, and cost-effective.

Having a champion and a road map to achieve earthquake safety is only half the battle, however. As I mentioned earlier, to lay such plans there must be significant technical information about earthquake effects and their relation to the losses. I would now like to complement this political tool by discussing a powerful tool for quantifying earthquake hazards and risks.

DEVELOPING AND USING SCENARIO EARTHQUAKES

The destruction caused by the 1971 San Fernando earthquake resulted in panic for politicians, including the federal government. The collapse of multiple freeway overpasses, severe damage to hospitals, and the near-catastrophic failure of the Lower San Fernando Dam left them helpless and frustrated. They wanted to do something positive; however, they were without factual and reliable information. To correct the lack of understanding, the Executive Office of the President commissioned a series of earthquake planning scenarios of metropolitan areas likely to experience damaging earthquakes in the not too distant future. The first of these earthquake scenario evaluations was for the San Francisco Bay Area. The study was under the leadership of Karl Steinbrugge, with the assistance of the U.S. Geological Survey. I was a member of Steinbrugge's scenario evaluation team. This was the start of the development of a very powerful tool to improve earthquake awareness.

By envisioning the effects of a credible earthquake at a specific location at a certain time of day, earthquake scenarios present a compelling portrayal of the seriousness of a destructive earthquake. The scenarios have the realism to communicate to policy makers, business decision-makers, emergency responders, and disaster recovery professionals. They provide the opportunity to appreciate the personal, scientific, engineering, and social issues surrounding the occurrence of a destructive earthquake.

To be effective, a scenario earthquake must be believable and credible. If earthquake scientists and engineers understate or highly exaggerate the effects and losses, there will be a loss of credibility and a lack of public acceptance, and the message will be ignored. Although the message of scenario earthquakes is very sobering, it clearly demonstrates that there is much that individuals, communities, building owners, corporations, state agencies, and policy makers can do to improve the seismic safety of buildings, utilities, and transportation systems through mitigation efforts. The message also can guide emergency preparedness and response efforts, as well as direct serious consideration to post earthquake recovery planning. All of these actions will significantly reduce the impacts and inevitable losses from future earthquakes.

An Example of a Regional Application of Scenarios

During my term as President of the Earthquake Engineering Research Institute, an interdisciplinary professional society headquartered in the San Francisco Bay Area, I had the opportunity to help plan the institute's 1995 annual meeting in San Francisco. We wanted to take advantage of the lessons learned from the 1989 Loma Prieta and the 1994 Northridge earthquakes. We planned a realistic earthquake scenario, to be presented during a day-long special seminar. The postulated earthquake was to occur near the meeting site on the morning of the seminar (Earthquake Engineering Research Institute, 1996).

The California Earthquake Probabilities Working Group (U.S. Geological Survey, 1988) had identified the Hayward fault as one of the most likely faults in northern California to release an earthquake that would significantly affect the Bay Area, as well as have a large economic impact on all of California. Our scenario earthquake was a magnitude 7.0 event released along the northern portion of the Hayward fault in East Bay area— a very credible event for the attendees. The fault would rupture along a 50-kilometer segment of the fault, the result of an average displacement of about one meter along this rupture length. The resulting earthquake would have a duration of strong shaking of about 20 seconds (about twice as long as the duration of the Loma Prieta earthquake), due to an assumed unilateral rupture along the rupture length of the fault.

A total of seventeen speakers were carefully chosen for their knowledge of past earthquake disasters and ability to clearly communicate the technical and public policy messages. They were an interdisciplinary group that could address most aspects of the earthquake they hypothetically had just experienced. The subject matter of the presentations included:

- the geologic and seismic characteristics of the Hayward fault and the scenario earthquake;
- the socioeconomic setting of the region near the Hayward fault;
- the postulated ground failure effects (surface fault rupture, liquefaction, and landslides) of the earthquake;
- the expected performance of buildings and transportation systems as they were affected by the ground failures;
- the expected impacts of the event on water and sewer delivery systems;
- the expected severity and distribution of the ground-shaking effects;
- the expected impacts of the event on transportation systems, including estimates of damage to bridges and major interchanges, traffic rerouting, and the constraints on emergency response due to crippled transportation systems;
- the expected impacts of the event on electric power, telecommunications, and gas and fuel delivery systems;
- the expected performance of critical facilities, including emergency operations centers, police stations, fire stations, and hospitals;
- the likely emergency response and relief activities and issues following the postulated event;
- the governmental response and expected critical issues and resources during the first 72 hours following the postulated event;
- the expected impacts of the event on post-earthquake housing needs, including temporary housing, and social recovery;
- the expected long-term regional impacts of the event on recovery of transportation systems;
- the expected regional coordination of recovery and reconstruction; and
- the expected issues related to economic recovery, including the bases for analyses of economic losses and economic impacts.

The day concluded with a call to action to reduce the known existing vulnerabilities—what actions, if taken, would make a difference given an actual earthquake at that magnitude at that location.

We planned the Hayward fault scenario in 1994, based on information from the Loma Prieta and Northridge earthquakes. After developing the scenario of a magnitude 7.0 earthquake on a 50-kilometer segment of a strike-slip fault, just one month before our annual meeting, the Kobe earthquake struck. There were striking similarities between the scenario we were planning and the Kobe earthquake. Using the recent information from Japan made our scenario even more realistic and sobering.

An Example of a Corporate Application of Scenarios

Pacific Gas and Electric Company (PG&E) is the U.S.'s largest investor-owned gas and electric utility. PG&E's customer service territory in central and northern California encompasses about 70 percent of the San Andreas and related faults. In 1985, the company established its Geosciences Department, an earthquake champion that initiated a comprehensive earthquake hazard and risk evaluation for all corporate facilities.

Using realistic earthquake scenarios, PG&E evaluated its gas and electric systems, including control facilities, buildings, power plants, dams, and hundreds of thousands of miles of transmission and distribution lines. We analyzed scenarios for damaging earthquakes on eight segments of four Bay Area fault zones. We estimated the magnitudes and the effects of the postulated earthquakes, including shaking, surface faulting, and ground failure phenomenon. When we looked at the combination of the eight scenarios geographically, it demonstrated that some critical gas facilities, major buildings, and electric substations would be hit by multiple events. Cases where multiple faults affected the same facilities became the highest priority for mitigation measures.

Earthquake performance improvements were prioritized not only according to life safety, but also considering the ability of the facility to serve customer and community needs following the scenario earthquake. This is a higher standard than the life-safety standard required by normal building codes. PG&E concluded that having a higher earthquake performance standard is prudent practice because (1) it is consistent with or exceeds the state of practice recommended by the SSC, (2) it minimizes earthquake risk to employees, users of the buildings, and the general public, (3) it enhances PG&E's ability to serve the community, especially during the emergency response after a destructive earthquake, and (4) it minimizes the potential for significant asset and revenue loss. Some facilities have been or are in the process of being replaced, retrofitted, or taken out of service. Some facilities are undergoing minor seismic upgrades, including the stockpiling of spare parts and supplies.

To test PG&E's ability to respond to a destructive earthquake, each year a corporate earthquake exercise is staged. The exercise lasts one day and the entire corporation, including upper management and local and state officials, is involved. The objectives of the exercises include familiarizing staff members with their duties during an emergency, testing the telecommunications and other capabilities of PG&E's Emergency Operation Center and Alternate Emergency Operation Center, testing and evaluating the information flow between the corporate EOC, field units, and external agencies, and informing field offices about the impact of major seismic events on their operations. The scenario earthquakes are different each year, and different facilities and capabilities are tested.

One aspect included in PG&E's scenario planning is the result of real-life experience during the Loma Prieta earthquake. It was learned that buildings can be closed by the city for long periods until an inspection can be performed by a qualified engineer and the building declared safe for occupancy. Because such delays are unacceptable to PG&E, we developed a post-earthquake building inspection program. For each building identified as "key," we developed inspection mobilization plans, taking into consideration the relative importance and ruggedness of the building, and the location and magnitude of the scenario earthquake. Agreements were signed with twelve consulting firms to ensure the availability of designated engineers following damaging earthquakes. Inspectors and alternates were assigned to the various key buildings for both working-hour and non-working-hour events. They were chosen based on their experience and expertise with the type of structure they were assigned to inspect, and their home or work location in relation to the key building. We then prepared a Post-Earthquake Instruction Manual to aid in the coordination of the structural inspections. The manual contains instructions for the post-earthquake inspection coordinator, location maps for the key buildings, contacts at the key buildings, phone numbers and addresses of inspectors and alternates, and inspection assignments. To make certain PG&E's efforts were recognized by the city, we held meetings with the building departments in San Francisco and Oakland to discuss the post-earthquake damage assessment program. Both building departments gave their enthusiastic support, and expressed their desire for other companies to adopt similar programs. Both building departments feel that PG&E's program will result in accurate and timely evaluations of their key buildings, and believe there will be no need to send city inspectors to buildings that are in our program.

As a result of the application of scenario earthquakes, PG&E has a priority-based earthquake risk management program that is substantially improving the earthquake performance of its gas and electric systems and essential facilities. During the period 1985 to date, PG&E has spent more that $500 million on seismic upgrades of its buildings, dams, power plants, and gas and electric systems. Given the likely occurrence of damaging earthquakes in central and northern California, PG&E facilities are expected to perform much more safely and reliably, and achieve quick recovery of services. This improved earthquake performance will reduce losses and serve vital functions during the emergency response period, significantly contributing to the speedy recovery of the communities it serves.

The Benefits of Using Scenario Earthquakes

An earthquake scenario approach to aid in managing earthquake risks is the only realistic and comprehensive means to consider future earthquakes for planning, mitigation, and preparedness purposes. It allows incorporation of all earthquake effects—strong shaking, surface faulting, ground failure, and tsunami. It enables all aspects of society—political, technical, industrial, academic, and social—to be informed and involved. Each segment of society can understand the impacts and contribute to improving seismic safety and reducing potential losses. It provides a means to create a focus on earthquake threats in the absence of frequent major earthquakes. And it provides a framework that can grow and improve as new data are provided by earthquake research or future earthquakes.

Planning scenarios also are an effective means to provide a balanced perspective of what matters most in managing earthquake risks. They are especially useful when setting priorities for mitigation activities, and can help to quantify the costs and implications of not mitigating certain risks. Scenarios are helpful in setting priorities for research efforts, in that they can indicate where additional data would help to address uncertainties. For example, if improved building and system performance are a goal, they can identify the research needed to develop the appropriate engineering tools. They facilitate the selection and refinement of loss reduction technologies, and encourage high-priority new technologies to be developed, tested, and applied. They also can identify critical issues that need to be considered in emergency response and post-earthquake recovery planning.

Earthquake scenarios enable us to realistically examine the earthquake performance of highly integrated and redundant systems, such as utility and transportation systems, and make informed and prudent decisions regarding the elements of those systems that must remain functional or be restored as soon as possible. We can consider the level of performance desired, operational interactions, and the human response element. Scenarios provide a means for individuals, corporations, and governments to plan the actions they will take, given the occurrence of the scenario earthquake and the expected interruption of utility and transportation systems.

Scenario earthquake analysis illuminates strengths and weaknesses at all levels of society, and is a mechanism to motivate actions that will preserve identified societal values. It clearly reveals needed practices and policies, and involvement in the playing out of a scenario increases the level of awareness and motivation of people. Through improved public awareness, it provides an opportunity to close the implementation gap between research results and user needs by putting into practice, through education and training, what is already known.

PREPRINT
Proceedings of the 5th International Conference on Seismic Zonation
Nice, France, October 17-19, 1995

EMERGENCY PREPAREDNESS

PROGRAM FOR THE POST-EARTHQUAKE INSPECTION OF ESSENTIAL BUILDINGS FOR A MAJOR UTILITY

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Abstract: The evacuation of buildings and the inability to reoccupy them after earthquakes can have severe impacts. For lifeline utilities, delay in the restoration of essential services can result. This paper describes the Post-Earthquake Investigation Program developed by Pacific Gas and Electric Company (PG&E), and implemented with the assistance of H. J. Degenkolb Associates, to minimize disruption in post-earthquake use of essential buildings. This program is aimed at ensuring the immediate structural inspection and evaluation of buildings essential to maintaining operations and conducting post-earthquake recovery. The methodology is based on assessing the effects of high-likelihood scenario earthquakes. Site-specific accelerations, soft ground effects, liquefaction, landslides, and anticipated building and infrastructure damage were considered in development of program details. Although PG&E is a gas and electric utility, this program is applicable to other types of organizations in earthquake regions.

Introduction

PG&E serves 11.8 million people, and has 4.2 million electric and 3.5 million gas customers in the service territory shown in Figure 1 which covers 94,000 square miles of northern and central California. PG&E has responsibility to the communities it serves for the safe and timely post-earthquake restoration of gas and electric service to meet emergency services and societal needs. Although power and gas outages are impossible to prevent, PG&E is taking actions to minimize the extent and length of outages by replacing or modifying components, and by reducing impediments to restoration of service through enhanced emergency response planning. One such action that involves both enhancement of emergency response plans and modifications is the Post-Earthquake Inspection Program.

Elements needed to develop an effective Post-Earthquake Inspection Program are: understanding the earthquake hazards in the area; assessing damage and disruption that specific earthquake scenarios can cause to both PG&E's system and the infrastructure; developing mitigation actions and response plans in regions where the there are both a high likelihood of earthquakes and high potential for significant damage and long term disruption of service to a large number of customers.

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Purpose

The evacuation of safe buildings and the inability to reoccupy them after earthquakes can unnecessarily delay the restoration of gas and electric service. Lack of timely inspections may expose occupants in unsafe buildings to unnecessary risks. The purpose of the Post-Earthquake Inspection Program is to ensure the timely structural inspection of "key" buildings by qualified registered engineers to:

1. Minimize re-entry time or allow continued occupancy of safe buildings.
2. Prevent the closure of safe buildings.
3. Quickly identify and minimize exposure to safety hazards.

Buildings designated as "key" PG&E buildings need to be occupied following an earthquake because functions within the buildings are essential to post-earthquake restoration of gas and electric service.

Buildings that are safe may be closed for a variety of reasons. After a damaging earthquake, employees may be afraid to reoccupy buildings until they have been cleared for occupancy by city-retained or other credible building inspectors, even though the damage may be cosmetic and the buildings may be structural sound. Building departments may be overloaded by the volume of buildings that require inspections, and it could take days to weeks for city-deputized inspectors to inspect some buildings. Overly conservative assessments may sometimes be made by city-deputized inspectors due to the need to make rapid evaluations and the inspectors' lack of experience in building analysis or lack of familiarity with the specific building being evaluated. For buildings that are conservatively evaluated, it could take days to weeks to get permission for reentry. For PG&E's key buildings, the potential for unnecessary evacuations and delays in reentry was judged to be unacceptable.

Seismicity and Selection of Scenario Earthquakes

PG&E's service territory has a well-established history of exposure to damaging earthquakes, as shown in Figure 1. Fault behavior analysis and the historical earthquake record provide the basis for assessing the location and general timing of future occurrences of earthquakes. The varying patterns of historical earthquake activity are consistent with the current scientific understanding of fault behavior, in that more rapidly moving faults release strong earthquakes more often, and faults with relatively longer continuous segments release relatively larger earthquakes. Recent earth sciences research has been used to assess the potential and probabilities for near-future earthquakes along the major faults of the San Andreas system. The Working Group on California Earthquake Probabilities (U.S. Geological Survey, 1988 and 1990) chose the time interval of 30 years (between 1988 and 2018) for their probability estimates, and they considered probabilities of specific fault segments that had the potential for the occurrence of magnitude 7 or larger earthquakes. Due to high rates of slip of the San Andreas and Hayward faults in northern and central California, the Working Group identified these faults as the most likely sources

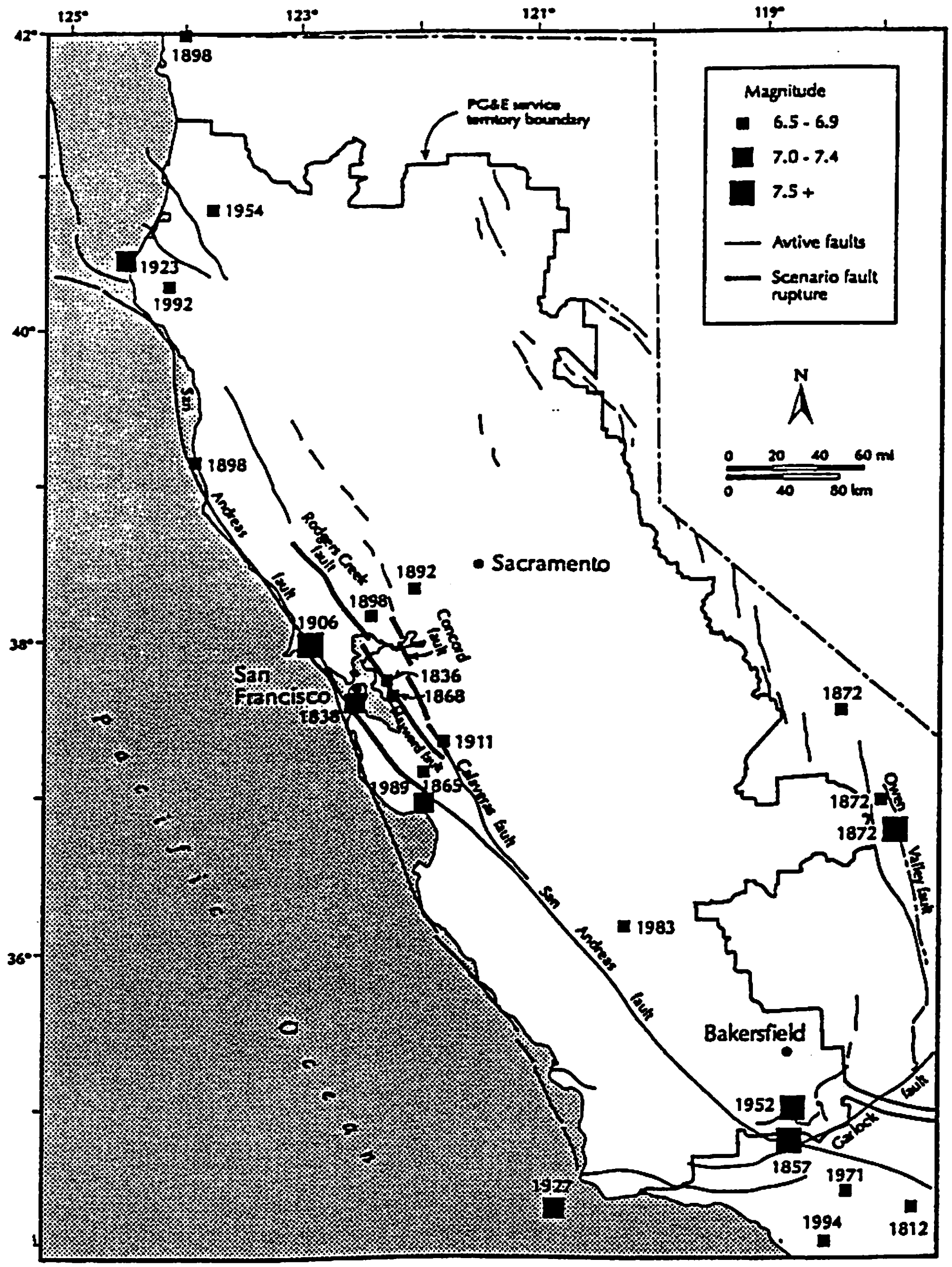

Figure 1. Scenario Fault Ruptures and Historical Earthquakes

for large earthquake in the next few decades. Although other similar-sized earthquakes may occur within this same interval, their probability of occurrence is assessed to be lower. PG&E has undertaken a number of earthquake scenario studies using these and other high-probability earthquakes to assess damage and potential disruption of gas and electric service, and to help prioritize mitigation alternatives. The scenario earthquakes chosen for study have the following characteristics: magnitude 6.5 or larger, high probability of occurrence, and potential significant customer impact.

The Post-Earthquake Inspection Program is being developed for the San Francisco Bay Area prior to other areas within PG&E's service territory due to the greater level of seismicity, the high concentration of both facilities and population, likely significant PG&E facility and infrastructure damage, and because it is the area where mobilization for post-earthquake inspections and system recovery would be the most difficult. Figure 2 shows the San Francisco Bay Area and location of key facilities within this area. Part of the difficulty in mobilization is closure of major transportation links. Cities within the Greater San Francisco Bay Area are connected by bridges, freeways, and tunnels. The city of San Francisco, where most of PG&E's engineers work, is connected to the East Bay by the Bay Bridge and the North Bay by the Golden Gate Bridge. In several of the high likelihood earthquake scenarios, both bridges are likely to be closed due to damage (months) or for inspection (days). Other bridges in the area (San Mateo, Richmond-San Rafael, Dumbarton, Benica-Martinez, Carquinez) are also likely to be closed. Closures of bridges and other transportation links such as tunnels and freeways will greatly disrupt the ability to get to some facilities in the San Francisco Bay Area.

We selected four of the earthquakes identified by the Working Group: earthquakes on the San Francisco Peninsula segment of the San Andreas fault, on the Rodgers Creek fault, and on the northern and southern segments of the Hayward fault. These fault rupture scenarios are shown in Figure 1 and in more detail in Figure 2. The Working Group scenario for the Peninsula San Andreas was modified slightly by extending the expected fault rupture an additional 10 miles to the north to allow for potential fault rupture close to San Francisco. We also considered scenarios for earthquakes along the Calaveras and Concord/Green Valley faults to the east of the Hayward fault. The Calaveras fault has been progressively rupturing in magnitude 5 to 6 1/4 earthquakes since 1979. The rupture fault scenarios are listed in Table 1 along with their estimated likelihood of occurrence.

For each scenario earthquake, likely behavior of each of PG&E's key buildings was assessed, as well as the likely status of essential transportation and communication components. Site-specific accelerations were tabulated for PG&E facilities. The effects of ground shaking, soft ground conditions, liquefaction, and landslides were considered in assessing the likely status of both PG&E and infrastructure components and systems following each scenario earthquake.

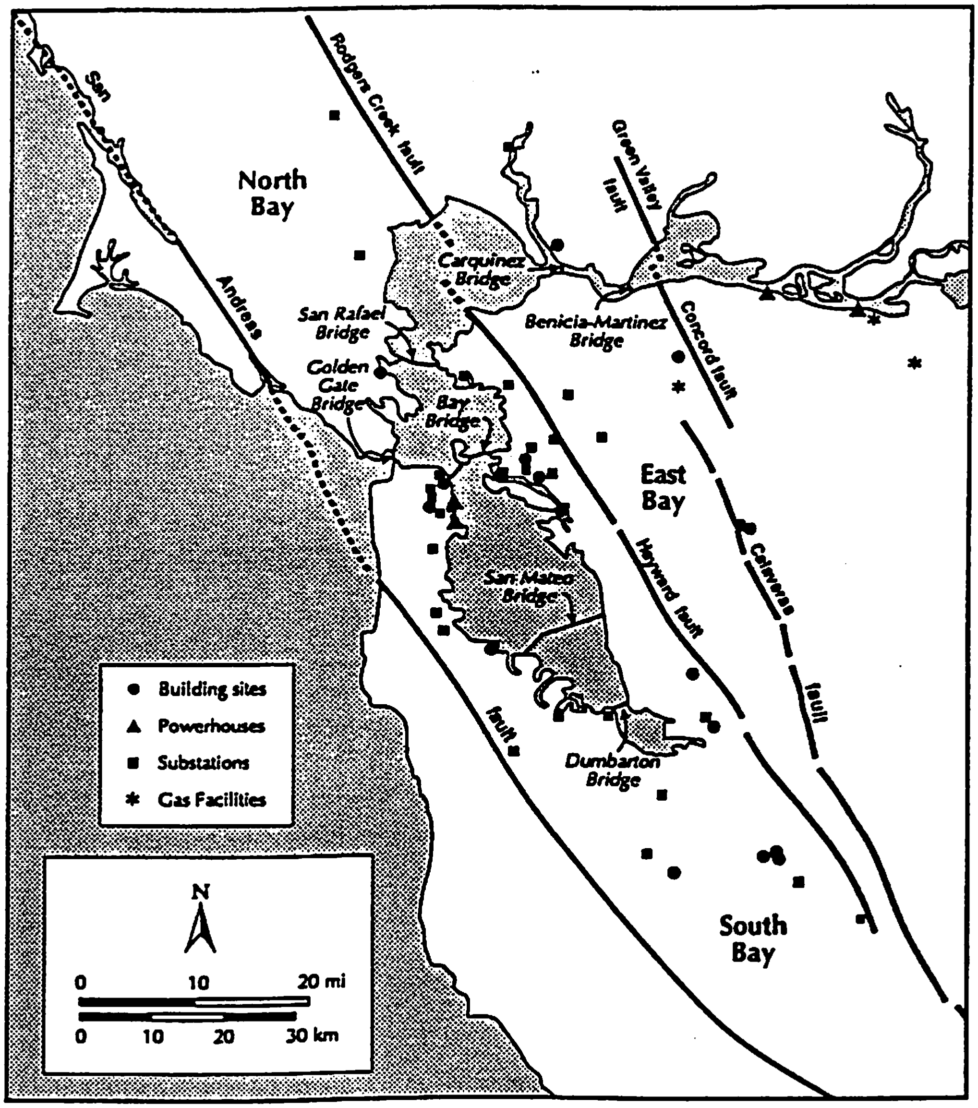

Figure 2. Key PG&E Facilities in the San Francisco Bay Area

Scenario Earthquake	30-Year Probability	Moment Magnitude
San Andreas Fault, San Francisco Peninsula Segment	0.23	7.0
Hayward Fault, Northern Bay Area Segment	0.28	7.0
Hayward Fault, Southern Bay Area Segment	0.23	7.0
Rodgers Creek Fault	0.22	7.0
Concord/ Green Valley Fault	approx. 0.1	7.0
Calaveras Fault, Northern Segment	approx. 0.1	6.5
Calaveras Fault, Central Segment	approx. 0.1	6.5

TABLE 1: SCENARIO EARTHQUAKES

Development of the Post-Earthquake Inspection Program

The Post-Earthquake Investigation Program involves four elements.

1. Priorization of buildings for inspection.
2. Retaining and assigning of qualified engineers to perform inspections.
3. Developing mobilization and communication plans that expedite the inspection of key buildings.
4. Making inspection assignment that allow adequate time for inspections, and performing pre-earthquake reviews of key buildings.

1. Priorization of Buildings:

Approximately 100 key buildings in the greater Bay Area have been identified by PG&E's operations and maintenance personnel. Figure 2 shows the location of the key buildings in the San Francisco Bay Area. These include substation control buildings, service centers, warehouses that house emergency supplies, emergency operation centers, telephone call centers, gas and power control centers, power plant structures, garages housing service vehicles, and other facilities. In general, these buildings will be given higher priority for inspection over other PG&E buildings.

2. Retaining and Assigning Qualified Engineers to Perform Inspections:

Outside consultants are needed to inspect PG&E buildings to supplement the number of available and qualified PG&E engineers. Following an earthquake many PG&E engineers would need to perform other post-earthquake tasks besides building inspections, and most of the key facilities are located such that they could not be reached in a timely manner by PG&E engineers from their home or work locations due to expected closure of critical transportation links. With the assistance of H.J. Degenkolb Associates, PG&E selected a number of firms throughout the greater Bay Area for possible participation in the program. Each firm was requested to furnish a list of engineers who could be made available to participate in post-earthquake investigations of PG&E facilities. Engineers had to meet the following requirements for inclusion in the program: California Civil Engineering (CE) or Structural Engineering (SE) registration; building design and analysis experience and expertise; training in use of ATC-20 , "Procedures For Postearthquake Safety Evaluation of Buildings"; good communication skills; and ability to make good assessments in pressure situations. From the resumes that were submitted, 50 engineers from eleven consulting firms were selected. Besides their technical qualifications, individual engineers were chosen based on their home and work locations relative to the location of key PG&E facilities.

For each key building, specific inspectors and alternates have been assigned for both working-hour and non-working-hour earthquake occurrences. Consultant engineers have been retained to perform most of the building inspections, including inspection of all high occupancy commercial buildings and most other commercial buildings. PG&E engineers were qualified and selected to participate in the program as inspectors for those types of buildings for which they have design and analysis experience, in particular power plant structures and some substation buildings. All PG&E selected engineers have either CE or SE registration, and have or will be given ACT-20 training.

3. Developing Mobilization and Communication Plans:

The effects of high-likelihood Bay Area earthquakes on transportation and communication systems were assessed and considered in the development of the program. It is anticipated that communications will be difficult due to overload of circuits and possible damage to the communication system, and that transportation will be difficult due to bridge, highway and road closures due to damage and the need for inspection. The program has the following elements to overcome communication and transportation barriers:

- Some key buildings have automatic response assignments. Inspectors are to respond and go the their assigned facilities without the need to be called upon the occurrence of given pre-designated earthquake events (given locations and magnitudes of earthquakes).

- Specific inspectors are assigned for both working and non-working hour earthquake occurrences such that they are likely to be within close proximity of their assigned building when the earthquake occurs.
- Inspectors are assigned to inspect specific buildings such that they do not have to use major transportation links that are likely to be closed. For instance, for working hour occurrences, engineers from consulting firms in the East Bay have been given the inspection assignments for buildings in the Oakland area, while engineers from consulting firms in San Francisco have been given the inspection assignments for buildings on the San Francisco peninsula. This was done because a trip that would normally take 15 minutes from San Francisco to Oakland may take 8 hours due to bridge closures.
- A voice mail box is established in Sacramento (a major city 100 miles northeast of San Francisco). The voice mail box was setup outside the local area to avoid locally overloaded telephone circuits and to improve chances that necessary communications can be made.
- Inspectors are instructed to report to the nearest PG&E manned facility to use PG&E company phone lines when communication through the local public network and the voice mail box cannot be made.

4. Making Inspection Assignments that Allow Adequate Time for Inspections, and Performing Pre-earthquake Reviews of Key Buildings:

Being able to conduct accurate and timely evaluations of the buildings is aided by pre-allocating enough time to make building assessments, and pre-evaluating the building structural system and likely behavior.

Assignment of inspectors was made to allow adequate time to make assessments. In making inspection assignments, the complexity and anticipated behavior of buildings, and the potential need for inspectors' assistance in implementing emergency shoring schemes was considered. For most complicated buildings and/or buildings expected to suffer significant damage, several inspectors were assigned. On the other hand, several rugged buildings with simple structural systems are often assigned to a single inspector.

For PG&E's general office complex (7 buildings, including a 34 story high-rise), a post-earthquake inspection manual is being developed by the consulting firms that are assigned to inspect these buildings. Included in the manual are the structural systems, criteria used in design or modification, likely areas of earthquake damage, significance of the damage, and areas of concern, if any. A number of other key buildings have been reviewed, and appropriate documentation including post-earthquake inspection manuals is being developed. This documentation will be given to the post-earthquake inspectors assigned to those buildings as part of their pre-earthquake preparation. In most cases, the task of pre-earthquake review and post-earthquake manual development is given to the specific consultant firm who is assigned the post-earthquake inspection of the building.

In several cases during the pre-earthquake building assessments, the likely behavior of the buildings was judged to be unacceptable, and structural modifications have been performed or are planned. For example, control buildings at three transmission substations have been modified, three office buildings are being modified, and a project is being developed to modify twelve distribution substation control buildings.

Conclusion

PG&E has responsibility to the communities it serves for the safe and timely restoration of gas and electric service, and responsibility to employees of minimizing their exposure to unsafe conditions. The Post-Earthquake Inspection Program, which enables more timely and accurate inspection and evaluation of PG&E buildings, is necessary to meet these responsibilities. To develop an effective program, regional and local earthquake hazards had to be understood; realistic, high-likelihood, high-impact scenario earthquakes had to be chosen, and the effects of these scenarios on both PG&E facilities and the infrastructure had to be assessed. The Post-Earthquake Inspection Program has received the enthusiastic support of PG&E's managers and operations personnel, and the city building departments where PG&E key facilities are located. Building department personnel have stated that the program is a good model for other organizations with a large inventory of buildings, and they encourage other organizations to develop similar programs.

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Example 1: Applications of HAZUS by the California OES Coastal Region

Presenter: Scott McAfee
OES Coastal Region

Applications of HAZUS by the California OES Coastal Region

Scott McAfee
GIS Analyst
Governor's Office of Emergency Services
Coastal Region, Earthquake Program
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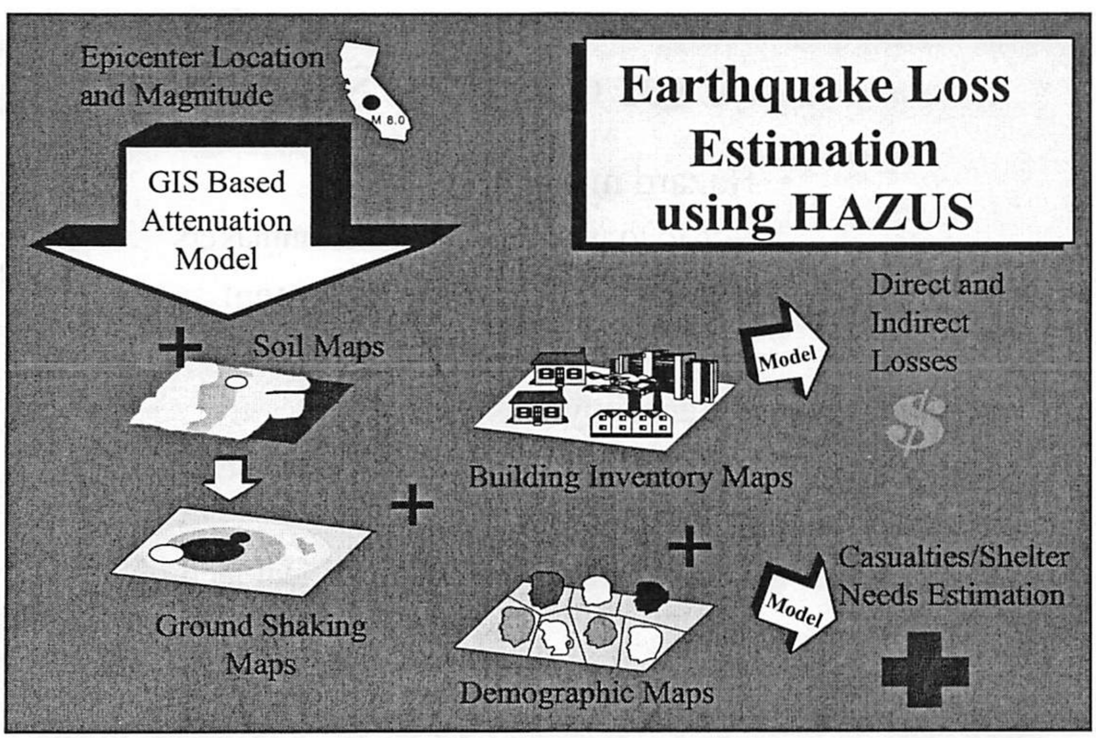
Uses of HAZUS

- Hazard mitigation
  - Aid to planners and decisionmakers
- Exercise and plan development
  - Specific scenarios
- Emergency Response
  - Early knowledge of trouble spots
  - Resource allocation
  - Estimation of losses to critical facilities

HAZUS Basics

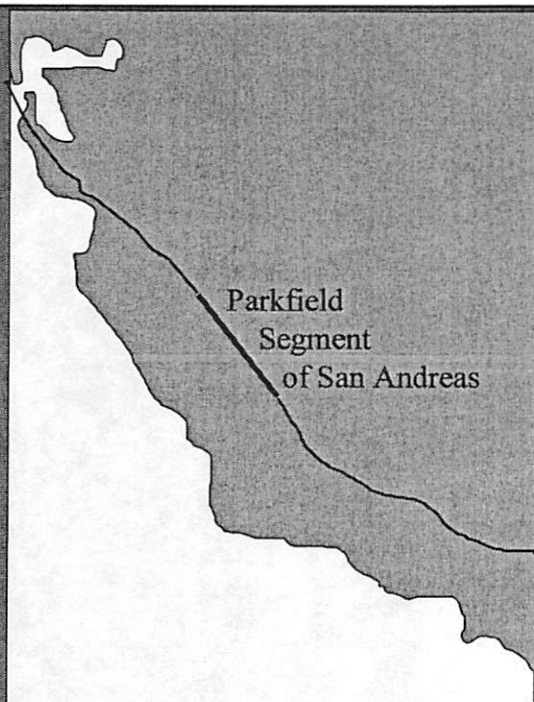
- Uses MapInfo ArcView
- Includes many databases
  - Aggregated to census tract level
  - Critical facilities, bridges, faults, and multihazard data
- Very flexible
  - More detailed data can be brought in



OES Utilization of HAZUS

- Plan development
  - OES Parkfield Response
- Mitigation
  - Cities of Berkeley/Richmond
  - Mulligan Medpartners/Kaiser
  - City of Oakland (Project Impact)
- Exercises
  - AIA Charette
  - Post-earthquake clearinghouse
  - City of San Francisco

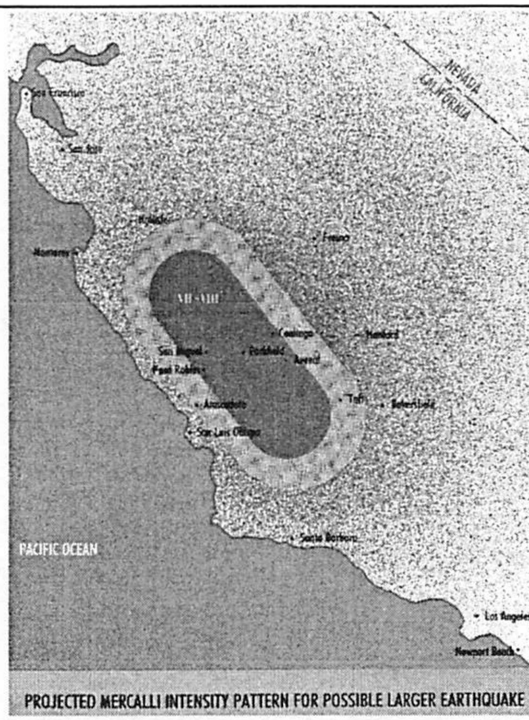
Parkfield Plan



Past Earthquakes of approx. M6.0:

1857
1881
1901
1922
1934
1966
1988???

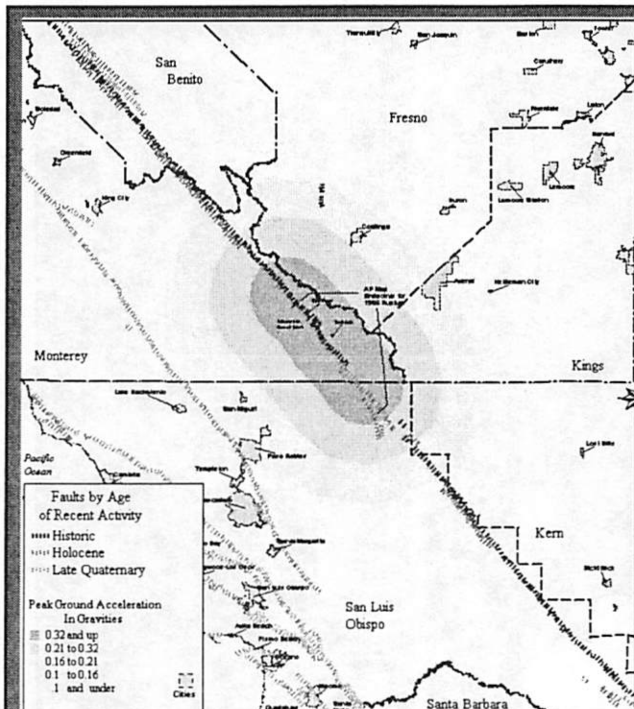
Parkfield
Plan



Map used
Before HAZUS

Past Earthquakes of
approx. M6.0:

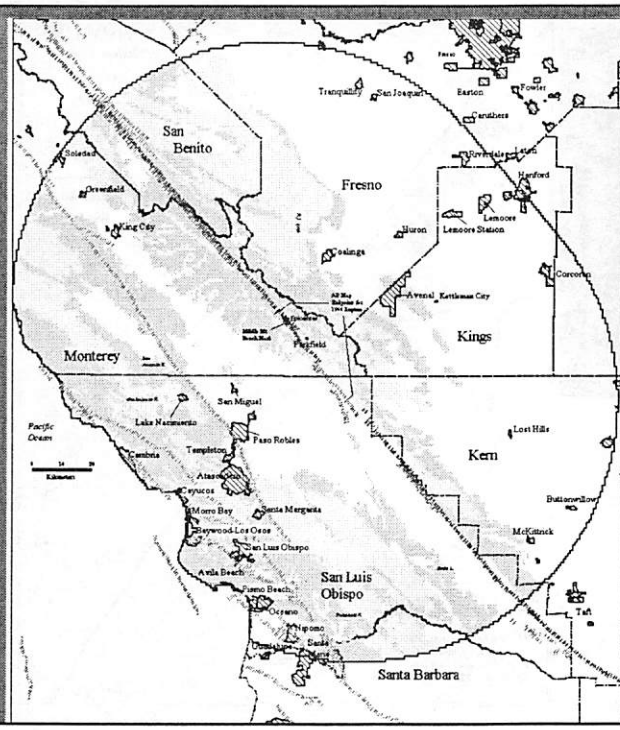
1857
1881
1901
1922
1934
1966
1988???



Parkfield
Plan

HAZUS Contour Map
Peak Ground Acceleration
for Magnitude 7.0

Parkfield Plan

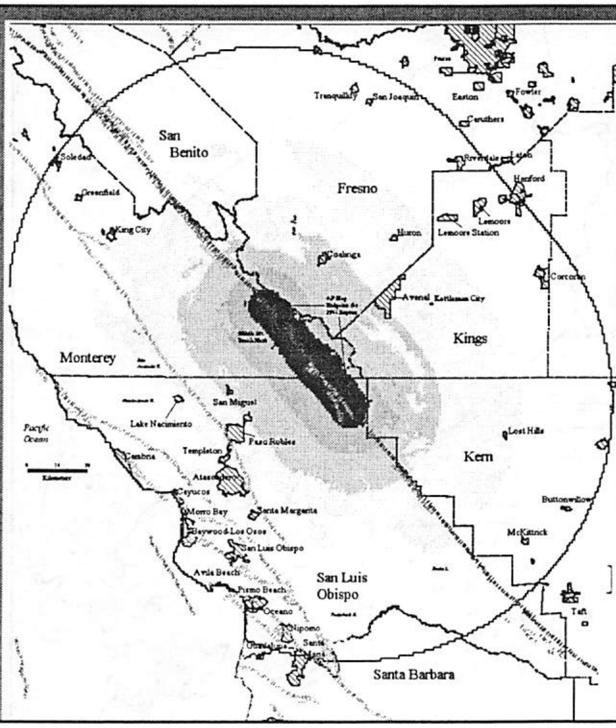


Geology of Parkfield Area by Site Class

Soil Site Classes from 1997 NEHRP Provisions

- Rock
- Very Dense Soil and Soft Rock
- Stiff Soils
- (No Data for Soft Soils)

Parkfield Plan



HAZUS Groundshaking Map Peak Ground Acceleration for Magnitude 7.0 (with geology)

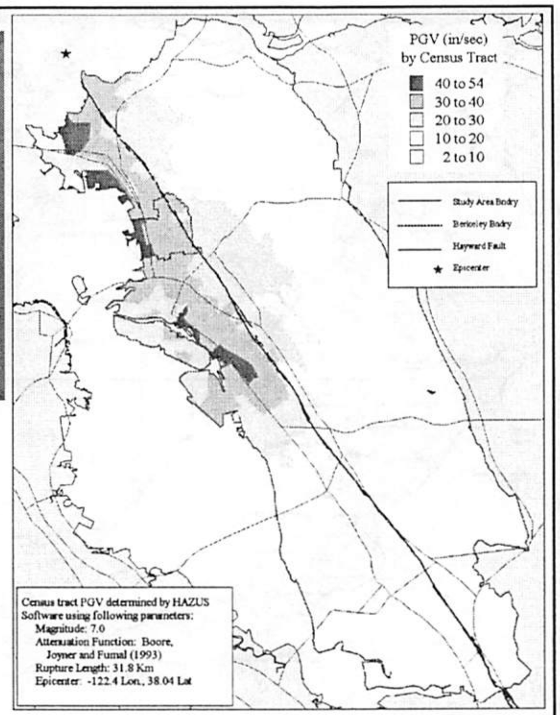
PGA Percent of Gravity

- 40 to 49%
- 30 to 40%
- 20 to 30%
- 10 to 20%
- 5 to 10%
- less than 5%

City of Berkeley:

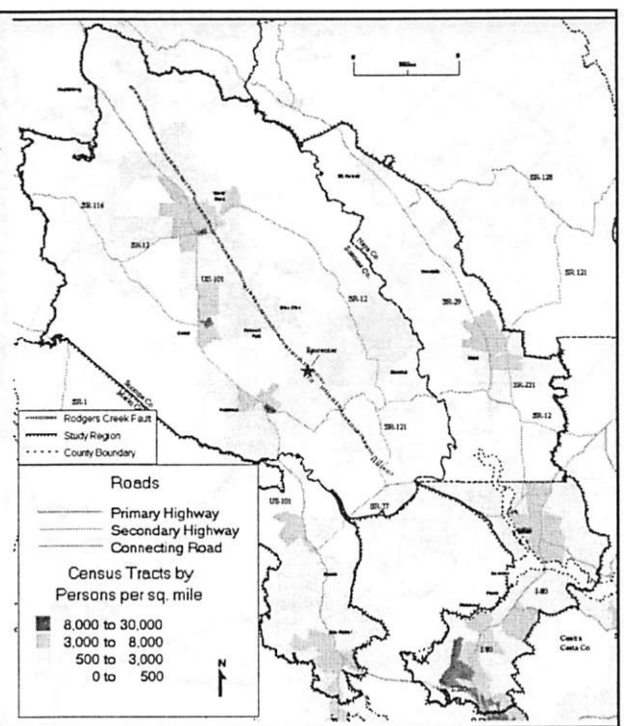
City Council Vote on City Hall Retrofit

Peak Ground Velocity M. 7.0 on North Hayward

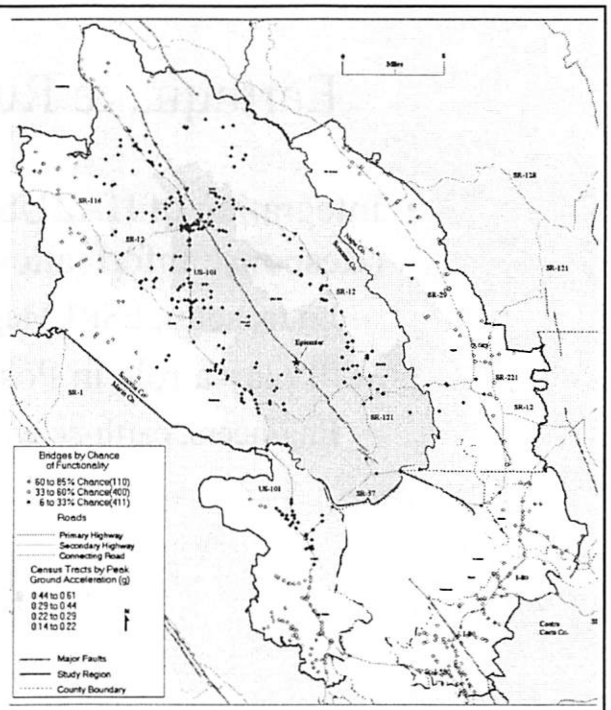


Clearinghouse Exercise:

Rodgers Creek Fault and North Bay Area Population Density

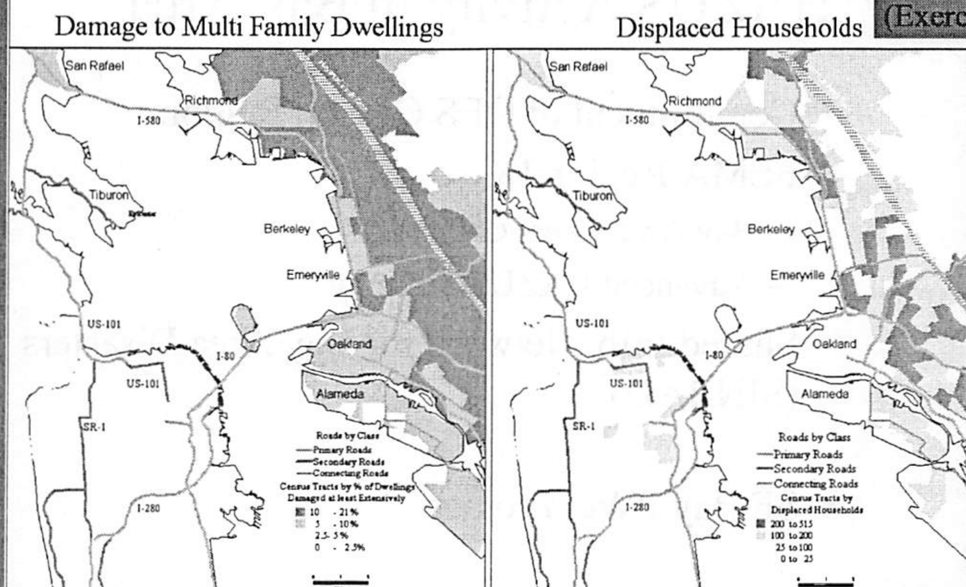


Clearinghouse Exercise: Rodgers Creek Event PGA – and Damage to Bridges



Housing Loss and Needs for Hayward Fault Earthquake (M 7.0)

AIA Charette (Exercise)



Earthquake Response

- Integration of HAZUS Outputs into RIMS (Response Information Management System)
  - Lotus notes, ESRI MapObjects, Internet
- Will play a role in Post EQ-Clearinghouse
  - Engineers, earth-scientists, social scientists

HAZUS Activity in Bay Area

- Commitment of OES Coastal Region
- FEMA Region IX
  - Bay Area Users Group
  - Advanced HAZUS Training
- Shared Info. Network for Bay Area Disasters (SINBAD)
- SF Bay PWG Project

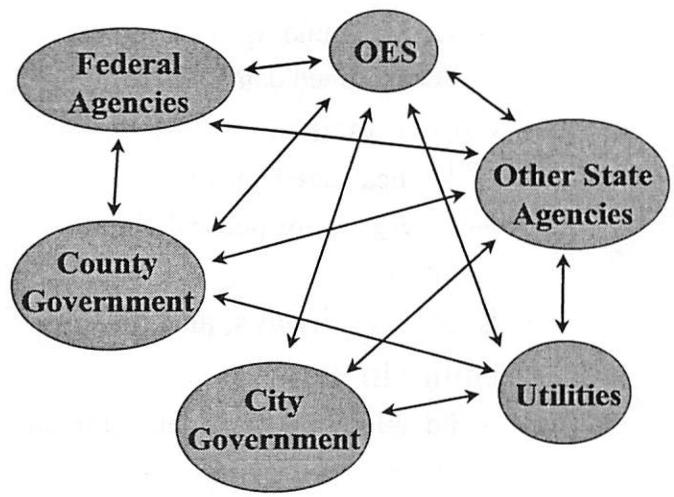
Useful Databases

- Geology
- Building Inventories
  - General building stock (by census tract)
  - User defined data
- Critical facilities
  - Medical care facilities
  - Emergency response facilities
  - Schools
- Streets, highways, and bridges
- Utility lifelines
  - Potable and wastewater, communications, power

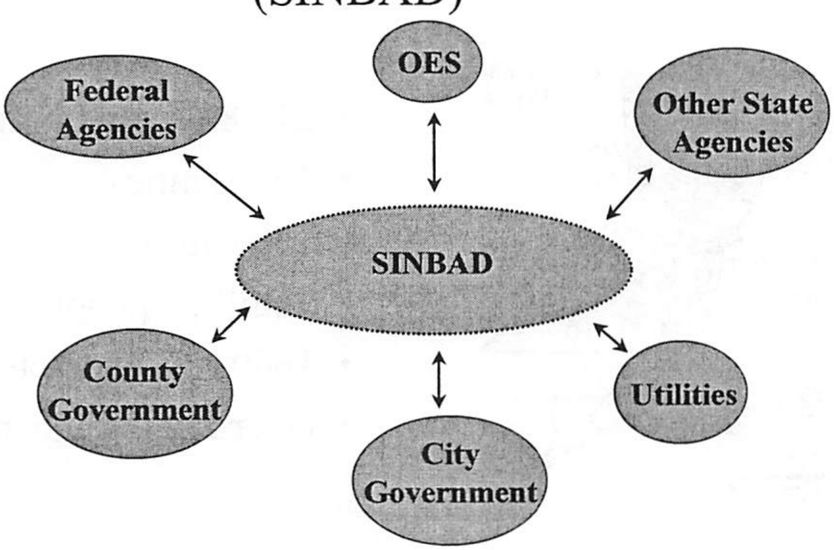
OES Coastal Region: A lot of Data

- 21,583 square miles
- 16 Counties
- 130 Cities
- 7 million people
- 1600 census tracts
- Over 2 million parcels

Data Sharing for Disasters (Actual)



Shared Information Network for Bay Area Disasters (SINBAD)



ADVANCES IN SCIENTIFIC AND ENGINEERING POST-EARTHQUAKE OPERATIONAL RESPONSE AND DISASTER INTELLIGENCE

Jim Buika[1], James Davis[2], Scott McAfee[3], Carl Mortensen[4], Sarah Nathe[5], and Susan Tubbesing[6]

ABSTRACT

The purpose of this paper is to demonstrate the emerging role for scientists and engineers as a vital support element to emergency response operations following a major earthquake in California. For the benefit of a national and international audience, this paper describes interrelated partnerships underway with emergency managers designed to rapidly collect, analyze, and disseminate disaster intelligence for emergency response operations. The authors 1) discuss emergency management requirements for disaster intelligence products during the operational response phase of an earthquake; 2) describe the goals and products of *TriNet*, a public-private partnership which has been advancing the state-of-the-art of "real-time" earthquake strong-motion analysis and communications technologies; 3) describe earthquake loss-estimation models and technologies which synthesize recorded earthquake data with hazard, inventory, and field-observation data bases into disaster intelligence; 4) introduce the *California Post-earthquake Information Clearinghouse Plan*, a plan for scientists and engineers which supports operational response; and 5) present the scope of work for a prototype partnership under development in the San Francisco Bay Area which is designed to develop and transfer disaster information products to interested organizations for response, recovery, and mitigation purposes.

The goal to deliver disaster information from scientists and engineers to responders will have the positive outcome of saving lives, reducing property losses, and reducing disaster-related costs for future California earthquakes. Today's unique and important collaboration between scientists, engineers, and emergency managers, under way in California, are transferable nationally as well as internationally and will improve the preparedness for, response to, recovery from, and mitigation against future earthquakes.

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Introduction

The purpose of this paper is to demonstrate the emerging role for scientists and engineers as a vital support element to emergency response operations following a major earthquake in California. Recent advances in "real-time" earthquake data collection, loss-estimation modeling techniques, telecommunications protocol, and operational response planning hold the promise of creating "products" for utilization by emergency managers during the response and recovery phase of an earthquake disaster. The present challenge to the scientific and engineering communities is to translate and transfer the products of these new technologies into a usable format, known as "disaster intelligence," to decision makers at all levels of government throughout the disaster area. Thus, scientists and engineers are encouraged to look beyond their traditional roles of academic research and project development to meet the challenge created by the dynamic needs of post-earthquake operational response and disaster intelligence.

For the benefit of a national and international audience, this paper describes interrelated efforts underway in California which are designed to meet this challenge. The authors:
1) discuss emergency management requirements for disaster intelligence products during the operational response phase of an earthquake; 2) describe the goals and products of *TriNet*, a public-private partnership which has been advancing the state-of-the-art of "real-time" earthquake strong-motion analysis and communications technologies; 3) describe earthquake loss-estimation models and technologies which synthesize recorded earthquake data with hazard, inventory, and field-observation data bases into disaster intelligence; 4) introduce the *California Post-Earthquake Information Clearinghouse Plan*, a plan for scientists and engineers which supports operational response; and 5) present the scope of work for a prototype partnership under development in the San Francisco Bay Area which is designed to develop and transfer disaster information products to interested organizations for response, recovery, and mitigation purposes.

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Emergency Management's Requirements for Disaster Intelligence

State and Federal Needs for Essential Elements of Information

Immediately after an earthquake, State and Federal emergency responders must anticipate what resources may be needed to support life-saving response operations at the local government level. Thus, responders in a support role first seek disaster information defining the size, scope, and location of the earthquake. This seemingly simplistic set of intelligence requirements is critical to expediting operations in the most timely and cost-effective manner. For example, some of the 27 national urban search and rescue teams will probably be deployed an hour after the earthquake. Since each team involves 62 members from around the country, one can envision the expenses incurred in overestimating the need for teams, while also understanding that lives could be lost by underestimating the need for teams.

One early objective of State and Federal support operations is to reestablish critical lifelines in and to the disaster area; such lifelines include communications networks, utility systems, transportation routes, and hospitals. A parallel objective is to define and shelter the affected population. Emergency managers seek early disaster data, known as the "Essential Elements of Information" to aid in developing logistics to conduct response operations (Federal Emergency Management Agency, 1995). This information includes:

1) the boundaries of the earthquake disaster;
2) the status of transportation systems;
3) access points to the disaster area;
4) the operational status of critical facilities;
5) hazard-specific information, such as ground ruptures and landslides;
6) forecasts for the size and location of future aftershocks;
7) the status of aerial reconnaissance operations; and
8) the status of damage effects to critical industries.

In the future, each of these essential elements of information may first be estimated via loss-estimation models. Early damage and loss models must be corroborated from all responders and investigators on scene, including scientists and engineers, to further understand the hazards and their relationships to the built environment.

State and Federal Early Response Actions

Immediately upon being informed of a significant earthquake, the Federal Emergency Management Agency (FEMA) and California Office of Emergency Services (California OES) activate regional operations and communications centers. Both operations are intended to generate an early definition of the damage area and to communicate this information to decision makers responsible for response operations and resource support. These respective operations centers are becoming more dependent on information technologies to predict damage, direct emergency assistance, and process requests for post-emergency assistance with speed, efficiency, and accuracy. Seven early State and Federal operations can be expedited from disaster intelligence derived from "real-time" earthquake data, as well as early scientific field investigations. These operations are as follows:

1) Compose, deploy, and direct the Preliminary Damage Assessment Teams to the disaster area (determine size, number, and technical requirements of teams);
2) Establish a joint State-Federal Disaster Field Office at a safe location along the perimeter of the earthquake aftershock zone (operational for two to six months);
3) Mobilize emergency communications teams and units to various locations within the disaster area;
4) Define Federal Mobilization Centers and Marshalling Support Areas for delivery of resources from out of state;
5) Coordinate aerial reconnaissance requests and define fly-over routes;
6) Coordinate, deploy, and direct the California Post-disaster Safety Assessment Volunteer Teams, which differ from the Preliminary Damage Assessment Teams;
7) Develop estimates of the scope and magnitude of earthquake effects and associated costs for Congressional budget consideration.

Under the *State of California Post-disaster Safety Assessment Plan* (California Office of Emergency Services, 1992), the State of California utilizes the services of volunteer building professionals to assist in the daunting task of damage assessment following an earthquake. The California OES coordinates the program while four organizations furnish their members for training and service. These are the American Society of Civil Engineers, the Structural Engineers Association of California, the California Council of the American Institute of Architects, and the California Building Officials.

Each of these organizations conducts ongoing training sessions for their members with support from California OES. Using the post-earthquake damage assessment procedures described in ATC 20 and 21 reports, the volunteers have been taught the standard criteria for determining safety of structures (Applied Technology Council, 1988 and 1989). Since 1989, 6,000 volunteer engineers and building officials have been trained and sworn in as official California Disaster Service Workers, which covers liability and workers compensation issues during disasters. Under California's master mutual aid program, the safety assessment volunteers are considered state resources and, as such, are available when aid is requested from the California OES or other State agencies. Following the Northridge earthquake, approximately 3,000 volunteers assisted California OES.

Technological Advances to Support Disaster Intelligence

TriNet Project: Rapid Generation of Strong Ground Motion Maps

New capabilities in seismic monitoring and communications include real-time analysis and transmission of strong motion data generated by regional earthquakes. The *TriNet* project facilitates the upgrade and expansion of the existing strong-ground-motion instrumentation network throughout southern California to 600 stations by the year 2001. The goal of the *TriNet* project is to automate the generation of earthquake ground motion maps using data recorded by the dense array of recording stations. First iteration maps will benefit emergency responders while refined maps will benefit scientists, engineers, building code officials, and government officials during the response, recovery, and mitigation phases following regional earthquakes in southern California. The project serves as a prototype for expanding the array to other high-risk earthquake regions. The principal *TriNet* partners are the California Division of Mines and Geology, the California Institute of Technology, and the United States Geological Survey, with the majority of project funding through the Federal Emergency Management Agency's Hazard Mitigation Grant Program.

TriNet products will include an initial map of ground shaking (SHAKEMAP) from the first reporting stations a few minutes after a regional earthquake. Beginning 30 minutes after the earthquake, this map will be augmented periodically to produce more comprehensive versions, incorporating data from most of the recording stations. The denser 600-station array will provide an improved understanding of the ground motions from which to interpret building performances. In the short term, the SHAKEMAP output will provide responders with the earliest forms of disaster intelligence, assessing the:

1) boundary of the disaster area;
2) intensity and distribution of shaking within the disaster area;
3) shaking intensities along transportation routes including seaports and airports;
4) probable access routes into the disaster area;
5) aerial distribution of vulnerability to aftershocks; and
6) patterns of building damage.

TriNet products will also provide positive intermediate-term and long-term mitigation benefits. During the recovery phase of an earthquake, *TriNet* data can provide useful background for the development of interim code requirements, such as those developed for the inspection and repair of steel moment-frame buildings after the Northridge earthquake. For long-term mitigation through improved building codes, ground motion records from the *TriNet* network will provide a significantly expanded basis for understanding the performance of buildings during earthquakes.

Advances in Emergency Management Communications and Protocol

The *TriNet* SHAKEMAP output, displaying recorded ground-motion data, will provide responders with the first regional look at the size, scope, and location of the earthquake shaking effects. The *TriNet* network software automatically generates a SHAKEMAP. This product can be transmitted to emergency managers in each county operational area by the Caltech-USGS Broadcast of Earthquakes, or "CUBE" communications software (Heaton, 1985; National Research Council, 1991; Eguchi and others, 1994 and 1997). California OES has adapted CUBE software as part of its emergency management reporting protocol which includes a dedicated telecommunications satellite system to manage disaster information for statewide operational response, known as the Operational Area Satellite Information System (OASIS), the Standardized Emergency Management System (SEMS) (Petris, 1993; California Office of Emergency Services, 1995), and the Response Information Management System (RIMS), based on the Lotus Notes® software package. This dedicated telecommunications hardware, reporting protocol, and software, coupled with the automated broadcast technology advanced by CUBE, have become the basis for the current ability to rapidly communicate disaster intelligence to emergency managers during response operations.

Application of Loss Estimation Models for Response Operations

Since 1992, the Federal Emergency Management Agency, with the National Institute of Building Sciences, has led the development of the HAZUS earthquake loss-estimation software, comprehensive GIS data bases for the nation, and the Building Inventory Tool for earthquake risk assessment purposes (Jamieson and Milheizler, 1997; National Institute of Building Sciences, 1997; Whitman and others, 1997). HAZUS runs on personal computers using MapInfo® and ArcView® software and is being distributed free by FEMA to local and State governments. The goals of the HAZUS project are first, to standardize a national loss-estimation and risk-assessment methodology which includes most types of natural hazards and second, to provide local decision makers with the tools necessary to develop building inventories and comprehensive risk assessments for their communities in order to promote risk reduction and preparedness activities.

HAZUS input requires three components: 1) the location and magnitude of an earthquake event or a ground motion map; 2) an inventory of structures and their susceptibility to damage from various ground motions; and 3) seismic hazard data, namely soil, landslide susceptibility, and liquefaction susceptibility data. For mitigation planning purposes, HAZUS can input any selected earthquake scenario and develop loss estimates. When coupled with mapped ground motion data from the *TriNet* SHAKEMAP program from a regional earthquake in southern California, HAZUS has the ability to produce initial loss-estimation products. This loss-estimation output will speed the decision-making process for response and recovery by replacing the more costly and time-consuming initial field operation, known as the State and Federal Preliminary Damage Assessment. The HAZUS output estimates building losses and repair costs, damage to utility systems and transportation lifelines, casualties and shelter needs, and economic loss estimates. This modeled "disaster intelligence" includes many of the Essential Elements of Information, listed above, which are required to determine the extent of the State mutual aid requirements as well as to determine if Federal resources should be deployed, via a Presidential Disaster Declaration (Federal Emergency Management Agency, 1992).

After the Northridge Earthquake, the California OES demonstrated the utility of using modeled loss estimates through its proprietary, prototype, loss-estimation software, known as the *Early Post-earthquake Disaster Assessment Tool* (EPEDAT) (Goltz, 1996; Eguchi and others, 1994 and 1997). Based on existing compiled data sets, EPEDAT produced an initial loss estimate within 10 hours of the event, and was substituted for the Preliminary Damage Assessment process which, in the past, has normally taken several days to complete. From the EPEDAT estimates, the President had ample information to release needed Federal response and recovery resources to supplement available California resources. For future earthquakes, "real-time" earthquake source parameters from the *TriNet* seismic network will be automatically fed into HAZUS and EPEDAT to produce loss-estimation models. The modeled outputs will first, shorten to minutes the Presidential Disaster Declaration time and second, guide early joint field operations by defining the number of field teams and prioritizing locations for team deployment, potentially saving lives and reducing property losses.

Seismic Hazard Data Base Development

Significantly, the 1994 Northridge earthquake was the first time that Federal and State emergency management personnel effectively used loss-estimation-methodology and Geographic-Information-System (GIS) products to display critical information and to positively influence the decision-making process during response, recovery, and mitigation operations. However, the Northridge loss-estimation results and GIS-map displays could have been more effective if more complete and accurate data bases had been available. The completion of accurate regional hazard- and building-inventory data bases for California remains one of the greatest challenges facing scientists, engineers, and government officials.

For future earthquakes, development of data bases delineating seismic hazard zones will lead to more accurate earthquake-loss estimates based on strong ground motion patterns recorded by the *TriNet* project. Accurately mapped loss estimates will expedite response operations and facilitate earthquake-resistant reconstruction. Since the 1994 Northridge earthquake, the California Division of Mines and Geology has accelerated the mapping of seismic hazard zones for metropolitan areas in southern California. When completed in 1999, this mapping project will produce a comprehensive seismic hazard data base for 36 quadrangles spanning most of the urban settings throughout Los Angeles, Orange, and Ventura Counties.

In addition, similar seismic hazard maps for San Francisco were released for public comment in April, 1997, and adopted as part of San Francisco's General Plan six months later. The maps identify areas of potential earthquake-induced landslides, liquefaction, fault rupture, and amplified ground shaking.

Following the 1989 Loma Prieta earthquake, the California Legislature established the Seismic Hazard Mapping Act (1990), which mandates the State Geologist to designate seismic hazard zones for use by local government in regulating the seismic safety of new construction. The concept of the act is patterned after the Alquist Priolo Earthquake Fault Zoning Act (1972) and followed recommendations of a two-year needs assessment of seismic hazard information. The purpose of this act is to encourage land-use management policies and regulations that will reduce and mitigate earthquake hazards and assist cities and counties in preparing their general plans. The current project has been funded by a FEMA hazard mitigation grant matched in part by the CDMG. As part of the grant, local decision makers are being trained in the application of these seismic hazard maps.

Operational Plan for Scientific and Engineering Response

Development of Scientific and Engineering Clearinghouse Operations

The demand by the public, the media, and emergency response personnel for scientific information immediately following damaging earthquakes has often thrust scientists and earthquake engineers into the unfamiliar role of supporting emergency response operations. Over the past generation, beginning with the 1971 San Fernando earthquake, scientists have conducted various ad-hoc response operations to meet the demands for information. The Department of Conservation's Division of Mines and Geology (CDMG), the California Institute of Technology Seismological Laboratory (Caltech), the Earthquake Engineering Research Institute (EERI), and the United States Geological Survey (USGS) have always been leaders in organizational response to earthquakes, establishing "clearinghouse" operations for information exchange purposes following the 1973 Point Mugu, 1975 Oroville, 1979 El Centro, 1980 Mammoth Lakes, 1983 Coalinga, and the 1992 Landers-Big Bear earthquakes (California Office of Emergency Services, 1997a).

The large magnitude and remote setting of the 1992 Landers-Big Bear earthquakes created a situation in which investigators from the world over, plus many others, descended upon and overwhelmed the small communities of Yucca and Landers. One of the lessons learned from this experience is that a central clearinghouse is necessary to manage the flow of field investigators to damage sites at municipal and private properties, prompting the call for a formal development of a prototype clearinghouse operational plan by Ranous and others (1993).

Teams from the Earthquake Engineering Research Institute have been conducting post-earthquake investigations since its inception in 1949, under a program partially funded by the National Science Foundation, known as *Learning From Earthquakes* (Earthquake Engineering Research Institute, 1996). The primary purpose of the *Learning From Earthquakes* program is to observe and document the effects of earthquakes on the built environment as well as effects on social, economic, and public policy. Over the years, results from the program have led to new knowledge, improved building practices, new research in earthquake mitigation, and improved field data collection and dissemination techniques. According to EERI's *Post-Earthquake Investigation Field Guide: Learning From Earthquakes*, multidisciplinary teams systematically gather data, record unique failures and dramatic impacts to the built environment, and investigate social, economic, and political impacts (Earthquake Engineering Research Institute, 1996). Traditionally, these observations have been disseminated to the broad professional community through public briefings, video tapes, comprehensive reconnaissance reports, and slide sets, often reaching thousands of people throughout the world within months of the event.

Since the Loma Prieta earthquake, the operational response protocol for earth scientists has been refined and formalized in the *United States Geological Survey Plan for Post-earthquake Investigations* (United States Geological Survey, 1996). The goals of the plan are to facilitate post-earthquake scientific investigations, assure rapid dissemination and use of USGS field investigation results, and facilitate delivery of technical support and information to response organizations.

During the 1994 Northridge earthquake, EERI and the USGS participated with the California OES in the prototype clearinghouse operation which was mutually beneficial to each of the organizations. The clearinghouse was operational for about two weeks as a collaborative effort of a number of California organizations involved in earthquakes. The information gathered by the individual field investigators became invaluable to all participants when it was shared in the briefing room late in the evening.

California Post-earthquake Information Clearinghouse Plan

With the technologies described above in hand, the next step is to corroborate damage and loss estimates provided by TriNet and HAZUS through the conduct of a systematic field reconnaissance effort. Field observations from scientists, engineers, municipal officials, and representatives of seismic safety organizations can add substantially to the information available to officials managing response and recovery operations. However, a plan is necessary to address not only the organizational aspects of coordinating field reconnaissance activities but also the technical aspects of translating and transferring this accumulated field disaster information to response officials on a continual basis. Such a plan must address management of a central clearinghouse operation as well as operational concepts, planning and intelligence, logistics, and finance of operations.

Since March, 1996, a group of 15 Federal and State agencies, academic institutions, and professional engineering organizations have jointly developed, refined, and exercised the *California Post-Earthquake Information Clearinghouse Plan* (Clearinghouse Plan) to operate a technical clearinghouse in order to coordinate operations and share information immediately following major earthquakes in California (California Office of Emergency Services, 1997a). These agencies and institutions perform response functions by conducting scientific and engineering investigations, reconnaissance operations, and information dissemination under various mandates and authorities.

Organizations involved in the clearinghouse planning process are listed in Table 1. Each of these organizations has a role in conducting field observations of natural phenomena, structures, or social systems; collecting data; or analyzing and disseminating information.

Table 1. California Post-earthquake Information Clearinghouse Collaborating Organizations

Applied Technology Council (ATC)
California Office of Emergency Services (California OES)
Department of Conservation's Division of Mines and Geology (CDMG)
California Seismic Safety Commission (CSSC)
California Institute of Technology (Caltech)
California Universities for Research in Earthquake Engineering (CUREe)
Earthquake Engineering Research Institute (EERI)
Federal Emergency Management Agency, Region IX (FEMA)
National Aeronautics and Space Administration (NASA/AMES)
Pacific Earthquake Engineering Research Center, U. C. Berkeley (PEER)
Southern California Earthquake Center (SCEC)
Structural Engineers Association of California (SEAOC)
Technical Committee on Lifeline Earthquake Engineering (TCLEE)
University of California Berkeley Seismological Laboratory (UCBSL)
United States Geological Survey (USGS)

The goals of the Clearinghouse Plan are to outline the clearinghouse purposes, identify the participating organizations and their roles, describe the management scheme, and detail operating procedures. FEMA and the California OES endorse this plan as the mechanism for integrating scientific and technical information into the information, planning, and disaster intelligence mechanisms established under the Federal Response Plan (Federal Emergency Management Agency, 1992) and the California State Emergency Plan (California Office of Emergency Services, 1997b).

Clearinghouse Organization and Management

The Clearinghouse Plan is organized into the five elements of the standardized Incident Command System: 1) management; 2) operations; 3) planning and intelligence; 4) logistics; and 5) finance. Five organizations form the Clearinghouse Management Group:

1) California Division of Mines and Geology and
2) United States Geological Survey, both responsible for seismological and geological assessments of earthquakes;
3) Earthquake Engineering Research Institute, whose charter is to investigate the structural and social effects of all major earthquakes in the United States and abroad;
4) California Seismic Safety Commission, responsible for recommending and advising the Governor on all seismic policy and legislation; and the
5) California Office of Emergency Services, responsible for disaster intelligence and coordinating State resources and response to all earthquake disasters.

Clearinghouse Operations, Planning and Intelligence, Logistics, and Finance

Following most future major earthquakes in California, the clearinghouse will function in the following capacities: 1) serve as the daily clearance, coordination, and debarkation point to the field for all investigators and officials who arrive at the scene; 2) collect and verify perishable reconnaissance information; 3) convey information to the Planning and Intelligence function of the California Regional Emergency Operations Center (REOC) and the Information and Planning emergency support function of the Federal Emergency Response Team; 4) provide updated damage information to all interested parties through briefings and reports conducted each evening; and 5) guide and track field investigators in the damaged area.

Locating the clearinghouse is a fairly big challenge. The clearinghouse should be as close to the affected area as possible with communications and transportation access in order to accommodate field investigators. At the same time, the Clearinghouse must share information with at least one of the three California OES REOCs, located in Los Alamitos, Sacramento, and Oakland. Since the REOC may not be proximate to the damaged area in certain earthquakes, the clearinghouse will be electronically linked in order to share data bases. The clearinghouse operation requires telephones, electricity, computers, work and display space, and a meeting room large enough to accommodate most participants for the all-important evening briefings.

For the Northridge earthquake clearinghouse operation, each participating agency bore the costs involved to perform damage assessments and reconnaissance activities. California OES provided the space and most equipment for the clearinghouse. *The Clearinghouse Plan* prescribes that each agency and participant is responsible for funding its own post-earthquake field investigations.

Delivery of Disaster Information to First Responders

The effectiveness of new information technologies, such as HAZUS and TriNet, for emergency management depends on the organizational and training efforts to transfer the products generated by these new technologies to the user community in a timely manner. With this premise in mind, a two-year organizational and training effort has begun in the greater San Francisco Bay Area as part of a regional earthquake risk assessment entitled, *Development Of "HAZUS" Risk Assessment Capabilities for the San Francisco Bay Area, California.* One objective of the regional project is to ensure the effectiveness of these new technologies after a major earthquake in California by augmenting the transfer of real-time earthquake data and loss-estimation information to local decision makers.

To accomplish the regional earthquake risk assessment, five additional project objectives include: 1) development of a comprehensive HAZUS user group of GIS professionals employed at Federal, State, and local government agencies, as well as from major utilities, universities, and corporations; 2) professional training in new technologies;
3) augmentation of regional earthquake-hazard data bases; 4) development of building inventories; and 5) emergency management protocol for production, analysis, and distribution of HAZUS post-earthquake products. This project envisions that, at the turn of the century, all city and county organizations will share a common, comprehensive, hazard-and-risk-GIS data base and software capability which will be the

basis for provision of the most accurate earthquake-loss estimates possible within minutes after a major local earthquake. The outcome from this HAZUS user group and risk assessment project will be to save lives, protect property, and reduce overall disaster costs. Pre-earthquake mitigation planning for the region will also be a natural outcome from this project. The project is being funded and coordinated by FEMA Region IX, San Francisco, with consultation and support from the California OES.

Conclusions

Scientists and engineers are advancing technologies which can now provide emergency managers with information products that will result in saving lives and protecting property during the response phase following earthquakes. Parallel with the development of the technological advances, organizational efforts are in progress designed to integrate information technologies and products into existing emergency management protocols, in order to meet the precise needs of responders.

With the advent of standardized earthquake loss-estimation methodologies and software tools to develop and catalog hazard, infrastructure, and building-performance data bases, response plans will begin to further incorporate products from these tools in order to guide post-earthquake scientific and engineering field operations, as well as emergency management response, recovery, and mitigation decisions. The success of future response operations following earthquakes will, in part, depend on accurate and timely disaster information and intelligence products generated by scientific and engineering organizations.

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Data Collection for Earthquake Loss Estimation in the OES Coastal Region

Scott McAfee[1]

Introduction

Earthquake loss estimation software has increased our ability to prepare for and respond to damaging earthquakes. Over the last few years, the Coastal Region of the California Office of Emergency Services has been using and further developing the earthquake loss estimation tool HAZUS. OES has used this tool to enhance its own planning and preparedness efforts as well as those of various public and private sector organizations. In addition, a computer program is being developed to integrate HAZUS results and other earthquake information into the OES Response Information Management System (RIMS), which aids the response efforts of federal, state, and local emergency management agencies during California disasters.

Role of GIS Databases in the Model

An integral part of HAZUS is a geographical information system (GIS), that allows for the relational analysis of data in a spatial environment. Since the model's primary purpose is to make estimates of "**how much** of **what** happened **where**?" this spatial component is essential.

Yet the foundation of such tools is not be the modeling software itself, or the GIS application that supports the models, but rather he underlying databases that provide detailed information on the area of interest. Though modeling programs can yield rough estimates with default information, such data can be lacking in detail, largely inferred, and/or spatially 'uniform'. It stands to reason the better the data used in the model, the closer to reality the output will be.

Once the data is in, the digital geologic maps coupled with epicenter data and an attenuation model will yield groundshaking maps of various kinds. These in turn are compared against maps of building stock, demographics, lifelines, and critical facilities to generate maps and tables of describing the physical, economic, and social impact on the region.

Specifically, input of an earthquake epicenter and magnitude can yield estimates on the location and extent of such things as casualties, sheltering needs, direct and indirect economic losses, bridge . functionality, and damaged building stock, hospitals, schools, and emergency operations centers. The databases contributing to the inputs can be large and hard to find, and collection for regions covering wide areas can be a challenge. Since GIS is still relatively new, much of the needed data may be unavailable in digital format. It will then become necessary to "digitize" existing paper maps and databases. Even digital data sets that exist individually in smaller areas throughout the region, such as utility district maps or county tax assessor files, can be difficult to obtain or lacking in crucial information. Hopefully, these problems will be overcome through time as more jurisdictions take advantage of GIS technologies, and mechanisms are worked out to facilitate in the sharing of data between and among jurisdictions.

Example of Data Collection: OES Coastal Region

The Coastal Region is an administrative region of the Governor's Office of Emergency Services. It serves sixteen counties containing over 7 million people and spanning close to 56,000 km^2. For the last 4 years,

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its GIS unit has been involved in collecting data for risk analysis. This data is presently being used with the HAZUS earthquake loss estimation tool, developed by Risk Management Solutions, Inc. for the Federal Emergency Management Agency in a project managed by the National Institute of Building Sciences. Following are some specific examples of problems and breakthroughs the Coastal Region GIS has had collecting data during this time, as well ideas for future methods and uses.

Geology

Digital databases of geology are required for the generation of local site effects of earthquakes, including liquefaction, landslide, and soil amplification. Of these, our GIS has only been able to compile site soil maps for amplification effects. With the completion of the statewide Seismic Hazards Mapping Program we look forward to incorporating liquefaction and landslide maps for our region into the model.

The soil map that we use is a patchwork of databases from different sources that well illustrate some difficulties of data collection over a large region. A number of databases have been acquired from the USGS' internet site, including geology of the south San Francisco Bay Area, Alameda County, and Contra Costa County; these exist at scales ranging from 1:62,500 to 1:125:000. All that was necessary was to convert the individual soil units to site soil classes, based primarily on either age and lithology of the unit or specific knowledge of the unit's properties. These site classes include firm and hard rocks (Type B); gravelly soils and soft to firm rocks (Type C); stiff clays and sandy soils (Type D); and Soft Soils (Type E). The remaining data for California is currently covered by digital versions of the California Department of Mines and Geology's 1:250,000 scale geological maps, which have been given soil site classifications by DMG. The resulting digital map exists as a variety of scales and sources (figure 1). It is by no means ideal, but is proving to be quite helpful in increasing the accuracy of the model until such time as accurate, standardized maps are available.

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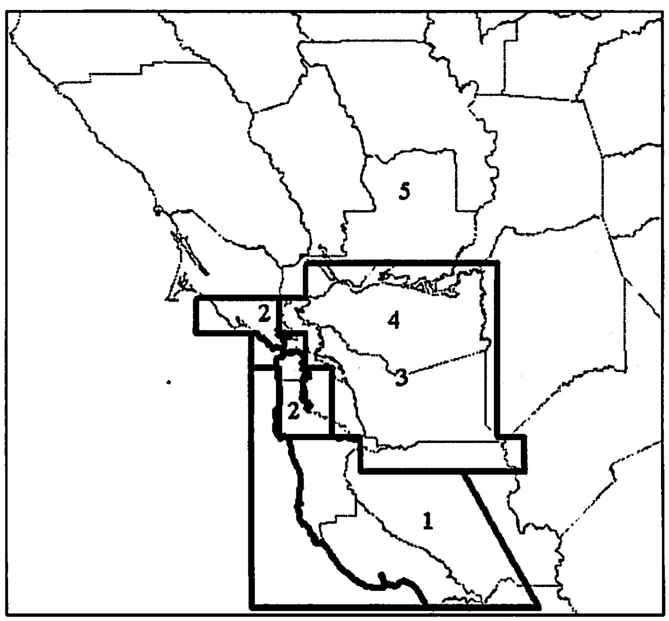

Figure 1: Sources of Geologic data for HAZUS

Building Inventory: General Building Stock

HAZUS is designed to utilize a building inventory of the particular study region containing sixteen building classifications, plus height subclasses. Values for building class are arrived at by using a classification scheme to map information on occupancy type (residential, commercial, industrial, etc.) to a model building type. HAZUS comes with a default scheme that is generalized to the state level. Since these relationships will vary from region to region, data needs to be collected on various building and occupancy types in different areas to modify this scheme.

HAZUS comes with software known as the Building-Data Import Tool (BIT) which is intended to improve the existing scheme by analyzing land use/building type relationships in large databases such as tax assessor databases. OES Coastal Region served as a pilot test case for the BIT tool, but found the assessors' databases too lacking in building type information to feasibly modify the mapping scheme from its default values. Out of sixteen counties, Alameda county had the most information with only 15% of records having a populated "building type" field.

An effort is currently underway to look closely at what methods can be used to improve the general building stock data for the East Bay, starting with the cities of Oakland and Berkeley. This project has the support and guidance of some of the original members of HAZUS' Project Working Group, who will help in this and other areas leading up to a comprehensive risk analysis of the region surrounding the Hayward fault. An eventual product will not only be improved data for HAZUS' general building stock, but guidelines for local governments on how to make those improvements.

Future plans to refine the Coastal Region general building stock inventory include incorporation of more specific building databases, regional workshops, and even field studies involving windshield surveys of those areas deemed lacking in accurate data. It should be noted that as with other databases collected for earthquake loss models, the building inventory can be put to other uses as well, such as land use studies and loss estimates from other models such as flood or wind damage.

Critical Facilities

While HAZUS uses general building stock data that is aggregated to the census tract level, critical facilities exist as individual records and include schools, hospitals, and emergency operations facilities. Like the general building stock, defaults for critical facility building types are generalizations. Obviously, improving these values would go along way toward estimating the functionality of such facilities following a major earthquake.

Other Data

Other databases that the Coastal Region needs to refine include high potential loss facilities (dams, nuclear power plants, and military installations) and utility lifeline systems (potable water, electric power, waste water, communications, and liquid fuels). These exist as default data within Hazus to one degree or another, but would benefit the modeling tool were they improved in detail and accuracy. Much of this data will be difficult or impossible to obtain, due to security issues. The next version of HAZUS will include a module to do network analyses on potable water lines, hopefully giving useful information on where temporary water resources need to be located. Good data from water utilities will be essential in enabling such a module.

Looking Ahead

Although collecting data for an earthquake loss estimation tool can be a daunting task for an organization interested in a large area, it doesn't have to be impossible. As more and more local jurisdictions and special districts realize the benefits of GIS and models such as HAZUS, they are beginning to understand as well the value of sharing their data with each other. It is OES' goal to work with and coordinate inter-agency and inter-jurisdictional data consortiums, in the hope of developing standards and relationships that will make the transfer of data easier and provide incentives for doing so. One such organization, the Shared Information Network for Bay Area Disasters (SINBAD), has been started in the Coastal Region.

Panel Discussion Notes

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JANIELE MAFFEI
GUY MORROW

Panel Discussion Members

Craig A. Cole
Craig Cole has 24 years of structural engineering experience in California. A Vice President at EQE International, he is a licensed California S.E. and member of SEAONC. He has been evaluating the seismic vulnerability of existing buildings, designing seismic upgrade designs and performing seismic probable maximum loss analyses for the past 14 years. Probable maximum loss analysis projects have included detailed non-linear structural analyses, preliminary engineering assessments and loss estimates of large portfolios of properties. Craig has visited the site of 6 significant earthquakes following the events, participating in collating and analyzing damage data from these events.

William P. Graf
Bill Graf is an Associate with Dames & Moore in Los Angeles. He is the manager of Dames & Moore's earthquake risk capabilities and earthquake risk software development. He has more than 19 years of experience in structural analysis and design, finite element analysis, dynamics of structures, earthquake engineering, and earthquake hazard and risk analysis. Since joining Dames & Moore more than 12 years ago, Mr. Graf has performed building reviews for seismic risk, including detailed structural analyses of high-rise structures for earthquake loads, and structural testing.

Mr. Graf holds B.S. and M.S. degrees in Engineering from the University of California, Los Angeles. He is a member of the Earthquake Damage Assessment subcommittee of the Structural Engineers Association of Southern California, and a member of the Earthquake Engineering Research Institute. Mr. Graf is a registered Professional Engineer in the State of California, and has published technical articles on dynamic analysis techniques, structural testing and earthquake financial risk analysis.

Mr. Graf has investigated earthquake damage to building and other structures following the 1987 Whittier-Narrows; 1989 Loma Prieta; 1991 Sierra Madre; 1992 Landers, Big Bear and Desert Hot Springs; 1994 Northridge, and 1995 Tauramena (Colombian) earthquakes.

Guy Morrow
Guy Morrow is a Vice President/Principal Engineer at Risk Management Solutions, Inc. At RMS, he has been involved in the development of numerous natural catastrophe risk models, both for the US and international countries. Prior to joining RMS, Mr. Morrow was an associate at Degenkolb Engineers. Mr. Morrow holds a B.S. in Civil Engineering from the University of Illinois and a Masters degree in Structural Engineering from the University of California at Berkeley. He is a registered Structural Engineer in the State of California.

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Janiele Maffei is a Structural Engineer and Principal with Degenkolb Engineers. Prior to joining Degenkolb eight years ago, Ms. Maffei had her own structural engineering consulting firm. She has over 20 years of experience in the field of structural engineering and is currently responsible for the technical support and future developments of ST-RISK.

Panel Member Question Responses

What part in the overall area of seismic risk analysis do you feel PML's play?

_CC:_ PML's play an important part particularly with respect to those with equity interest in structures, i.e. owners, property insurers, and real estate lenders. They provide a simple way of relating the concept of seismic risk in financial terms. Unfortunately, too few people (including those who request PML's, those who use them, and those who provide them) understand what a PML is, and its limitations.

_BG:_ Seismic risk assessments (i.e., PML's) play an important role in the property transfer process to distinguish – in financial terms – existing buildings that constitute good seismic risks from intermediate and poor seismic risks. Seismic risk assessments can help to encourage seismic rehabilitation of vulnerable buildings in high hazard areas, since owners of these buildings may not be able to obtain loans without some form of risk reduction (retrofit) or risk transfer (insurance).

Seismic risk assessment methods are also essential for performance-based design of new buildings, and retrofit to meet specific performance goals. As performance-based design is incorporated in building codes, seismic risk assessment methods will become even more important to translate engineering response into reliable damage cost estimates. Reductions in damage from retrofit or special design must be cost-justified in today's world. In this way, seismic risk assessments 'pave the way' for performance-based new design and performance-based retrofit design. Seismic risk assessment methods will be unavoidable in tomorrow's structural engineering practice.

Both risk assessment of existing buildings and performance-based design rely on poorly defined relationships between seismic hazards and building damage. The single greatest need in seismic risk assessment is for uniform and comprehensive collection of earthquake damage statistics, including:

- instrumental measurement of ground shaking at the site or nearby, on similar ground conditions;
- description of any special hazards and their effect;
- engineering description of the building design features and pre-earthquake structural conditions;
- engineering description of damage; and,
- accurate data on repair and replacement costs.

_GM:_ Currently, it is possible that a PML estimate can end up playing an important part in a seismic evaluation. Right or wrong, it expresses the expected performance of a building in terms of a single monetary number that is relatively easily understood by a user with a non-technical background. A distinction should be made between loss analyses that are performed as part of a more extensive seismic evaluation and those performed solely for the purpose of estimating financial losses. In the former, a financial loss estimate can be a useful means of comparing different locations or evaluating the cost trade-offs of seismic strengthening. However, a performance "grade" system that describes the expected performance may be more appropriate than a single "PML" loss number. In the latter case, a stand alone loss estimate with no other description of estimated building performance is not really an appropriate manner to quantify the seismic performance of an individual building. However, such analyses may be appropriate on an individual basis if a number of risks are being evaluated over a period of time for the purpose of making a series of financial decisions.

JM: PML's, or probable maximum loss valuations, are a rating of a building's expected earthquake damage as represented by a percentage of its value. Typically, they are provided at the request of lending institutions during real estate transactions. PML assessments were developed as a tool for the insurance industry approximately twenty years ago. These risk assessments are an important engineering service that structural engineers can provide to insurance, financial and real estate clients. PML's are an effective tool for the real estate industry, allowing them to make informed decisions about the potential earthquake risk of a particular building. They should not be represented as an in-depth study of the building's structural system or expected performance. Rather, they are an appropriate screening device that can be used to identify building characteristics that are known to have contributed to earthquake damage in past earthquakes. Structural engineers are the best source for this information.

Do you feel there should be a standardization of PML calculations? If yes, what procedure(s) do you think should be incorporated into a standard?

CC: There should be a standard as to the definition of a PML. The PML can then be used by various participants without confusion. I do not believe that a standard method of calculating PML's should be developed by the structural engineering community because there is very little real actuarial data upon which to judge the appropriateness of different approaches for most types of construction. However, I do believe that a standard method of gathering data for determining the PML would be useful. In this way, once a major earthquake occurs meaningful data could be easily gathered and used to develop a standardized procedure. With a standard definition, there would be significantly less confusion by those using the estimates we develop.

BG: There are many sources of inconsistency in the current practice of assessing PML's. Some of these problems can be reduced by establishing definitions and standards of practice. Other problems relate to limitations in the state-of-the-art, or the irreducible differences in experience and judgment between practicing engineers. In my opinion, the best course of action at present is for professional organizations (SEAOC, ASTM, ASCE) to produce guidelines for seismic risk assessment, with recommendations for appropriate standards of practice.

Definitions of Seismic Risk: One common definition of PML is the "loss estimate, with 90% confidence of nonexceedance, for seismic hazards having an average recurrence of 475 years." With some training, this type of seismic risk estimate can be made with some degree of consistency by a practicing Civil or Structural Engineer. However, this 'defined' PML has many draw-backs in financial decision-making and in professional practice.

Recommendation: Implement a better standard to describe seismic risk:

- one that considers the particular client perspective (lender, owner, or insurer); and,
- one that more clearly associates probability with loss.

Structural Vulnerability Assessment by Non-PE's: PML's are financial risk estimates, but these reviews often involve life-safety issues. As an example, the building in question may be a pre-1976 tilt-up or an unreinforced masonry building without parapet bracing or wall anchors. In these cases, the Civil or Structural Engineer has a responsibility to inform the owner and lender of any life-safety concerns, and the available structural remedy. The life-safety implications also point out why it is imperative that an experienced Civil or Structural Engineer perform the structural vulnerability assessment. Currently, there are Architects, contractors, and in some case P.E.'s doing this work without the necessary qualifications, training or experience. By State law, you must be a licensed Professional Engineer in order to make any statement regarding the adequacy of the structural systems for gravity or lateral loads. In some cases, these non-P.E. PML practitioners may be violating the law, in addition to failing to identify critical structural weaknesses.

Recommendation: The standard of practice for seismic risk assessments conducted for owners, prospective purchasers and lenders should require that

Do you feel there should be a standardization of PML calculations? If yes, what procedure(s) do you think should be incorporated into a standard? (cont.)

structural vulnerability assessment be conducted by a registered Professional Engineer (Civil or Structural).

Special Seismic Hazards: PML's involve not only the assessment of structural vulnerability but also seismic hazards. Published information for probabilistic ground shaking in California is now readily available from sources such as the United States Geological Survey (USGS) and California Division of Mines and Geology (CDMG). However, there are cases in which the P.E. may not be adequately trained or qualified to make necessary judgments regarding seismically-amplifying ground conditions, surface fault rupture, liquefaction, landslide, tsunami, seiche or other so-called 'special seismic hazards'. Site-specific assessment of the probability, extent and severity of damage from these hazards may require consultation with other professionals, such as an engineering seismologist, geologist or geotechnical engineer. In these cases, the Civil or Structural Engineer must inform the Client of the need to involve these other professionals.

Recommendation: Where 'special hazards' are encountered, the standard of practice for seismic risk assessments conducted for owners, prospective purchasers and lenders should recommend that other professionals be consulted as needed to assess the probability, extent and severity of damage from these hazards.

A recommended standard of practice for seismic risk assessment should include the following elements:

- Definitions of terminology, and recommendations for the discussion of seismic risk with clients and other engineering professionals;
- Recommendations for levels of study appropriate for different clients, and minimum scopes of work and minimum qualifications for professionals to conduct each level of review;
- Recommendations for structural vulnerability assessment related to life-safety issues;
- Structural vulnerability assessment, related to the determination of building damage functions;
- Seismic hazard assessment, related to the determination of site-specific seismic demand for damage assessment;
- Assessment of 'special seismic hazards', with recommendations for use of other professional, where appropriate;
- Treatment of hazard uncertainty and building damage function uncertainty;
- Schematic algorithms for computing structural damage from ground shaking;
- Recommendations for the scope and contents of the seismic risk report to clients, with definitions, suggested formats for description of seismic hazards and vulnerability, explanations of methods and interpretation of results, as well as disclaimers appropriate for each defined level of study;
- A list of sources of information on seismic hazards, building damage functions, vulnerability assessment and structural rehabilitation standards.

Do you feel there should be a standardization of PML calculations? If yes, what procedure(s) do you think should be incorporated into a standard? (cont.)

The standard of practice document should be updated frequently, as new information and methods emerge. The scopes of work and minimum qualification standards should be presented in a way that can be distributed to clients and incorporated in client criteria and contracts.

GM: There are a multitude of methodologies that can be utilized in performing different phases of a loss estimate, such as:

- The manner in which uncertainty in both the ground motion and vulnerability are considered
- The type of seismic model (e.g. sources used, incorporating time dependence)
- The structure vulnerability relationship used in the analysis
- etc.

Different methodologies/assumptions have their own merits and it is probably not possible or appropriate to define one standard procedure for performing a loss estimate. Particularly, because loss estimates are used for different purposes, they require different levels of detail in the analysis methodology. However, there should be some standard ways in which the methodologies and assumptions utilized in the loss estimate are defined and reported.

JM: Standardization of PML evaluation procedures may not be necessary. Instead, standardization of terms and the requirement that the PML methodology meet certain general characteristics should be implemented. This can be accomplished by the development of a supplement to the guidelines established for the evaluation of existing buildings. Guidelines such as FEMA 310 and 273 already include guidance on building characteristics and performance that contribute to damage. The final step in developing a PML methodology is the quantification of that damage.

Guidelines should be established that allow for comparison of PML evaluations. These guidelines should include standard definitions of terms. Currently there are numerous definitions of PML being used by the structural engineering community. This causes confusion and undermines the client's confidence in the risk assessment procedure. It is not uncommon to find values as disparate as 14 and 60 on the same building. Unfortunately, without standard definitions of critical terms, it is difficult to identify if the discrepancy lies within the definition of terms or within the procedure.

Do you feel the definition of PML should be standardized? If yes, how would you define it and why?

<u>*CC:*</u> The standard that is typically utilized is a conservative estimate, having approximately a 90% confidence level of nonexceedance that damage to a building would not exceed a given value when subjected to the ground shaking at the building site that has a 10% probability of being exceeded in 50 years. I believe this is a useful definition. If clients want to look at ground shaking with different probabilities of occurring, the nomenclature of the damage estimates should reflect the difference.

<u>*BG:*</u> As stated previously, one common definition of PML is the "loss estimate, with 90% confidence of nonexceedance, for seismic hazards having an average recurrence of 475 years." This definition exists, and is widely used -- with some variations. With some training, this type of seismic risk estimate can be made with some degree of consistency by a practicing Civil or Structural Engineer. This definition is convenient for professional engineers, without really addressing the clients' direct concerns.

This defined 'PML' has many draw-backs as a standard in financial decision-making and in professional practice:

- The level of probability (or frequency of occurrence) for the <u>loss</u> is unknown. The definition combines a statement of probability for the seismic hazard and a statement of confidence level for the losses that may occur in the defined hazard. The definition does not lead to an unambiguous description of the probability of a particular loss.
- The selected level of probability for the hazards is not appropriate for some clients. An owner may be interested in risks within a 50-year building life, so a '10% chance of exceedance in 50 years' (or 475-year recurrence) may be relevant, unless the building life is intended to be shorter. Lenders and insurers generally are interested in a different exposure period, and hence a different return period, for risks.
- The calculations to arrive at a <u>loss</u> with specified probability are somewhat more complex than simplistic PML estimates. In common practice, a typical PML calculation involves use of ATC-13 tables to find mean damage and 90% confidence damage level for the specified hazard level. In a more complete probabilistic calculation, the variability (statistical variance) in building damage functions increases somewhat above the mean damage level for hazards having the desired probability. However, the probabilistic loss estimate will generally be far less than the traditional 90% confidence PML. Most clients incorrectly associate the PML estimate with the stated hazard probability, and make short-term business decisions based on the long-term hazards compounded by high confidence limits. The actual return periods of the losses quoted as PML's may be from 1500 years to as much as 10,000 years. These return periods have little relevance to a typical 20-year loan.
- PML is a point estimate of risk. A more thorough depiction of seismic risk is achieved when several different loss levels and their respective return periods are plotted in a continuous curve. The loss levels and return periods should span the ranges of client interest. This allows the client to inspect the

Do you feel the definition of PML should be standardized? If yes, how would you define it and why? (cont.)

> risk at any level, from frequent, low levels of loss to rare catastrophic losses. The client is also enabled to take certain actions, such as change the loan life, to achieve acceptable risks.

Software to allow probabilistic calculation of seismic losses is available from a number of vendors, including Dames & Moore. Use of the software will help provide more rational loss estimates, suited to financial client needs.

GM: Different users of PML results will have different reasons for conducting a loss analysis and, therefore, a single standard "PML" definition is not appropriate (e.g. "loss with a 90% probability of non-exceedance associated with a 475-year ground motion"). Additionally, the term "PML" should probably not be utilized due to the different criteria that go into loss analyses that are currently all being characterized as "PML" loss evaluations. However, there should be some standardization in the manner in which the ground motion and vulnerability assessment are made and described.

There are two ways to define the hazard and vulnerability criteria for a loss estimate. The first is to define the ground motion in terms of either a scenario, or in terms of an annual probability of exceedance (i.e. return period). Based on that ground motion, the loss is described in terms of a probability of non-exceedance (e.g. 90% probability of non-exceedance (PNE) given a specific ground motion intensity).

A second and more rigorous methodology is to consider the uncertainties in ground motion and damage in tandem for each event analyzed, whether it be a scenario or probabilistic analysis. In the case of a probabilistic analysis, the overall loss will then be associated with an annual probability of exceedance.

In either case, the criteria should be clearly stated in the analysis report. For example, in the case where hazard and vulnerability uncertainty are treated independently:

> The expected loss due to a Hayward 7.0 event
>
> or
>
> The 90% PNE loss due to a 475-year ground motion.

In the case where uncertainty in hazard and vulnerability are treated concurrently:

> The loss with a 0.2% annual probability of exceedance.

A criteria that often gets associated with a "PML" estimate is the 90% PNE loss for the 475-year ground motion. This is a conservative approach given that the ground motion has a 0.2% annual probability of occurrence and given that ground motion, there is only a 10% chance of exceeding the loss. The expected loss for a 475-year ground motion would likely be more reasonable.

Rather than having a standard that defines what the results of a PML analysis should represent, what is needed is a user's guide explaining appropriate methodologies (and technical terms) that can be utilized in developing a loss estimate. This would include the manner in which ground motions are determined and the meaning of "a xx year return period ground motion" and "90% probability of non-exceedance loss". With an understanding of the basic assumptions/procedures available, the user can then stipulate the type of analysis that best fits their needs.

Do you feel the definition of PML should be standardized? If yes, how would you define it and why? (cont.)

JM: PML is defined in our software as the expected maximum percentage monetary loss which will not be exceeded for 9 out of 10 similarly constructed buildings at a given MMI level. MMI, Modified Mercalli Intensity, provides a rating of the intensity of earthquake shaking on a scale of I to XII. This is most commonly requested for real estate transactions involving single buildings or numerous buildings on a single site. For real estate transactions involving numerous sites, it may be more appropriate to identify the mean or median loss. Median loss is the expected loss which will not be exceeded for 5 out of 10 buildings. Mean loss is the average loss for buildings with similar characteristics experiencing the same intensity of shaking. The establishment of standardized definitions for seismic risk assessment is essential.

It is important to understand that buildings will have different PML values for earthquakes that produce different shaking intensities at their location. Consequently, an important step in establishing a PML value is the definition of an appropriate scenario earthquake. Most lending institutions have their own guidelines that identify this scenario earthquake. The most common request is for the earthquake that has a probability of exceedance of 10% in 50 years.

Comment on the implications of using spectral acceleration vs. MMI in calculating a PML.

_CC:_ MMI is a highly subjective and qualitative quantity. It is dependent not only on the strength and character of the ground motion but also on the quality of the construction affected. It is a very useful quantity for use after an earthquake has occurred to characterize the general severity of earthquake effects in an area, but not very useful for engineering purposes when any precision is required. Spectral parameters (acceleration, but also displacement and velocity) provide a much better definition of the important characteristics of ground shaking that affect structural response. However, it should be remembered that ground motion for a future event, no matter how characterized, can only be approximated – not precisely calculated, and will always be an uncertain quantity.

_BG:_ The use of spectral acceleration, adjusted for site ground condition, better represents the seismic demand of ground shaking than Modified Mercalli Intensity (MMI) based on peak ground acceleration or peak ground velocity. For this reason, design codes use spectral acceleration to determine seismic design forces. Other parameters of seismic demand (i.e., duration of shaking, etc.) appear to be somewhat less important to structural performance. Future large-magnitude earthquakes in engineered urban environments may demonstrate the need for a more complete description of seismic demand.

At present, we need building damage functions that predict damage level (e.g., repair cost as a fraction of building replacement value) based on rational structural classes, observable design features and spectral acceleration. In the future, we should avoid or eliminate MMI as a measure of seismic demand.

_GM:_ Using spectral acceleration offers the potential to provide refined loss estimates, taking into consideration a particular buildings' characteristics and seismic setting. It definitely can provide a more detailed indication of the physical response of the building. However, there is less empirical data relating spectral acceleration to damage/loss as compared to the amount of data relating MMI to damage/loss. If spectral acceleration is used, a relationship between the building response (both structural and non-structural) and consequential financial loss must be established. There is little data upon which to base that relationship and developing the relationship for an individual building will be associated with the same type of uncertainty inherent in using MMI as a damage/loss predictor. Nevertheless, as more data is assembled in the future, spectral acceleration will likely become a more standard approach to performing loss estimations.

_JM:_ Modified Mercalli Intensity was originally used as the hazard input in PML evaluations because there were limited acceleration records available for buildings that experienced earthquakes. What was available was a subjective identification of building damage in specific geographic locations. The MMI scale allowed the quantification of these damage assessments. With the advent of the strong motion instrumentation program and the ability to develop spectral acceleration values for buildings, the use of MMI is being challenged. Because of the subjectivity of MMI, the use of spectral

Comment on the implications of using spectral acceleration vs. MMI in calculating a PML. (cont.)

acceleration appears to be more accurate. However, spectral acceleration does not capture all the characteristics of ground motions that contribute to building damage, such as duration and near field effects. While this will be the hazard input of the future, it is important to recognize the complexity of the transition to spectral acceleration. It requires an understanding of the building's non-linear behavior.

Please comment on the variability of PML calculations. If several engineers perform a PML calculation on a building with the same information provided, what do you feel is an acceptable range of results?

CC: Currently, there is extreme variation in the PML estimates provided by different engineers. This difference can be attributed to a variety of factors, including:

- For most construction types, there is an almost complete lack of a sufficient statistically valid data base of actual losses and repair costs that can be used to develop realistic and meaningful estimates. This forces engineers to rely extensively on judgement and to guess.
- Lack of agreement as to what the definition of PML is in terms of whether it is probabilistic or deterministic, and at what exceedance probability and confidence level.
- Lack of understanding on the part of many PML providers, as to what the PML is or how to go about deriving a value.
- Due to the limited scope of effort placed into many PML evaluations, a lack of understanding of the actual construction of the building being evaluated, and its vulnerabilities
- Wide inconsistencies in the estimates of ground motion

BG: There are several sources of discrepancy in current PML calculations. Different engineers may use different hazard estimates, different damage functions, different approaches to 'confidence limits', etc. (The situation becomes even more complicated where 'special hazards' enter the picture!) Wide divergence is to be expected under these circumstances. Clients must select experienced, qualified engineering consultants. Clients and the selected engineering consultants must work together to establish uniform seismic risk criteria suited to client needs, uniform and appropriate scopes for investigation, and clear report presentation formats, in order to obtain more consistent results.

The use of seismic risk software can also help to achieve consistency in results. Seismic ground shaking hazards and site effects can be standardized. The software can provide a standard set of loss functions and statistical functions for treatment of loss variability, appropriate to the level of review. Finally, the software can do complex loss calculations to arrive at loss-recurrence (i.e., loss for known return period or probability), rather than a simplistic (and perhaps misleading) PML calculation.

GM: It's difficult to stipulate an acceptable range of results given the fact that different levels of effort may go into a loss estimation. If the loss estimates were associated with a qualitative description of expected building performance, it would be easier to determine if different results were the result of differences in expected performance of the building or due to different assumptions regarding the economic loss associated with the estimated level of damage.

JM: Every aspect of our profession is based on judgment. Consequently, there will always be a possibility that different engineers will arrive at different results. An acceptable range of difference is where the conclusion about the building is similar. If the extremes of the PML ranges will give you different conclusions about the building,

Please comment on the variability of PML calculations. If several engineers perform a PML calculation on a building with the same information provided, what do you feel is an acceptable range of results? (cont.)

then more study is required to narrow the range. For example, a PML range of 20 +/- 2 percent indicates that there will be non-structural damage and some minor structural damage. Whereas, a PML range of 20 +/- 12 percent may indicate anywhere from significant structural damage to almost no damage. The second range would require further study to get a more accurate assessment.

Overview of Probable Maximum Loss Estimates

Presenter: HAROLD ENGLE, JR.
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OVERVIEW OF PROBABLE MAXIMUM LOSS ESTIMATES

By Constantine Shuhaibar[1] and Harold Engle, Jr.[2]

ABSTRACT

A timeline of the development of Probable Maximum Loss (PML) estimates is presented. PML estimates were first used by insurance companies to quantify their risk, after the 1925 Santa Barbara earthquake. To improve their PML estimates, structural engineers working for insurance companies classified buildings based on earthquake resistance. One of the first seismic building codes was the byproduct. In the 1980s, two landmark documents were published: one by Karl Steinbrugge and the other by the Applied Technology Council. These two documents greatly increased the popularity of PML estimates. Owners, lenders, and potential buyers of buildings started making substantial financial decisions based on PML estimates. Currently, several PML procedures are in use and an ASTM standard is under development.

BEGINNINGS

1906. The Great San Francisco Earthquake and subsequent fire destroyed the city. Buildings were rebuilt as fast as possible, in many instances directly on top of collapsed ones, using the same construction practices. However, a few people started asking for earthquake insurance. Insurance companies issued earthquake policies as extensions to fire policies.

The July 30, 1930 issue of The National Underwriter lists the first statistics on earthquake insurance in California. The table below is an excerpt.

Year	Premiums ($)	Losses ($)	Insurers
1916	362	0	1
1917	5,967	0	2
1918	5,826	1,179	3
1919	32,490	0	9
1920	79,725	622	15
1921	49,000	4,725	31
1922	61,372	1,109	38
1923	213,909	11,813	58
1924	298,132	692	66
1925	1,898,383	730,772	126

1923. The Great Tokyo Earthquake hit a booming post World War I "modern" city. The devastation was almost complete. However, three buildings designed by Prof. Tachu Naito of Waseda University in Tokyo survived with minor damage. The most notable of which was the Industrial Bank of Japan building. Prof. Naito was one of the first structural engineers to use bracing to resist calculated lateral forces due to earthquakes.

By this time, people in California had forgotten about the 1906 earthquake. The Tokyo earthquake seemed too remote for any serious public interest. Insurance companies did take notice, but their loss to premium ratios were so low that an organized research effort was unjustified.

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1924. Prof. Tachu Naito was hired by the Board of Fire Underwriters of the Pacific (BFUP) to report on earthquake damage to twelve buildings in Tokyo. The detailed reports included: Name of Building, Size of Building, Foundation Material, Kind of Structure (Frame, Walls, and Ornamentation), Nature of Damage, Original Cost of Building, Nature of Repairs, Cost of Repairs, Any Factors Affecting the Costs, and Date of Construction.

1925. Santa Barbara was shaken by a moderate earthquake and partly destroyed. This brought back memories of the 1906 earthquake, and a veritable stampede for earthquake insurance began. Premiums increased six folds from the year before. Losses rose to 38% of premiums; the highest percentage ever. Insurance companies were not prepared. They needed to quantify their risk accurately to be able to set their rates adequately.

Shortly after the 1925 earthquake, the BFUP established an Earthquake Department to rate buildings in the San Francisco and Los Angeles areas for earthquake insurance purposes.

Two objectives were set: developing a classification system for buildings, based on earthquake resistance, for the purposes of setting insurance rates; and developing a set of standards which when applied to existing buildings could segregate the ones with earthquake resistant properties from the ones with little or no earthquake resistance, and when applied in the design of new buildings would add enough earthquake resistance to ensure minimum damage after severe shocks.

A period of information gathering followed. Available sources of information were: existing building codes, published literature on past earthquakes, and academic experts. Existing building codes proved non-uniform and lacking any earthquake related requirements. Considerable information was available on the 1906 San Francisco, 1923 Tokyo, and 1925 Santa Barbara earthquakes; the information from Tokyo was the most valuable and complete. From academia, Prof. Perry Byerly of the University of California at Berkeley, Prof. Romio Martel of Caltech, and Prof. Tachu Naito shared their knowledge of seismology, structural analysis, and seismic design.

1927. Harold Engle, Sr. in San Francisco and John Shield in Los Angeles, working for the BFUP, began "chasing" earthquakes. A field investigation form titled "Earthquake Inspection Report" was developed for new and existing buildings. It contained the following sections: Location of Risk, Adjoining Buildings, Foundations, Frame, Walls, Floors, Roof, Miscellaneous, Sketch Sheet, and Notes on Design. Structural analysis was used to check buildings for an acceleration of 3 ft/sec^2 (about 0.1g). The objective was to reasonably estimate the physical damage, as a percentage of building cost, resulting from a severe shock.

Photographs of damaged buildings, building and component costs, damage to buildings and components, and trends in regional construction costs were documented for the San Francisco 1906, Tokyo 1923, and Santa Barbara 1925 earthquakes. Wherever possible, Earthquake Inspection Reports were completed.

1928. Using the information collected since the Santa Barbara 1925 earthquake, the Earthquake Department of the BFUP was able to achieve its first objective: developing a classification system for buildings, based on earthquake resistance, for the purposes of setting insurance rates.

Eight classes were incorporated in the 1928 Earthquake Tariff and linked to insurance rates. Class I was considered least susceptible to damage and Class VIII most susceptible.

"Class I are frame dwellings and other frame buildings not exceeding three stories in height or 3000 square feet in floor area, excluding all buildings with masonry veneer. Classes II and III are required to have strong reinforced concrete walls throughout, or reinforced concrete partitions or a combination thereof. Class II has a steel frame, Class III a reinforced concrete frame. In these two classes, the walls and partitions, not the frames, are depended on to furnish the resistance. Class IV are frame buildings not qualifying under Class I, excluding all buildings with masonry veneer. Classes V and VI represent buildings in which there is little or no dependable resistance. Their frames rarely have much bracing. The walls are of unit masonry, which is deficient in adequate shearing and tensile strength. Class V has a steel frame, Class VI a reinforced concrete frame. Class VII comprises brick bearing walled buildings and the so-called "C" Class skeleton frame, wood floor building, which is a menace to life and investment and should be done away with. Class VIII are buildings of tile, concrete block, adobe bearing walls, or masonry veneer or any building not covered by any other class. Bridges, reservoirs, dams, steel and concrete stacks."

1929. Based largely on the Tokyo 1923 earthquake information and the principles of Prof. Tachu Naito, the Earthquake Department of the BFUP was able to achieve their second objective: developing a set of standards which when applied to existing buildings could segregate the ones with earthquake resistant properties from the ones with little or no earthquake resistance, and when applied in the design of new buildings would add enough earthquake resistance to ensure minimum damage after severe shocks. One of the first seismic building codes was born.

The Standards adopted by the Board may be summarized as follows:

1. Provision for the lateral force produced by an earthquake acceleration of about 3 ft/sec^2.
2. Rigidity of construction, obtained through the factors of:
   (a) Adequate footing interconnection on uniform ground.
   (b) Rigid type of bracing, preferably that furnished by properly designed rigid wall and partition construction, in which adequate tensile as well as compressive strength is incorporated in walls and partitions. Bracing to be symmetrically located about center of mass of building.
   (c) Regular shape, avoiding use of long, slender, laterally unsupported wings. Natural period of vibration of various parts must be about the same.
3. Separation of buildings so they do not pound together.
4. Penalty for buildings located on uniform saturated ground.

1935. The BFUP published *Recommendations of Board of Fire Underwriters of the Pacific for Earthquake Resistant Design of Buildings, Structures and Tank Towers*, prepared by Harold Engle, Sr. and John Shield. It is a document about fifty pages long, with another fifty pages of photographs of earthquake damage to different types of structures. It served as the "Blue Book" of its day. Its title page contains the phrase: "for the use of those, who in designing new buildings and structures, wish to take advantage of the Special Rate provisions in the Board's Earthquake Tariff."

It included the following chapters: Recommended Lateral Force Provision; General Recommendations for Design, Materials and Construction; Tank Supporting Structures and Towers; List of Notable Earthquakes in California and Nevada 1769-1934; Modified Mercalli Intensity Scale of 1931; and Examples of Tank Tower Analysis (using moment distribution techniques).

These recommendations reflected many of the lessons learned from the 1933 Long Beach and the 1935 Montana earthquakes.

1940. Interest in the subject of earthquake insurance decreased somewhat, at the expense of the Earthquake Department of the BFUP. Harold Engle, Sr. devoted most of his time to his professional practice, and was able to devote to earthquake insurance only as much time as he could spare as an individual.

1947. The Pacific Fire Rating Bureau (PFRB) replaced the BFUP.

REFINEMENTS

1950. From the end of World War II in 1945 to 1950, earthquake insurance premiums more than doubled. The Earthquake Department was reactivated. Karl Steinbrugge and Donald Moran were added, to soon replace, Harold Engle, Sr. in San Francisco and John Shield in Los Angeles, respectively.

1954. Karl Steinbrugge and Donald Moran published "An Engineering Study of the Southern California Earthquake of July 21, 1952, and Its Aftershocks". In this document, the same building classification system established in 1928 was used with slight refinements. In the conclusions section, the authors state that "The earthquake tariff, which is primarily based on the performance of buildings according to their material of construction, is becoming outmoded as earthquake resistive buildings become common. Studies on new rating methods are in progress."

1957. The Earthquake Grading System, under development since the 1930's, was introduced by the PFRB. The system is based upon grading the lateral force adequacy of building components. Tables contain "charges" or penalties for each building component. The lower the earthquake performance of a building component, the higher the "charge" or penalty. The total building "Point Grade" is the sum of all of its component "charges". The building "Point Grade" corresponds to a certain "Word Grade" and a Probable Loss %. One of the first PML procedures was born. The table below is a modern example.

Word Grade	Point Grade	Probable Loss %		
		Total %	Loss Over 5% Deductible	Loss Over 10% Deductible
Minimum	0-10	5	0	0
Slight	11-30	10	5	0
Moderate	31-45	25	20	15
Serious	46-65	40	35	30
Severe	66-96	60	55	50
Excessive	Over 96	75	70	65

1975. Karl Steinbrugge, while writing *Insurance Relationships Among Monetary Losses, Intensities, and Building Classes*, issued a "challenge" to Harold Engle, Sr., Henry Degenkolb, and Frank McClure. The "challenge" was to further breakdown and refine already accepted building class PML values. A discussion followed, concerning the fact that replacing an earthquake damaged building component could cost more than its original value. It was agreed upon to use building component PMLs exceeding 100% in such cases.

LANDMARKS

1982. The first of two landmark documents on PML estimates was published: *Earthquakes, Volcanoes, and Tsunamis: An Anatomy of Hazards* by Karl Steinbrugge.

The book is divided into twelve chapters, they are: What is an Earthquake?; Earthquakes-Where, How Often, and How Large; Implications of Active Faults, Magnitude, and Intensity; Landslides and "Poor Ground"; Building Classifications and Their Basis; Building Damage; Non-Building Damage; Comments on Rates and Deductibles; Probable Maximum Loss; Fire Following Earthquake; Tsunami (Seismic Sea Wave); and Volcanoes.

In Chapter 9, Probable Maximum Loss, a PML calculation procedure is outlined. The first step is building classification. The second step is obtaining a class PML from tabulated values based on the building classification. The third step is modifying the class PML based on: occupancy type, walls (exterior, interior), diaphragms (floor(s), roof), ornamentation (exterior, interior), mechanical/electrical systems, unusual conditions, hazardous exposures (tank and overhanging walls, pounding of adjacent buildings), and site dependent hazards (proximity to active faults, foundation materials, landsliding potential).

Chapter 9 also mentions two alternative PML methods: analysis of construction costs, and dynamic analyses. Analysis of construction costs needs experienced personnel and reliable cost data. "Engineering judgment based on actual damage experience will establish a probable loss for each construction component, and the sum of these individual component losses is the expected building loss." Dynamic analyses that can model building behavior so accurately that "the output is expected damage" are still in the future. Moreover, nonstructural damage currently cannot be modeled. "In time, however, these methods have the potential to replace those previously discussed."

1985. The second landmark document on PML estimates was published: *ATC-13, Earthquake Damage Evaluation Data for California* by the Applied Technology Council.

This document contains estimates of percent physical damage at seven levels of earthquake intensity for 78 existing facility classes in California, including 36 building classes. Damage estimates represent the consensus opinion of more than 50 earthquake engineering specialists.

TODAY

1999. The popularity of PML estimates has been steadily increasing since the publication of the two landmark documents. The current economic boom in California is another factor.

Owners, lenders, and potential buyers of buildings have joined insurers in requesting PML estimates. The appeal of defining the earthquake resistance of a building with a single number, easily understood by non-technical decision-makers, is undeniable.

Substantial financial decisions are being made based on PML estimates. Owners evaluate their holdings, single building or portfolio, to determine the cost-effectiveness of seismic retrofits. Lenders use 20% as a cutoff point or "deal-breaker" in approving real estate loans. And potential buyers often request PML estimates as part of a due-diligence investigation.

Currently, several PML procedures are in use and an ASTM standard is under development. Other papers in this seminar discuss those two items in more detail.

CONCLUSIONS

PML estimates are useful tools, with important strengths and limitations. The timeline presented above reveals the origins of these strengths and limitations.

The strength of PML estimates is in that they bridge the gap between technical structural engineering evaluations and non-technical decision-makers. Understanding their risk, decision-makers often choose to upgrade the seismic resistance of their deficient buildings. As in the 1920s, economics can raise earthquake resistance standards.

The first limitation of PML estimates is the fact that they were developed by insurance companies to determine earthquake insurance rates for classes of buildings. Applying the same principles to single buildings takes experience. It is not uncommon to find large differences in PML estimates provided by different structural engineers using different assumptions. The second limitation relates to the two landmark documents, the source of most of the values produced today. Both documents are outdated. New information about pre-Northridge steel moment resisting frames is not included. New structural systems such as steel eccentric braced frames are not addressed.

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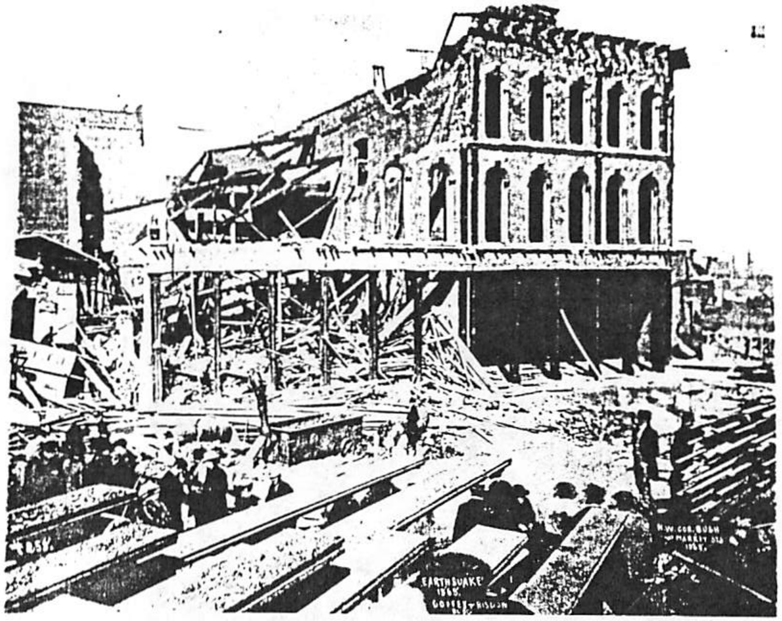
E.Q. DAMAGE - S.F. 1868



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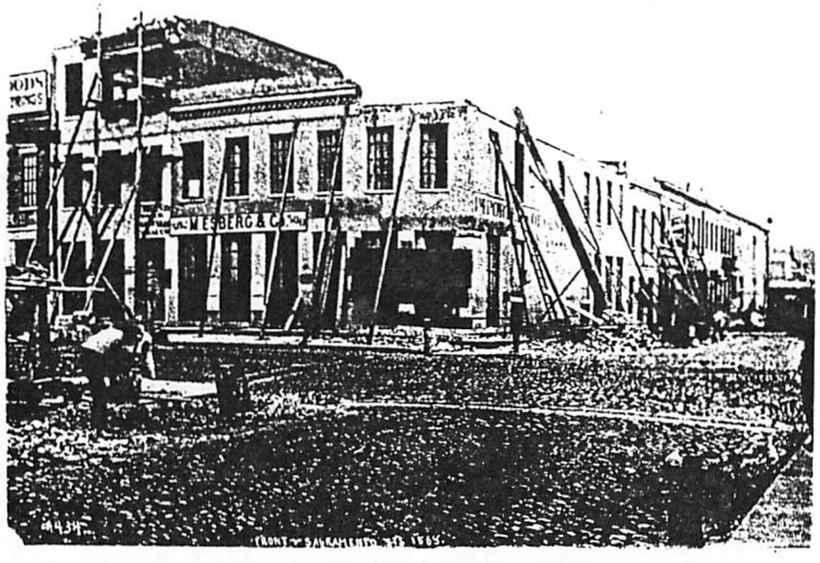
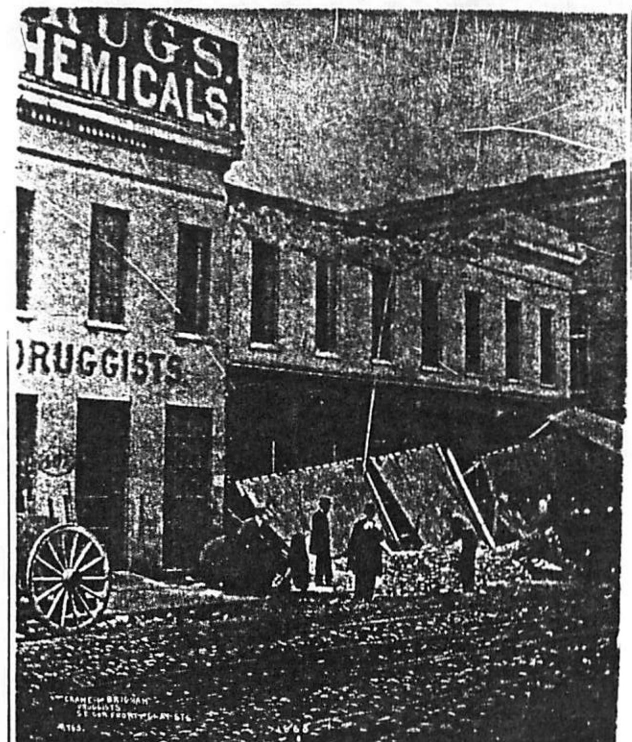
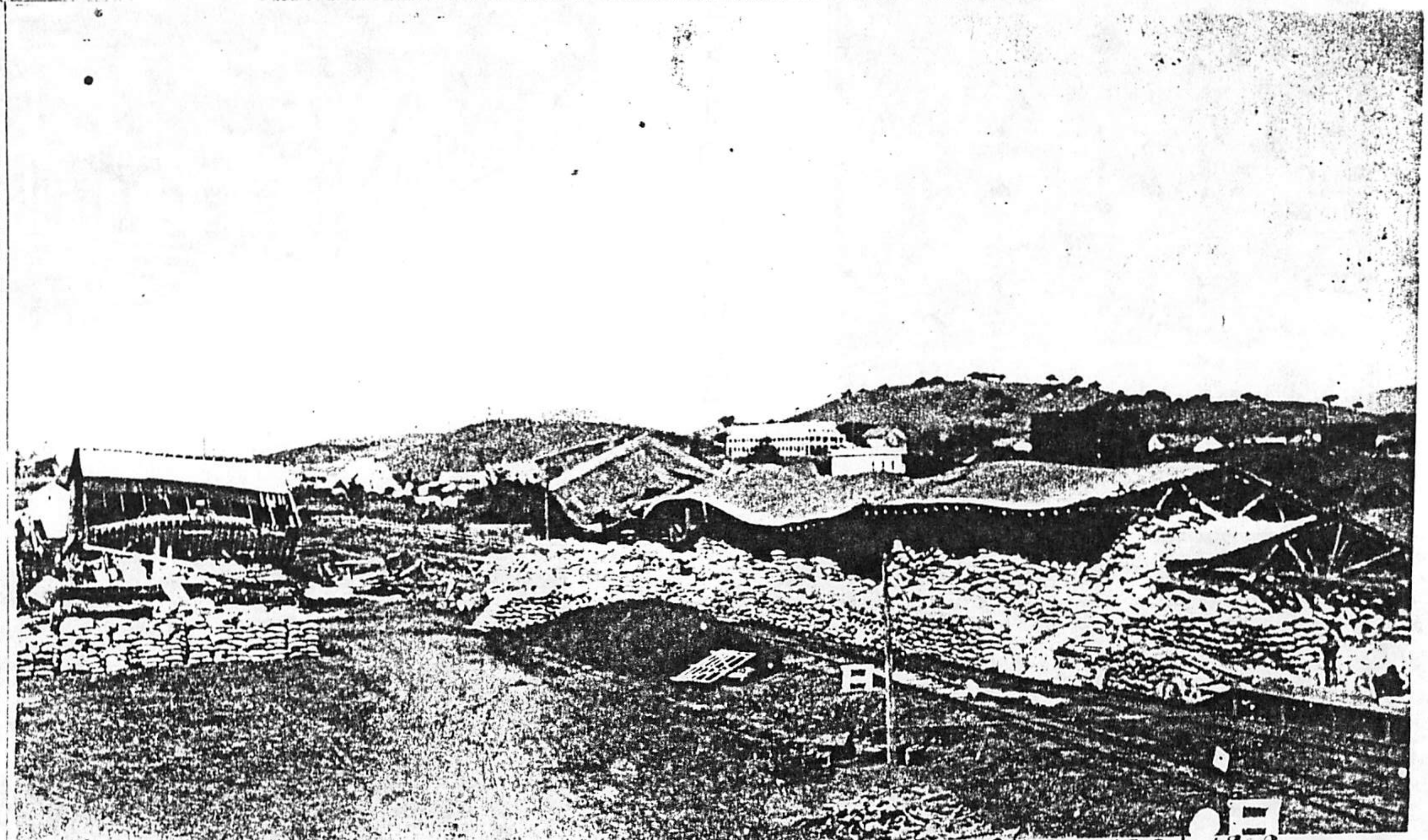
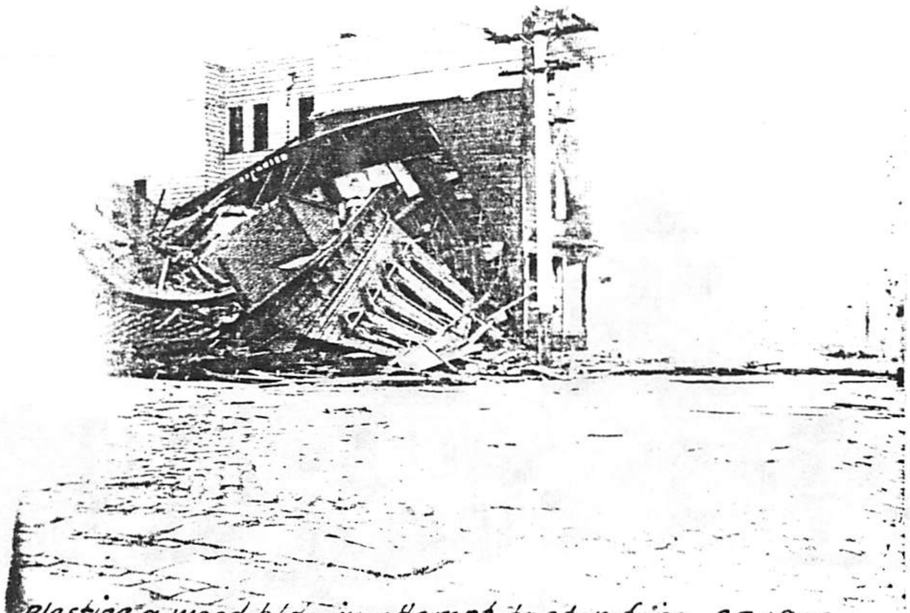






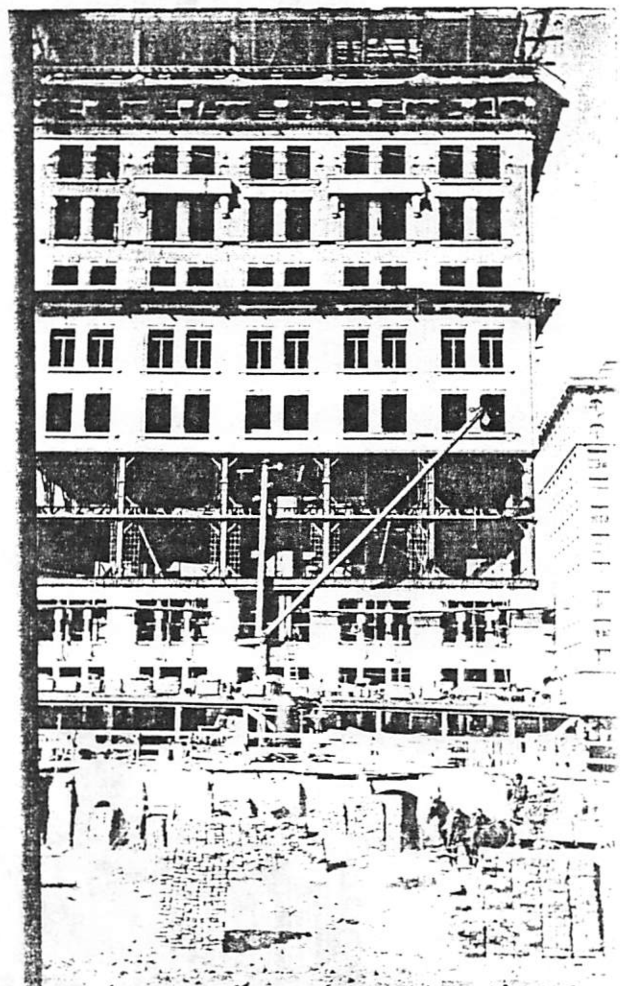
STORE HOUSE HAYWARD-S CALIF. OCT 21 1868



Blasting a wood bldg. in attempt to stop fire. S.F. 1906

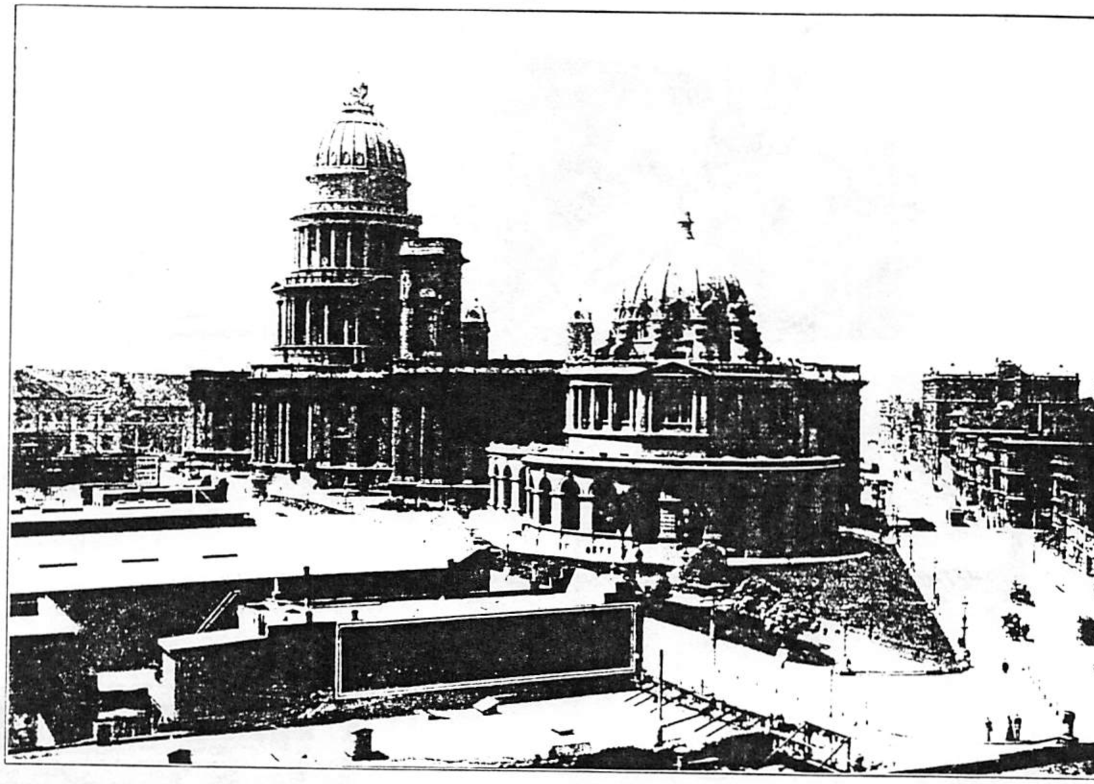
Butchertown - On piles. S.F. 1906

2

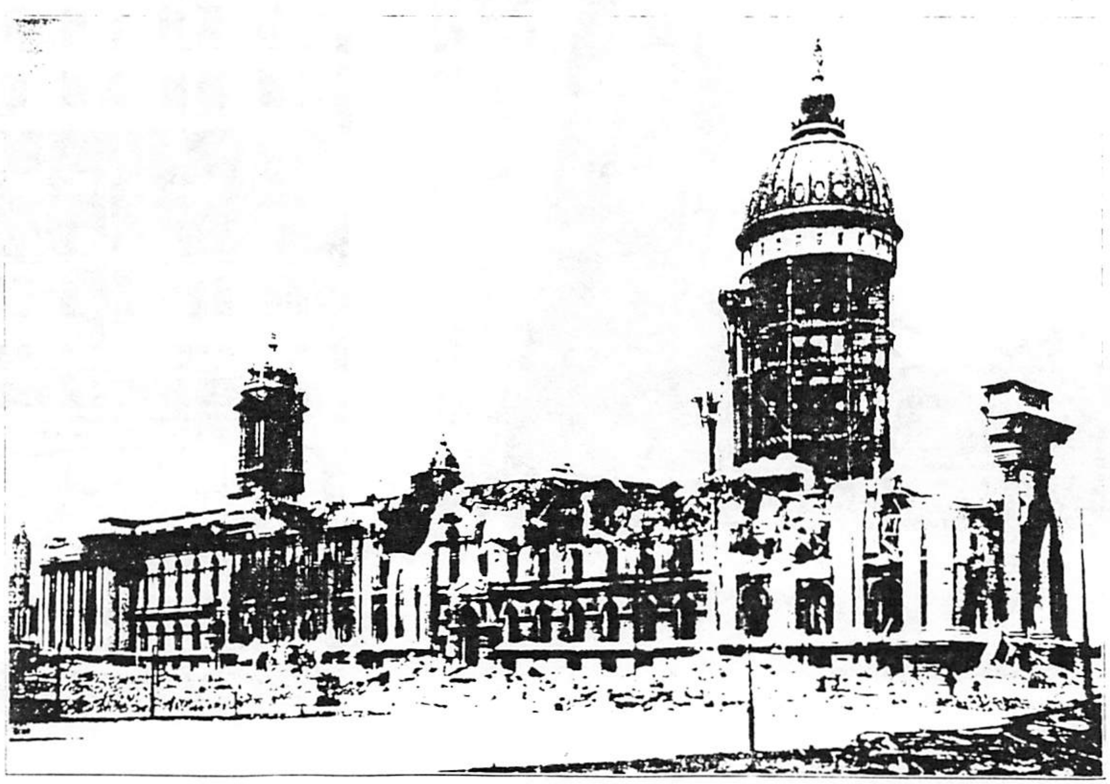


Royal Ins. Bldg. under construction 1908

3

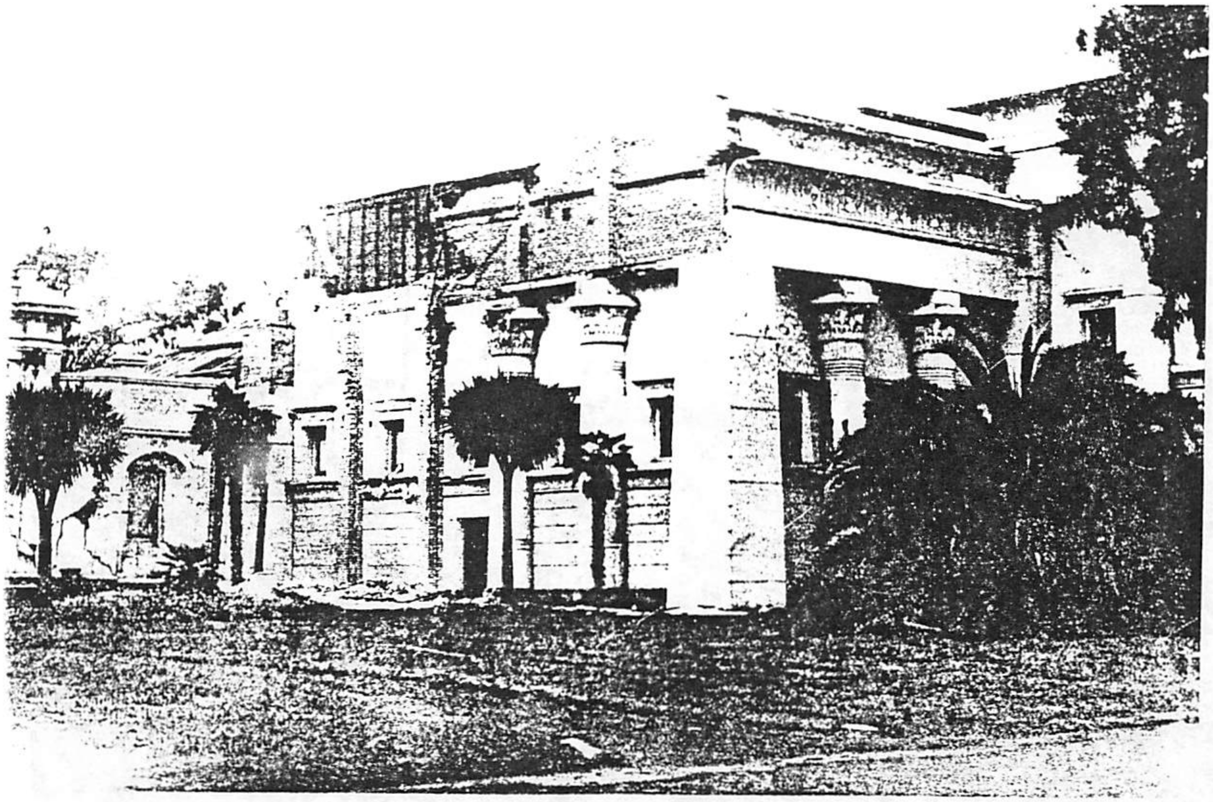


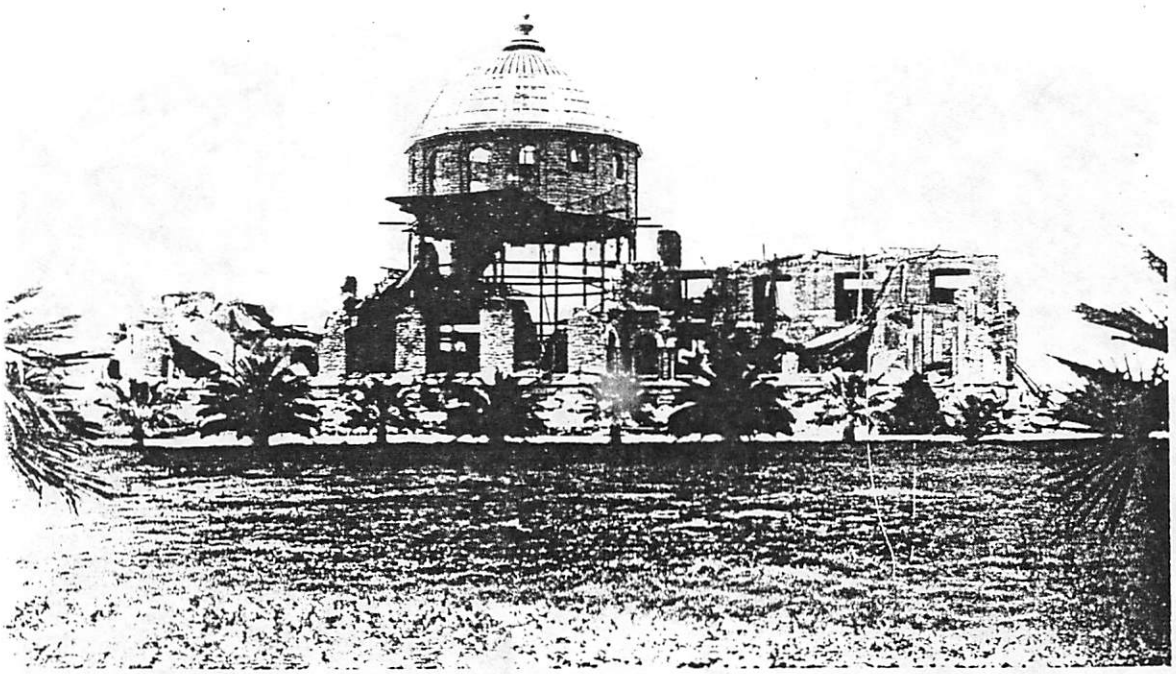
City Hall before the Fire and Earthquake.



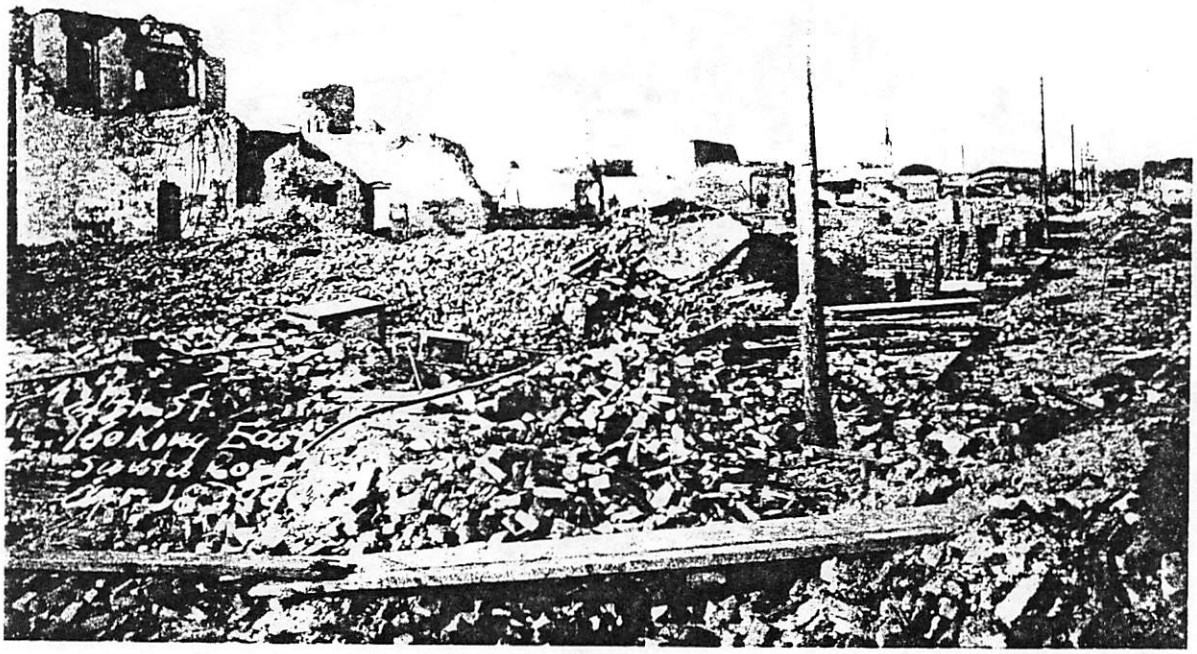
City Hall, San Francisco, Damaged by Earthquake.

2

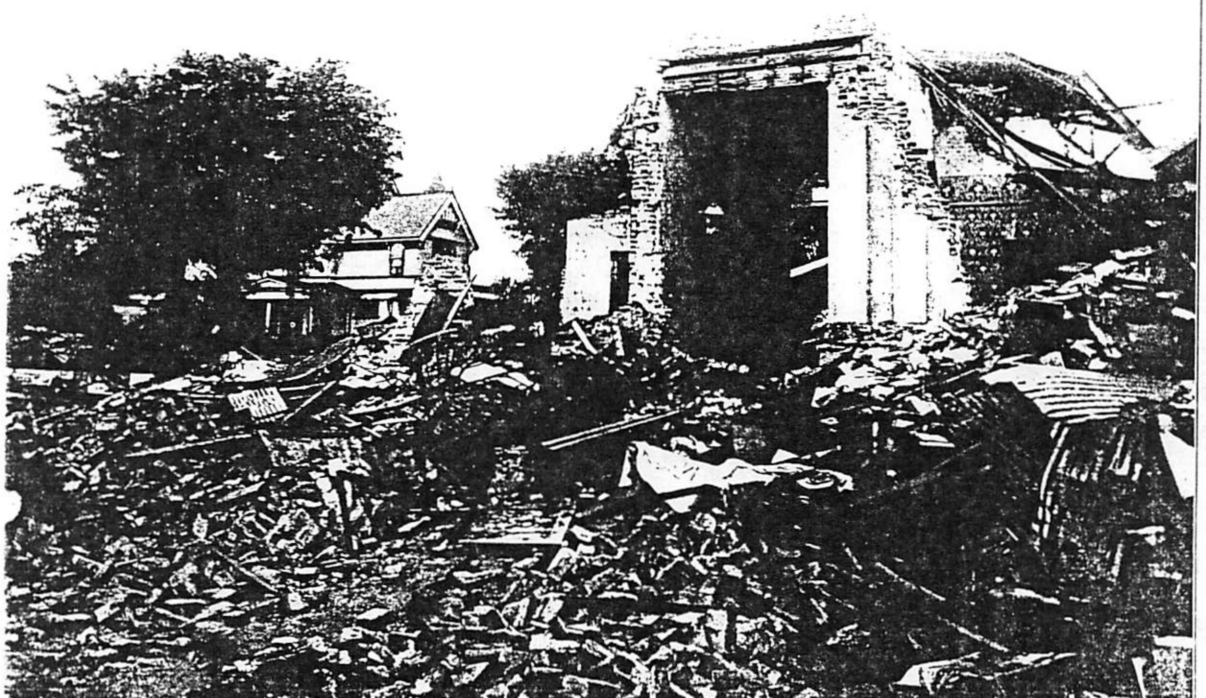




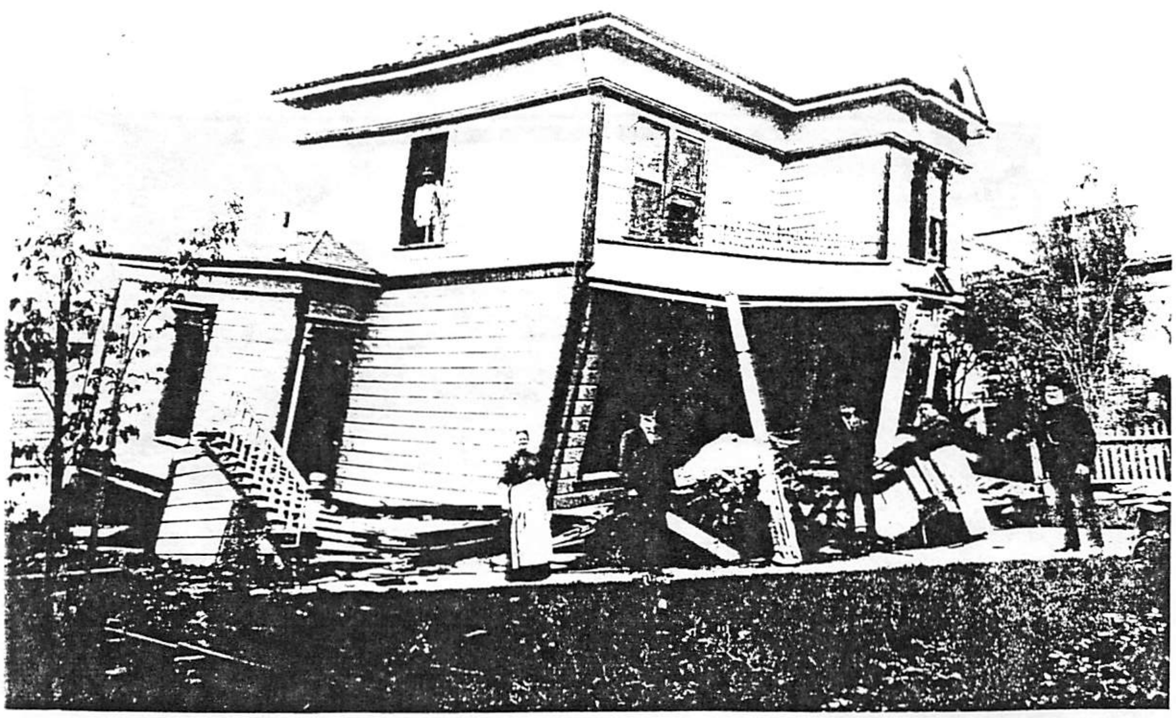
Stanford Library, Stanford University, Damaged by Earthquake.



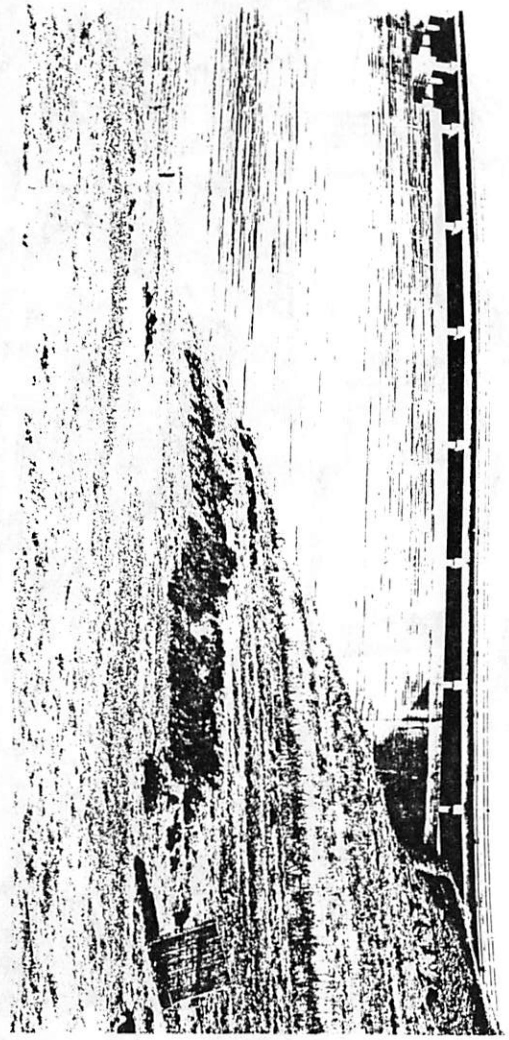
Santa Rosa.
Apr. 18, 1906
Hall of Records



Santa Rosa.
Apr. 18, 1906
McDonald Ave Res.

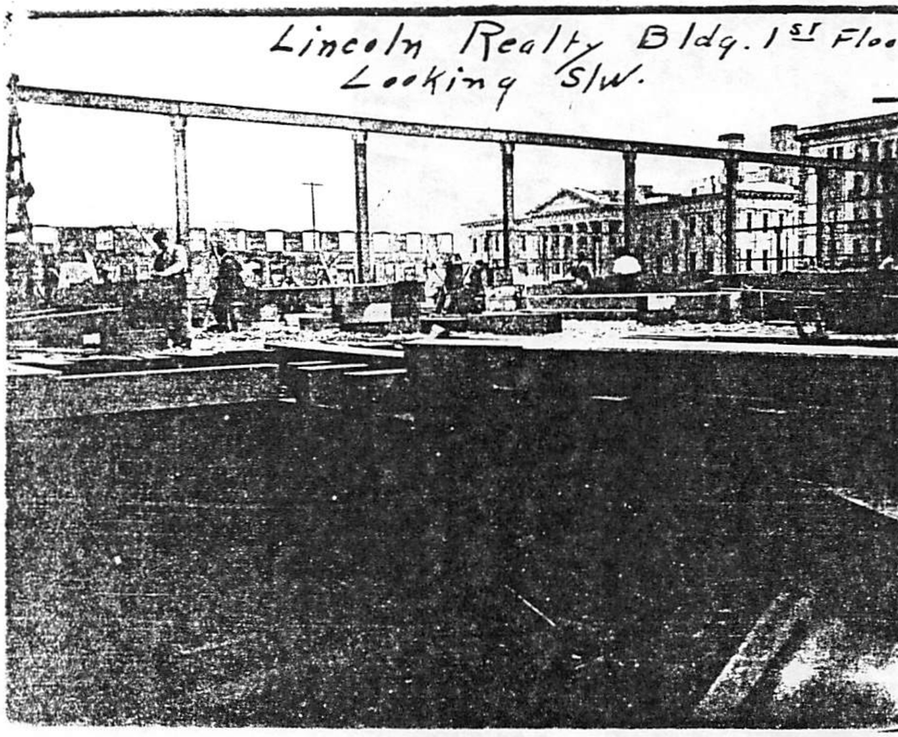


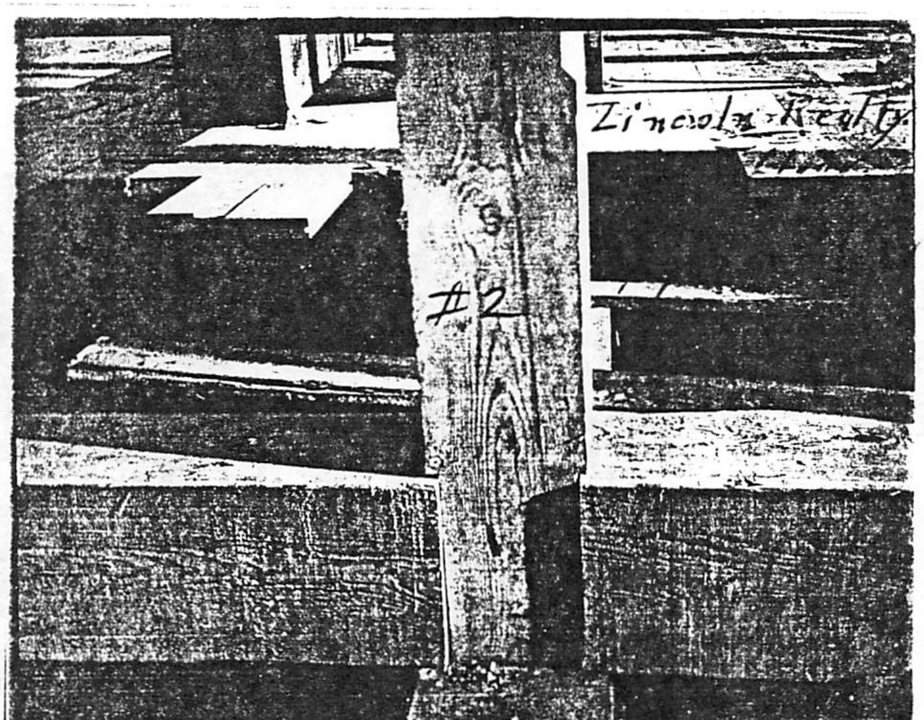
San Andreas Fault.

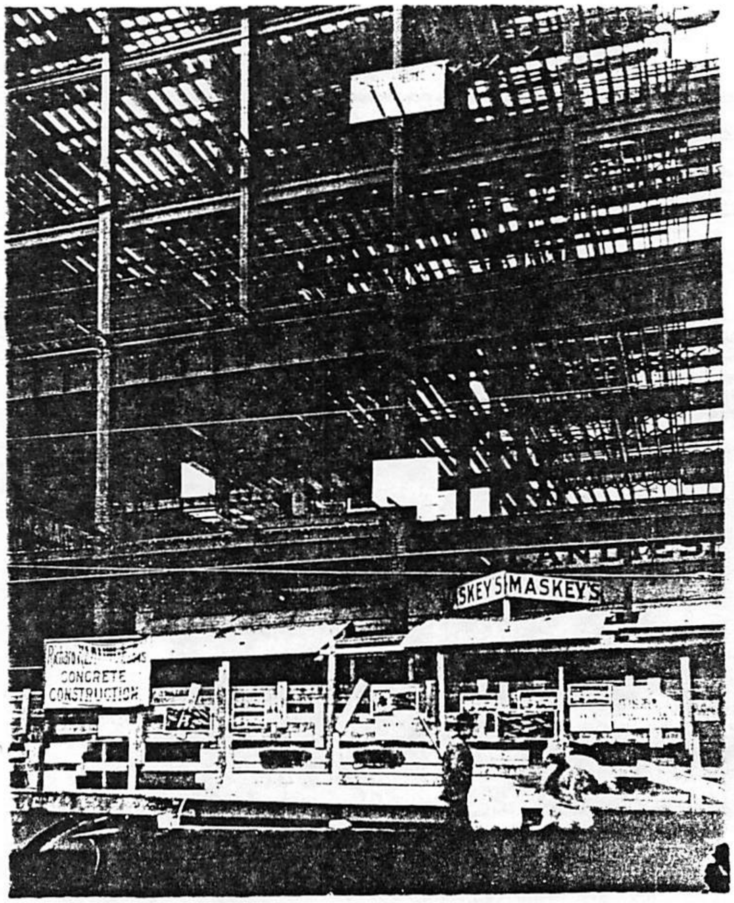


Crystal Springs Dam and Reservoir. (See previous page also) Pictures taken during the unusually low water level in Spring of 1931. Reservoir allmost dry. Probably lowest stage since dam was completed in 18[illegible].

Lincoln Realty Building, San Francisco

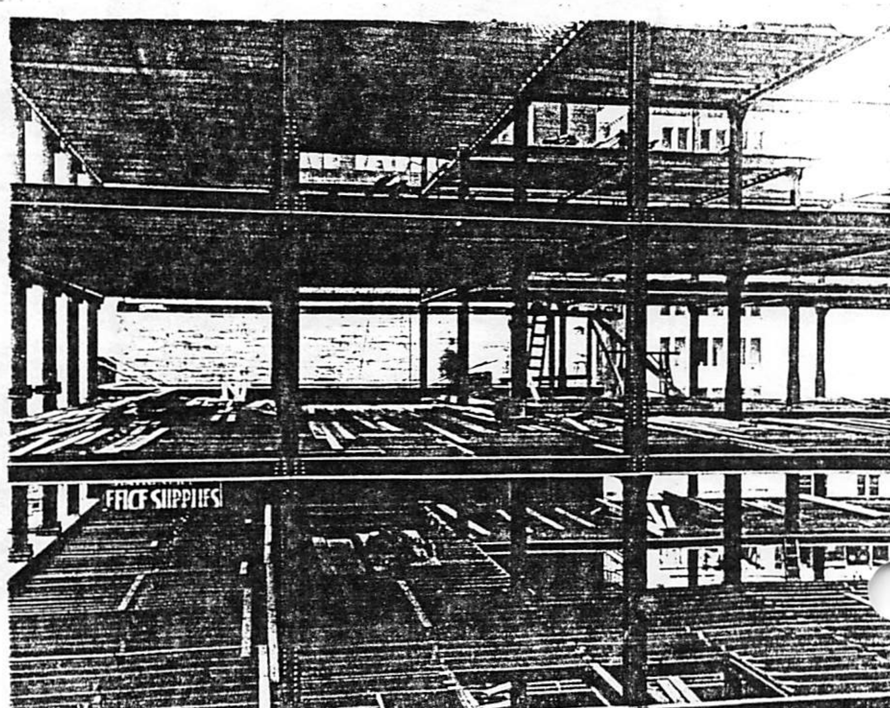






Maskey's Building
on Kearney Street
August 15, 1908

Maskey's Building
South side
From 3rd floor of
the Chronicle Building
August 15, 1908



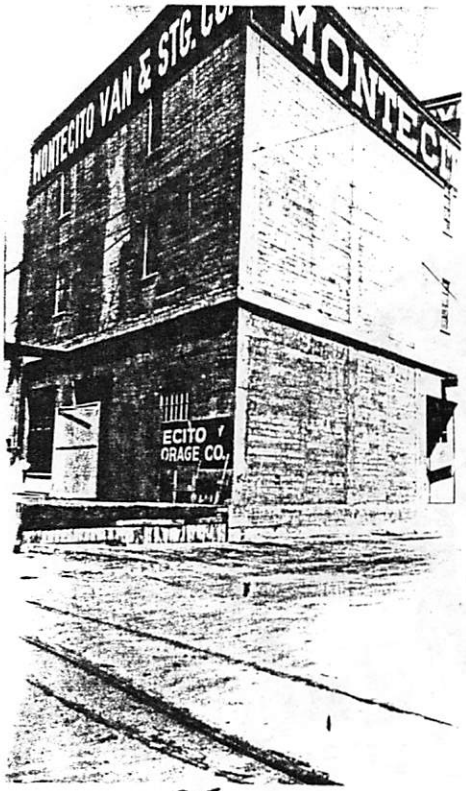
State St. SW cor. Mason

17a

Hotel Californian

17b

Santa Barbara-Shock of 6-29-25



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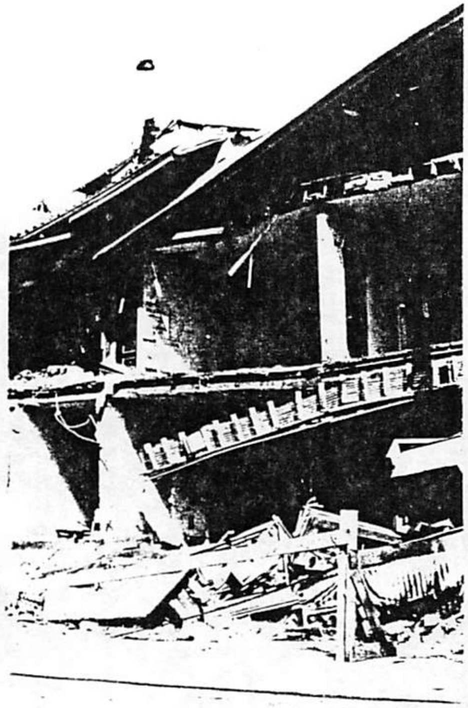
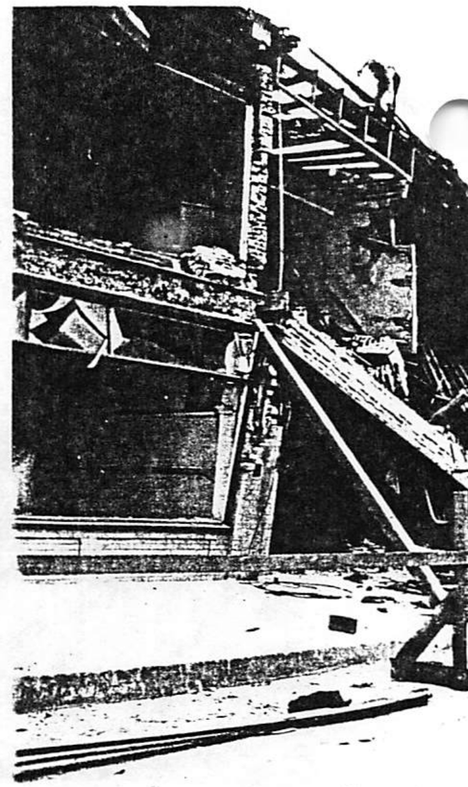


Santa Barbara-Shock 6-29-25
11-15 W. Ortega St.

25b



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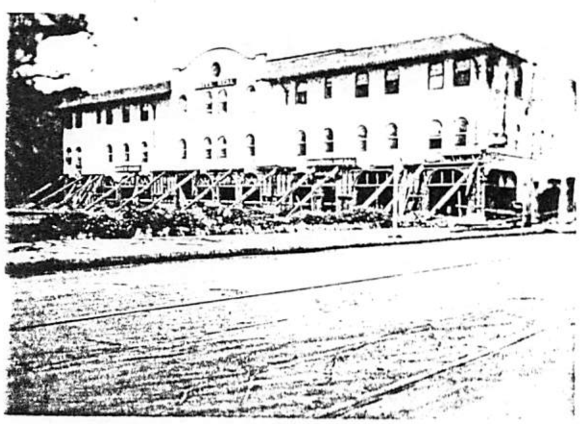

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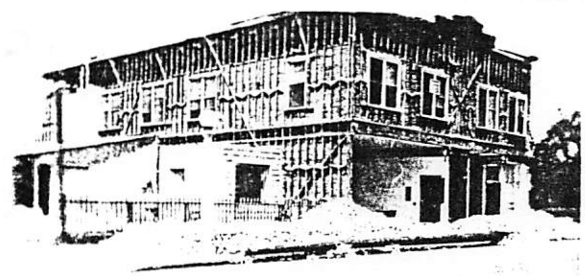

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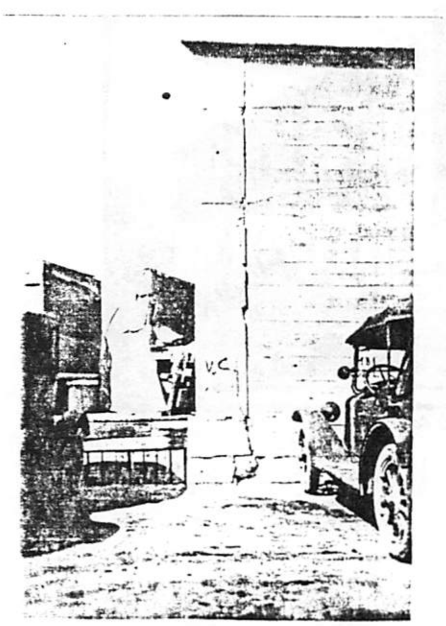

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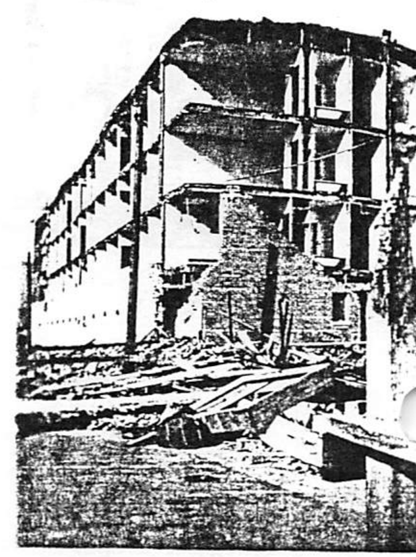

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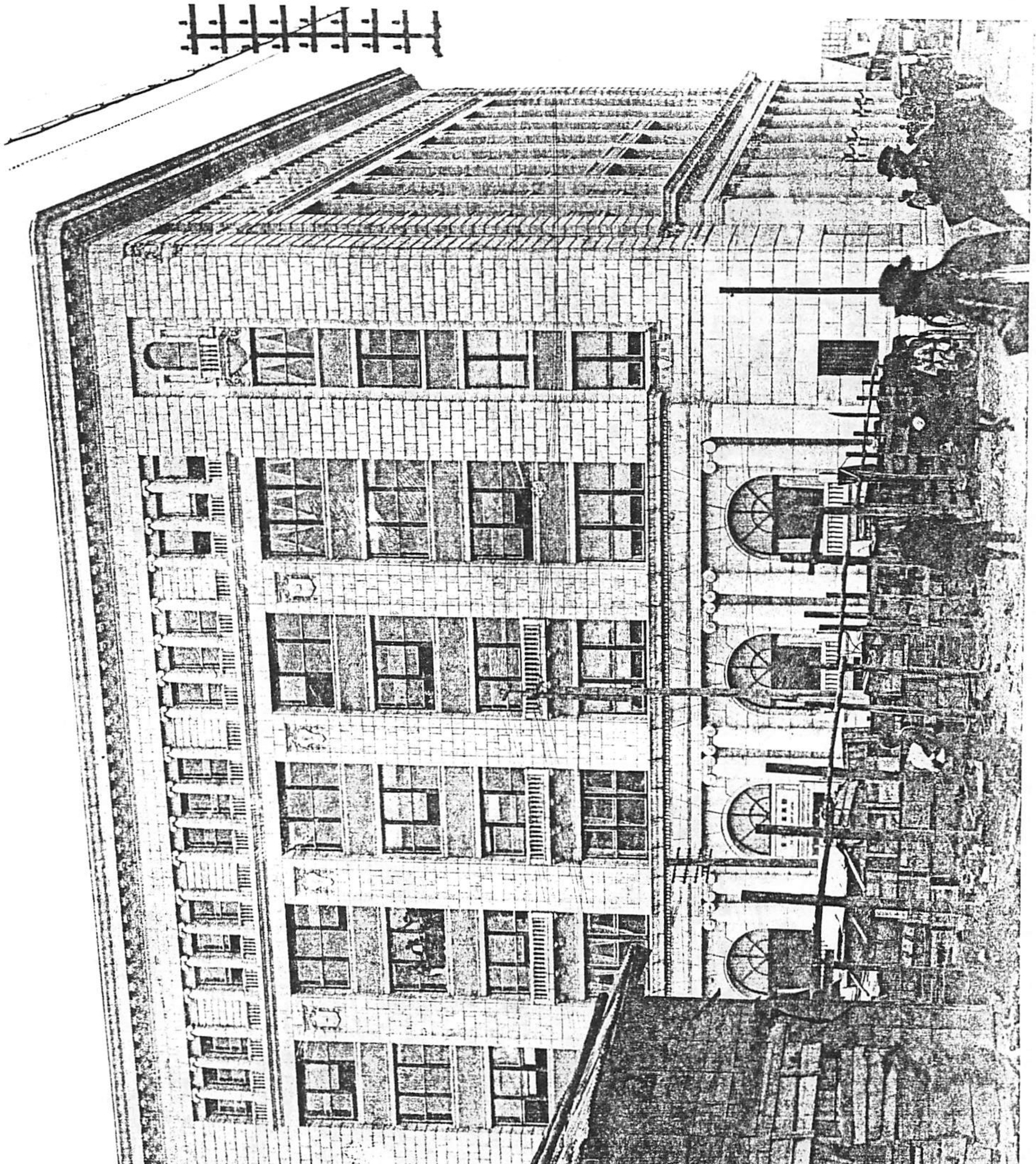
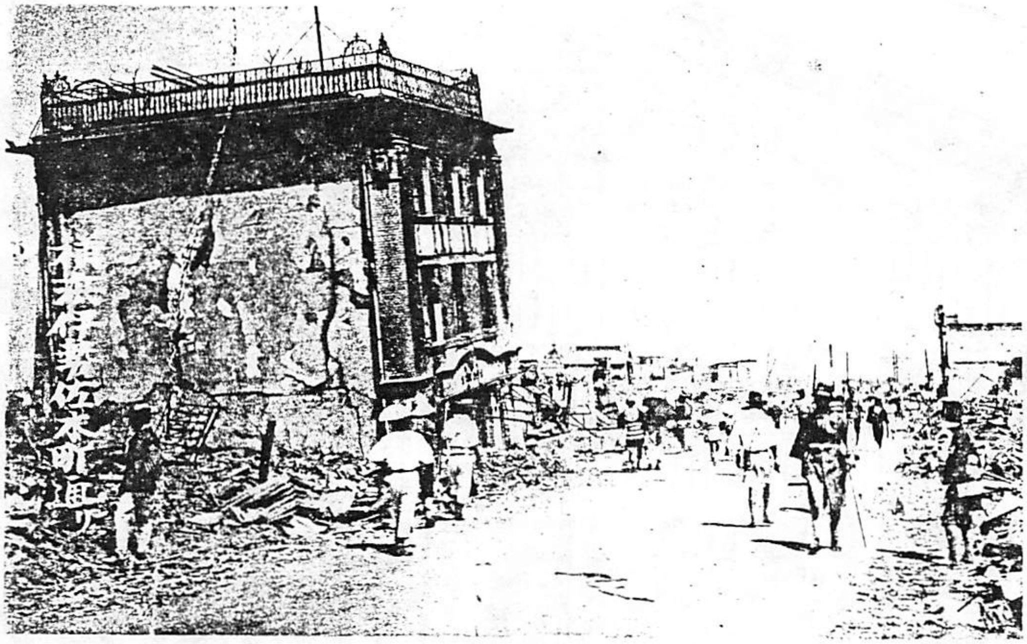
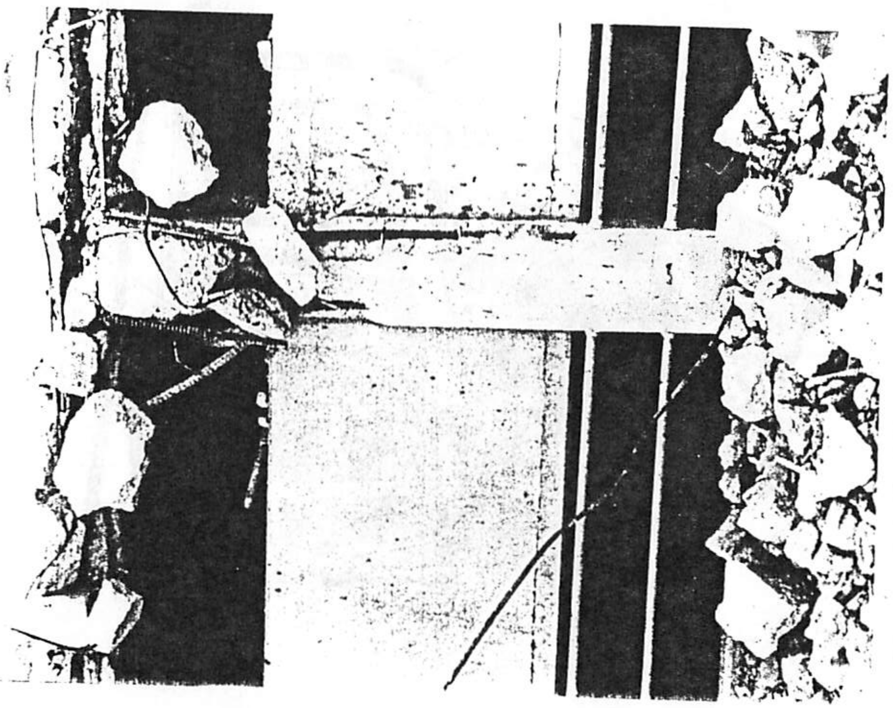
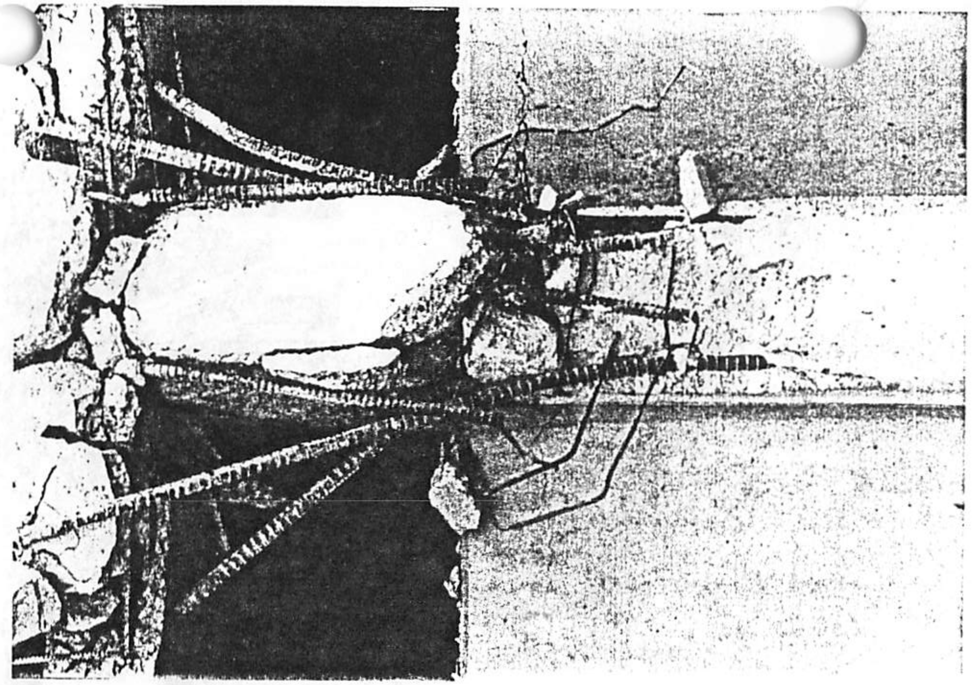
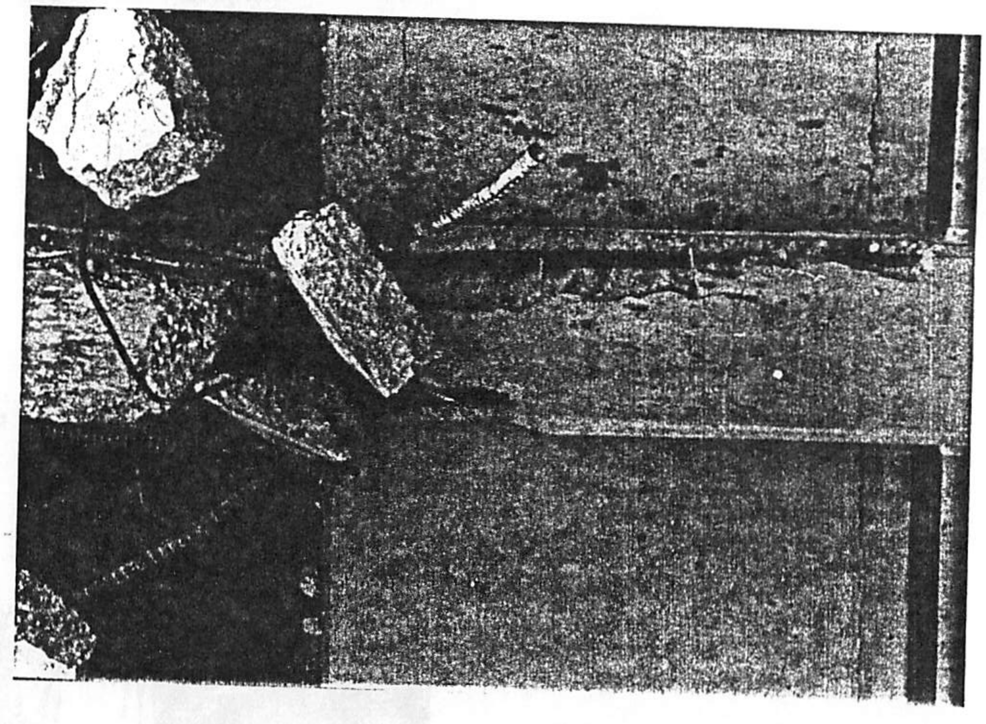




Damaged buildings - Japan 1923








from Power


STORE
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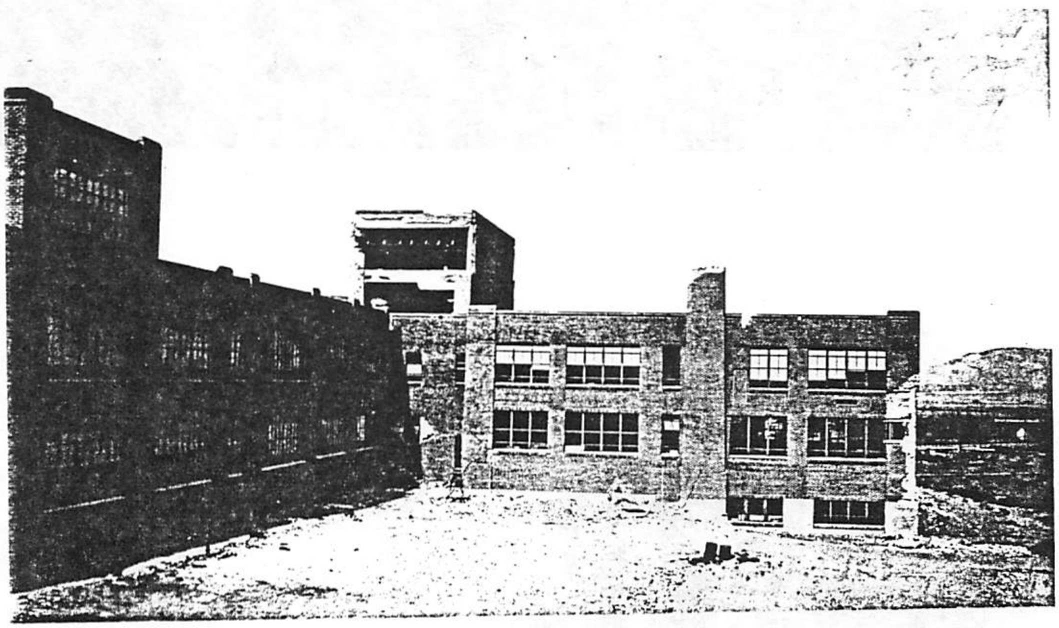

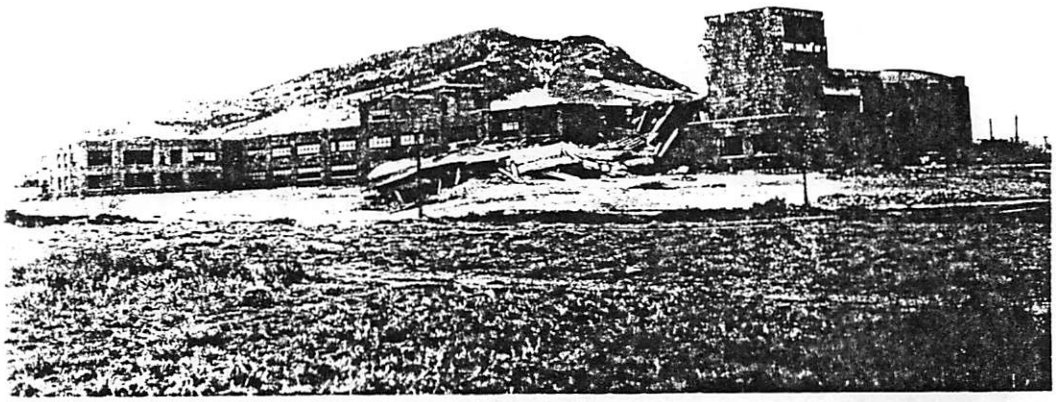

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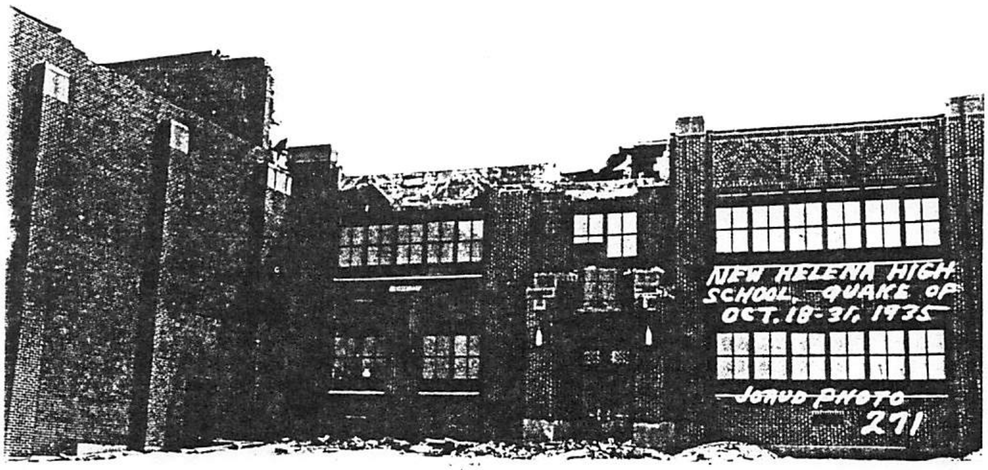
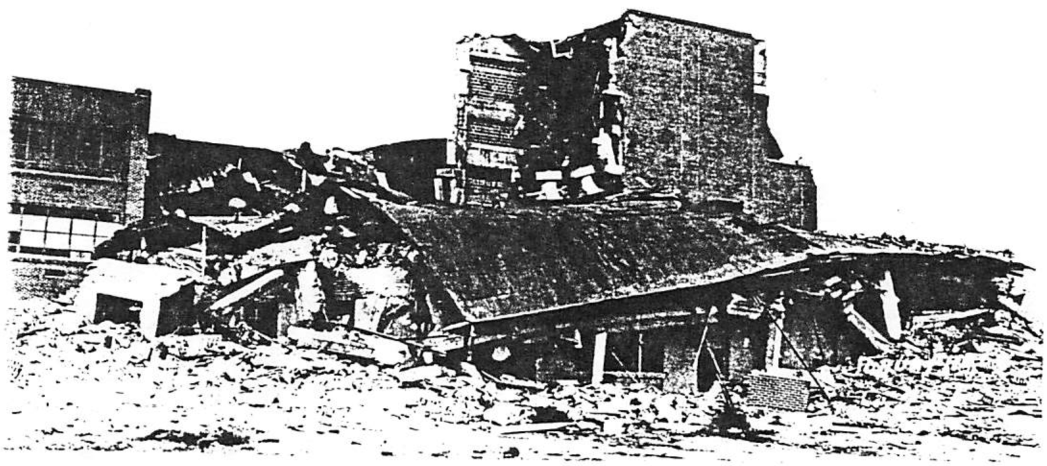
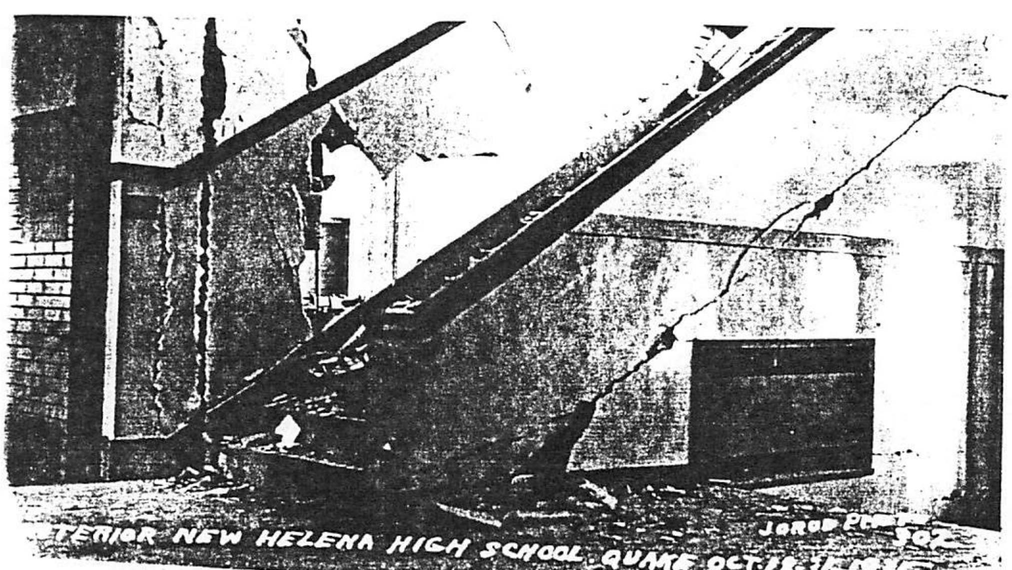


After Shock of
October 31, 1935



New Helena
High School
after the
shock of
October 31,1935,
which caused
the total collaps
of the north wing



New Helena
High School,
shattered tile
partitions.
Excessive damage
at stair and
elevator wells
often occurs,
probably the
enclosures form
relatively rigid
shafts through
the structure.
Photograph taken
after the shock o
October 31, 1935.

Estimation of Earthquake Damage Loss

Presenter: TED ZSUTTY

"PML"

Steinbrugge and Engle definition:
" The probable maximum loss for an individual building is that monetary loss expressed in dollars (or as a percentage of insured value) under the following conditions:

1. Located on firm alluvial ground, and
2. Subjected only to the vibratory motion from the maximum probable earthquake.

The building class probable loss (class PML) is defined as the expected maximum percentage monetary loss which will not be exceeded for 9 out of 10 buildings in a given earthquake building class under the conditions stated."

Figure 1.

Definitions and Notations

D or R = Damage ratio = %repair cost / building value

S_i = Damage State= Selected range of damage ratios like (50%to75%)

SL = Scenario Loss = damage ratio due to a given scenario earthquake

SEL = expected or mean scenario loss

SUL= upper 90% scenario loss

PL_T = Probable Loss = upper 90% loss due any damaging earthquakes in an exposure period of T years

Figure 2.

PROBABILITY AND STATISTICS

Given Events D and E :
Conditional Event of
D given E = $D|E$
has Probability

$$P[D|E] = P[D \cap E] / P[E]$$

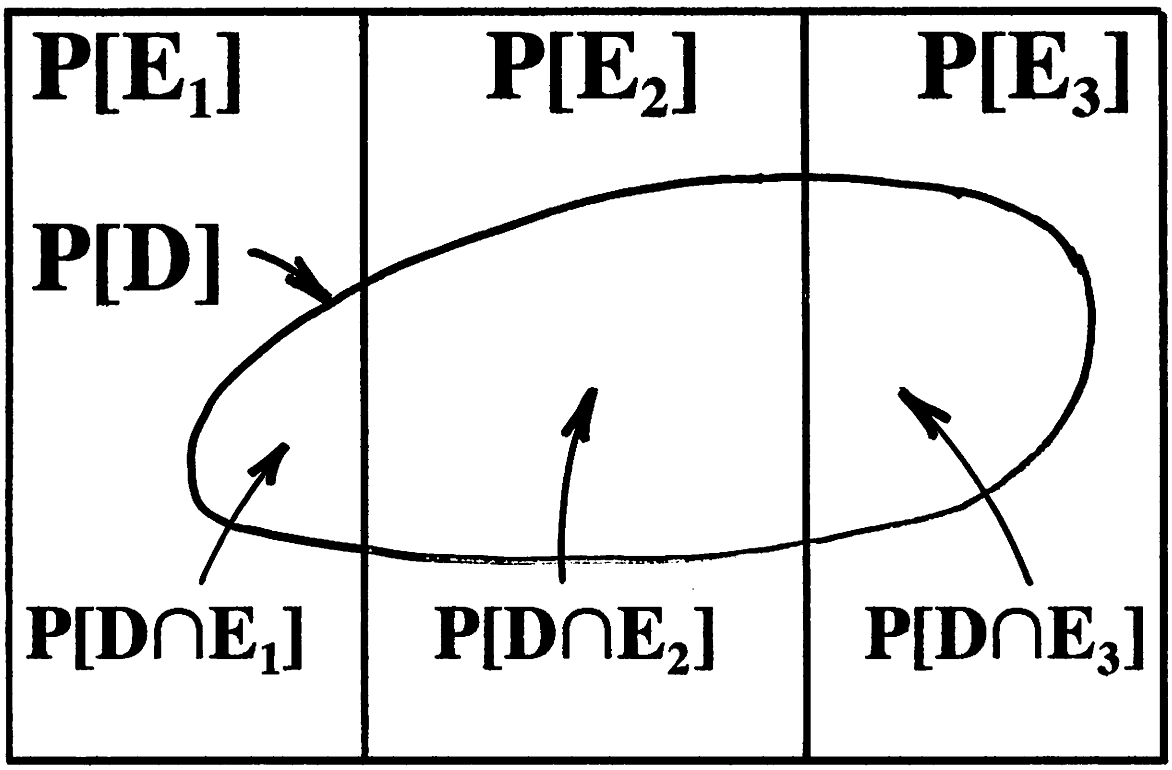
giving

$$P[D \cap E] = P[D|E]\, P[E]$$

where $D \cap E$ is the joint event of both D and E.

Figure 3.

Given N multiple events E_i, all mutually exclusive and exhaustive, and event D



Total Probability Law gives

$$P[D] = \Sigma\, P[D \cap E_i]$$
$$= \Sigma\, P[D|E_i]\, P[E_i]$$

Figure 4.

Probability Distributions

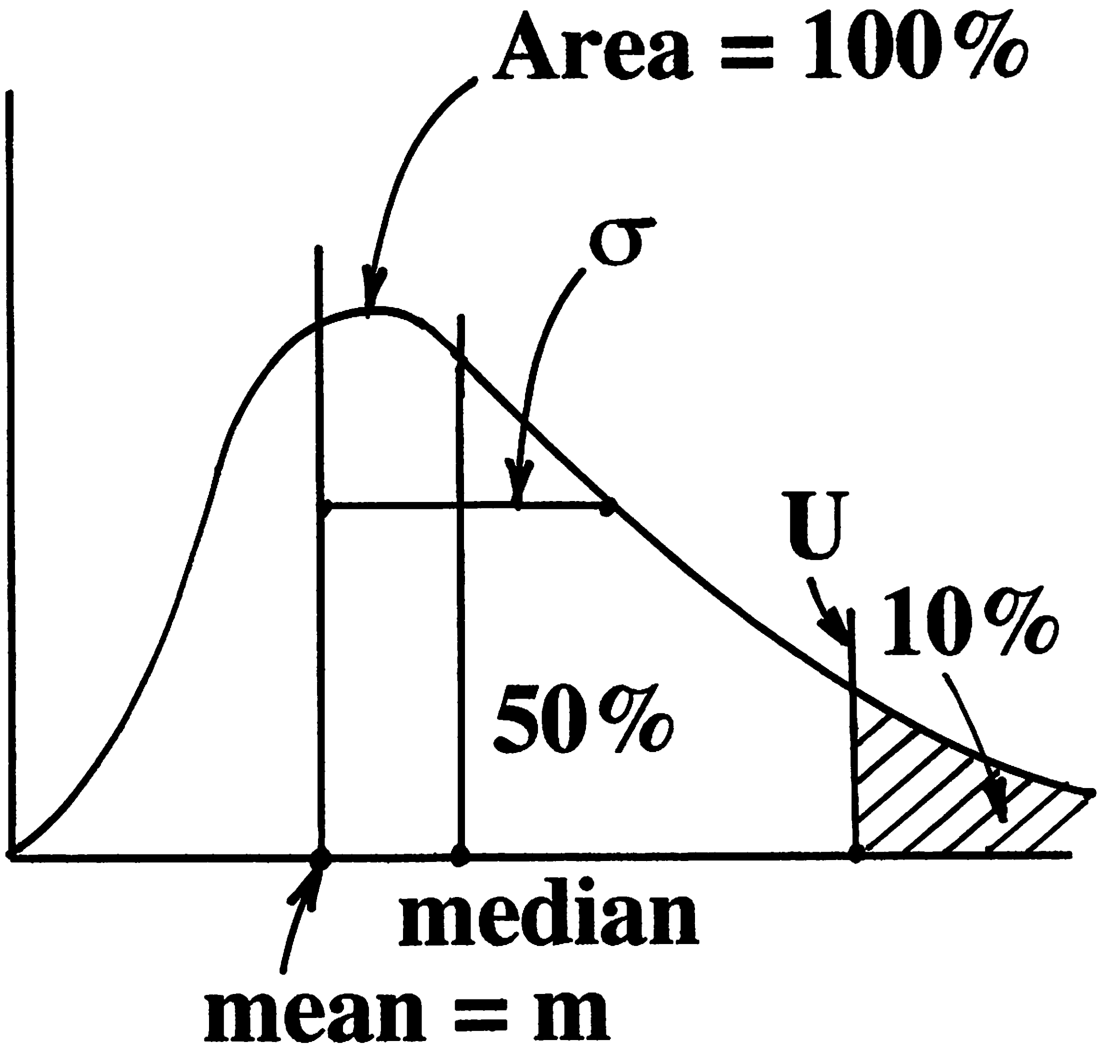


Figure 5.

The Normal Distribution

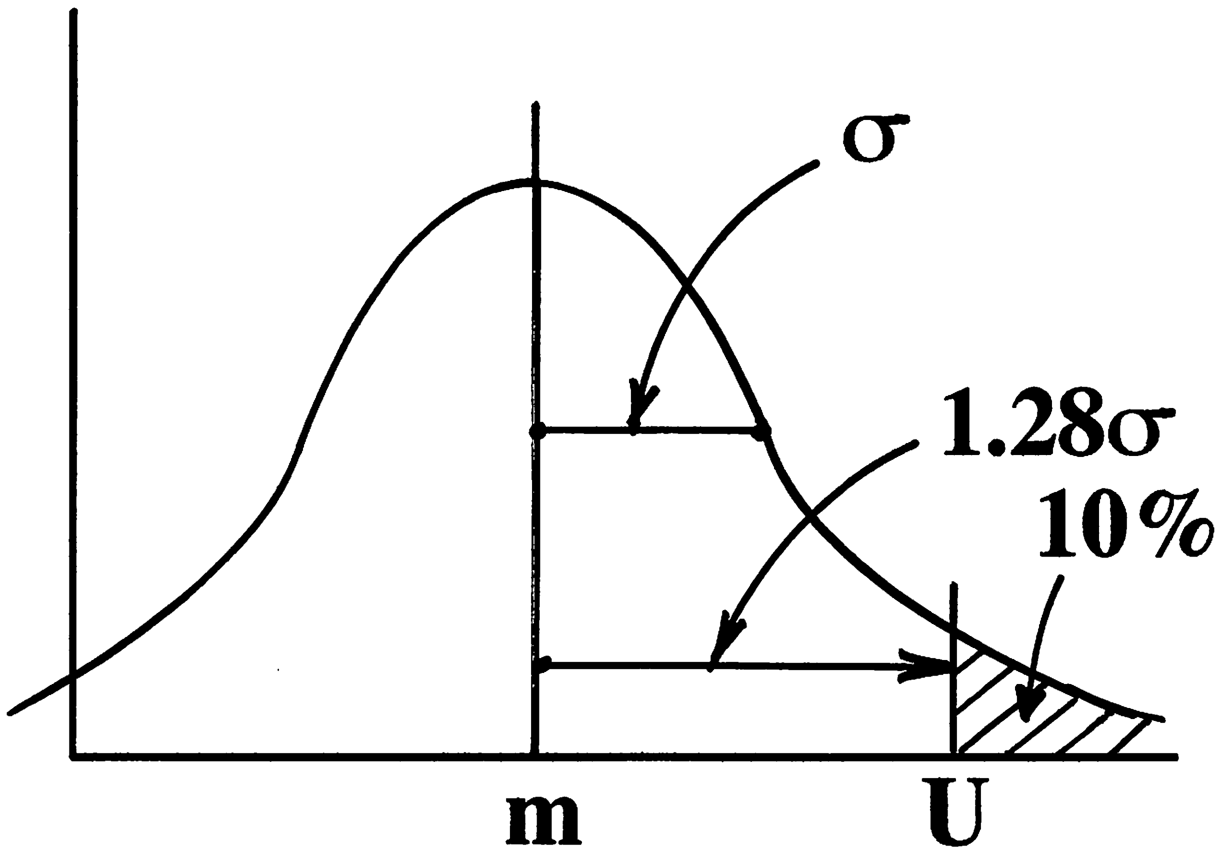
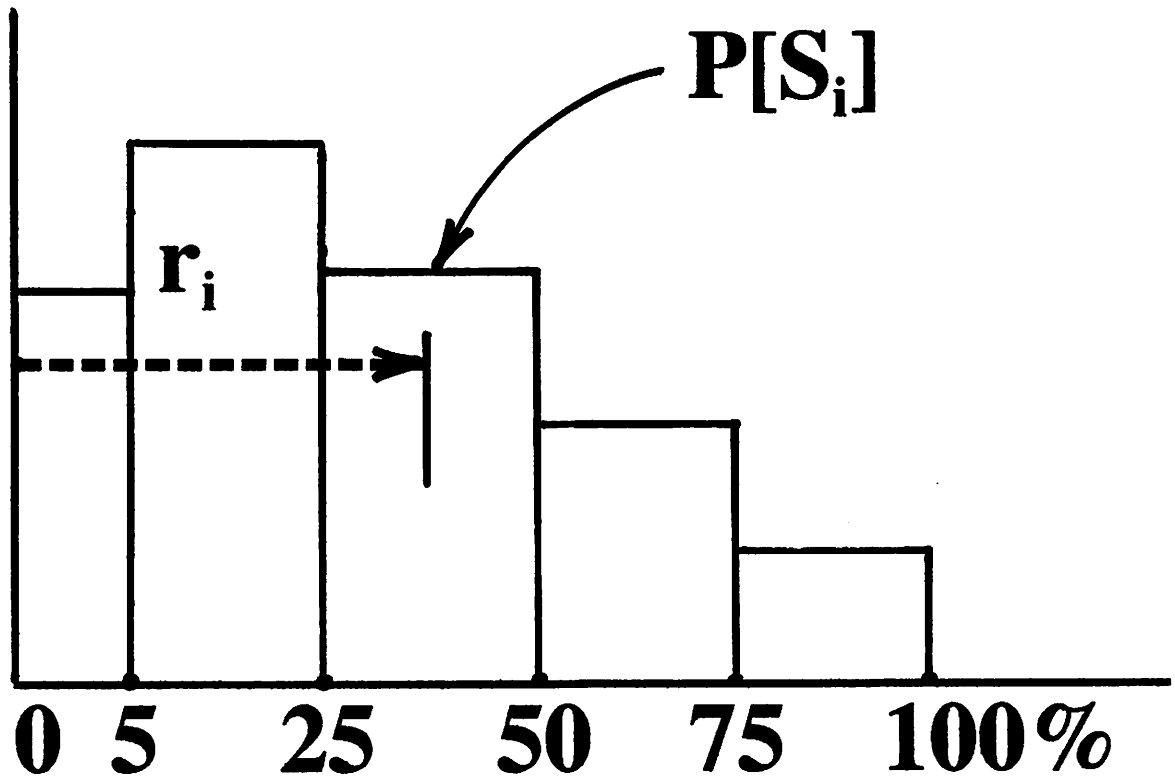


Figure 6

Probability Mass Function



$$m = \Sigma\, r_i\, P[S_i]$$

$$\sigma^2 = \Sigma\, (r_i - m)^2\, P[S_i]$$
$$= \Sigma\, r_i^2\, P[S_i] - m^2$$

Figure 7.

Given random variable X with mean m and variance σ^2 and a constant multiple C ,

mean of CX = Cm

Variance of CX = $C^2\sigma^2$

Figure 8.

<u>Central Limit Theorem</u>

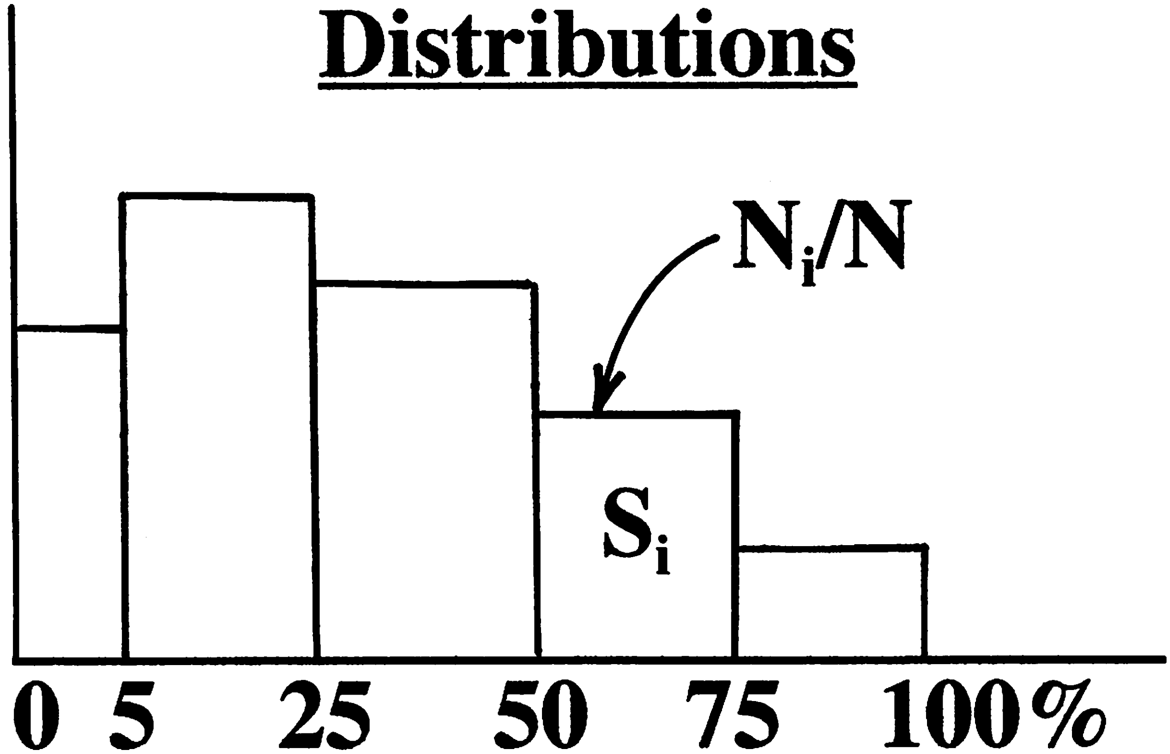
Given K independent random variables X_i

each with mean values m_i variances σ_i^2 ,

The sum ΣX_i may be considered to have a Normal Probability Distribution with mean value = Σm_i and Variance = $\Sigma \sigma_i^2$

Figure 9.

Observed Damage Distributions



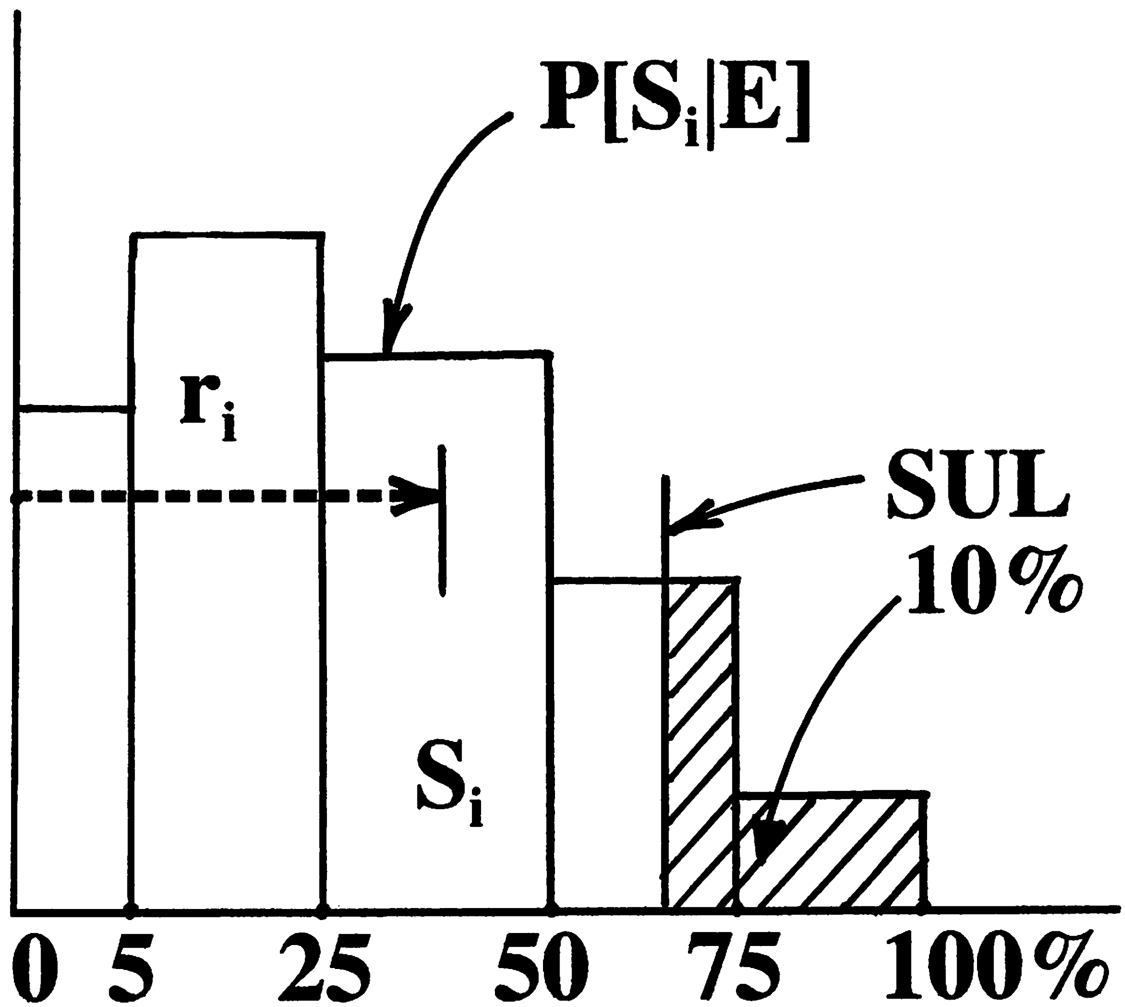
D = % damage ratio

S_i = damage state for a given range of D.

Given N buildings of a specified type, subject to common ground motion, N_i = number of buildings having D in range S_i

Figure 10.

Predicted Damage Distributions



SEL = m = Σ r$_i$ P[S$_i$|E]
for given earthquake E

Figure 11.

Expected Damage Predictor

SEL = K(B±C)(F)(E)

K = Empirical Constant

B = Building Type Factor

C = Correction Factor for Attributes or Deficiencies

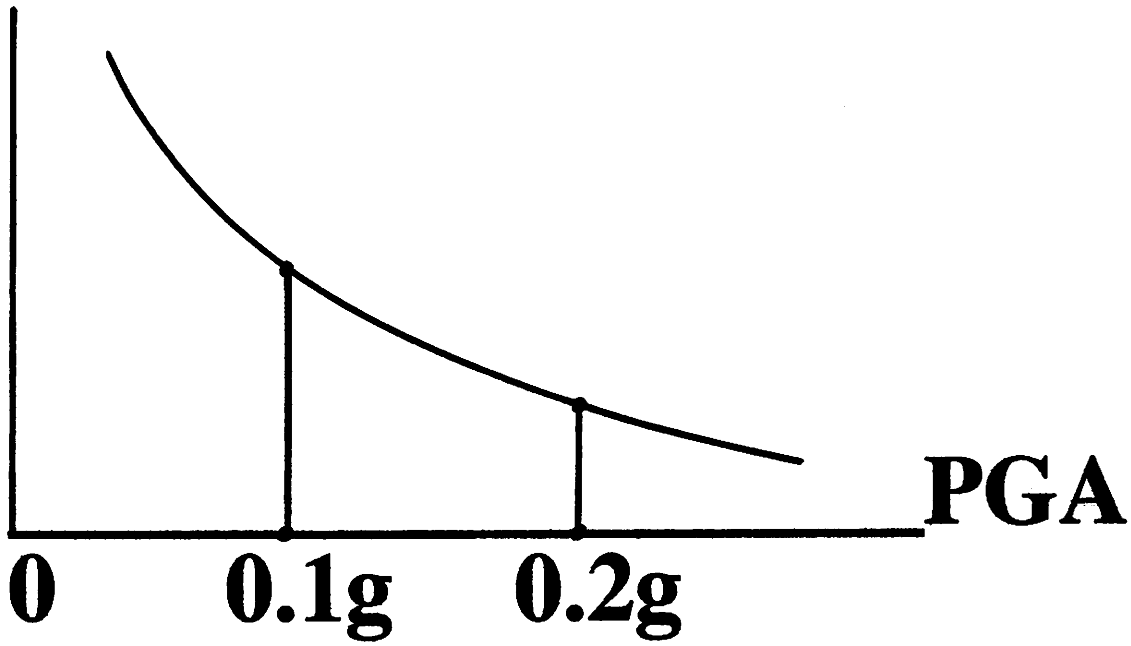
F = Factor for harmonic amplification and duration

E = Measure of earthquake ground motion intensity

Figure 12.

SEISMIC HAZARD

$H_T(a)$ for T years



$H_T(a) = P[PGA > a]$

If $E_i = [0.1g \leq PGA \leq 0.2g]$

$P[E_i] = H_T(0.1g) - H_T(0.2g)$

Figure 13.

Total Hazard of a Damage State S_j and the PL_T

From Seismic Hazard $H_T(a)$ find the $P[E_i]$ for the set of possible earthquakes at site.

Predict $P[S_j|E_i]$ using damage distribution function.
Find $P[S_j] = \Sigma\, P[S_j|E_i]\, P[E_i]$ for all S_j , then the PL_T is the damage ratio D_{90} in the S_j having $P[D \leq D_{90}] = 90\%$ for T years of exposure.

Figure 14

<u>Portfolio Loss Estimation</u>

Given K buildings at different independent site locations, each with: SEL_j , σ_j^2 , and value C_j .

Mean loss $m = \Sigma C_j SEL_j$

Variance $\sigma^2 = \Sigma C_j^2 \sigma_j^2$

Upper loss $U = m + 1.28\, \sigma$ by Central Limit Theorem

Portfolio SEL $= m / \Sigma C_j$

Portfolio SUL $= U / \Sigma C_j$

Figure 15.

Notes on Portfolio Loss

$$\text{Portfolio SEL} \neq \Sigma\, \text{SEL}_j$$

because of different property values C_j. Example: 0.12 at $5M and 0.40 at $100M

$$\text{Portfolio SUL} \neq \Sigma\, \text{SUL}_j$$

because of the different C_j and because the SUL of a sum is not equal to the sum of the individual SUL_j values

Figure 16.

Levels of Loss Studies

L0 = Screening Level using questionaire.

L1 = Quick observation and short code calculations.

L2 = Detailed observation and detailed code calculations.

L3 = Detailed inspection and evaluation of main cost components. Spectral or Time History evaluation of accelerations and drifts for damage estimates.

Figure 17.

NEED FOR A NEW ATC-13

1) Update building type descriptions and characteristics.

2) Update Expert Opinions based on new data and analysis.

3) Use Spectral measures S_S and S_L rather than MMI.

4) Ask experts for SEL and the σ of the random SL.

Figure 18.

GENERAL COMMENTS

1. Do perform a reality check on the estimated loss by visualizing the possible type of damage that could occur in the building and its cost of repair. Is this near to the damage ratio times building value ?

2. Does loss estimation have a role in performance based design ? For example, the probabilistic description of performance rather than a definite promise.

Figure 19.

THE ASTM STANDARD GUIDE FOR ESTIMATION OF BUILDING DAMAGEABILITY IN EARTHQUAKES

Refer to the 1999 Tall Buildings Conference Paper by Chuck Thiel and Gary Varum, Co-Chairs of the ASTM Committee E06.25.55 .
This paper is included in these Seminar Notes.

Figure 20.

ESTIMATION OF EARTHQUAKE DAMAGE LOSS

Ted Zsutty

DESCRIPTION OF TERMS AND CONCEPTS FOR LOSS ESTIMATES

Background

The original definition of a PML given by Steinbrugge and Engle is: " The *probable maximum loss* for an individual building is that monetary loss expressed in dollars (or as a percentage of insured value) under the following conditions:

1. Located on firm alluvial ground, and
2. Subjected only to the vibratory motion from the maximum probable earthquake.

The building *class probable loss* (class PML) is defined as the expected maximum percentage monetary loss which will not be exceeded for 9 out of 10 buildings in a given earthquake building class under the conditions stated in the previous paragraph."

In a formal statistical terminology this original PML definition could be expressed as "the 90% upper confidence limit on the damage ratio for a building in a given structural classification subjected to the 10% risk in 50 year level of earthquake ground motion." Currently, however, the term "PML" has taken on a range of definitions and values because of the various and often undefined assumptions and procedures employed in loss estimation reports from different providers. For example; mean , median, upper-bound, or even judgmental opinions are given for specified or unspecified descriptions of causative earthquakes. As a result, users can receive widely different "PML" evaluations for the same property from different providers, and the usual vagueness of definition and procedures makes it difficult to resolve the differences. It is therefore recommended that the term "PML" be discontinued and that the following terms and definitions be used.

Measures of Earthquake Damage Loss

SL = Scenario Loss = the random damage ratio due to a defined scenario earthquake; commonly the level of ground motion having 10% risk of exceedence in 50 years, or a selected maximum capable event. For example, a Magnitude 7.0 on the Northern segment of the Hayward Fault for a building site in Oakland.

SEL = Scenario Expected Loss = expected or mean damage ratio due to a given scenario earthquake.

SUL = Scenario Upper-Bound Loss = upper-bound,usually the 90% upper confidence limit, of the actual random damage ratio SL due to the given scenario earthquake.

PL_T = Probable Loss = upper-bound,usually the 90% upper confidence limit, of the damage ratio due to any of the damaging levels of earthquakes that could possibly occur at the building site during a selected future time period of exposure, such as T = 50 years.

Discussion

The SEL and SUL with their defined scenario earthquake provide a measure of the relative seismic damage resistance of a building as compared to the behavior of acceptable structures in the user's portfolio or experience. For example, the user may feel confortable with SEL values less than 20% and therefore would reject a building having an SEL of 30%.
The SEL and SUL provide an answer to the question of "What is the loss if the large scenario earthquake were to occur ?". It is important that the user be aware of the definition, either the SEL or the SUL, when comparing loss estimates with acceptable standards: noting that an SEL of 20% can have a SUL value of about 30%. It is therefore an important responsibility of the provider to define the particular loss measures given in the loss estimation report.
Because the SEL and SUL are conditioned to the occurrence of the scenario earthquake, they cannot provide a measure of the risk of loss due to the exposure of the building to the total seismic hazard during a selected time period of exposure.. At a given location a building might suffer: 2% damage due to a minor earthquake with 80% hazard in 50 years; 10% damage due to a moderate event with 50% hazard in 50 years; 20% damage due to the 10% hazard in 50 year event; and larger damage if a greater maximum capable event were to occur. For purposes of economic decisions, the user may require a measure of the level of loss due to the total risk of exposure to any of these events that could occur during the selected life period of 50 years.
The PL_T provides the particular damage ratio that has a given reliability (such as 90%) of not being exceeded during the selected life T. It considers: all of the damaging levels of earthquakes; their hazard of occurrence; the probabilities of damage levels due to each of the possible levels, and convolves these hazards and probabilities to obtain the upper bound damage ratio due to the total seismic hazard for the building site.
The following simplified example shows the basic concepts of the procedure for evaluating the total hazard probability that a given damage level will not be exceeded. In actual applications the calculation would be performed by either a numerical integration or a Monte Carlo evaluation of the seismic hazard relation convolved with the damage probability function for the structure.

EXAMPLE:

A two story wood framed condominium building is located in a seismic region where the hazard over a 50 year period is: Probability of a zero to small earthquake $P[Q_S] = 0.4$; Probability of a moderate quake $P[Q_M] = 0.4$; and Probability of a large quake $P[Q_L] = 0.2$, and any one of these events must occur during the time period.
The first step is to evaluate the Probability of a damage ratio greater than 50%, $P[D_{50}]$, due to the exposure to this total seismic hazard. By the use of experience, records of seismic damage data, empirical relations, and possible analysis of performance and cost estimates, the provider is able to estimate the conditional Probabilities of D_{50} given that a particular quake Q has occurred: $P[D_{50} \mid Q_S] = 0$; $P[D_{50} \mid Q_M] = 0.2$; and $P[D_{50} \mid Q_L] = 0.6$

Using the relation for conditional Probability , $P[D_{50} | Q] = P[D_{50}$ and $Q] / P[Q]$, the joint Probability of the events D_{50} and Q both happening at the same time is

$P[D_{50}$ and $Q] = P[D_{50} | Q] X P[Q]$. For the complete set of earthquake events this gives,

$P[D_{50}$ and $Q_s] = (0.0)X(0.4) = 0$
$P[D_{50}$ and $Q_M] = (0.2)X(0.4) = 0.08$
$P[D_{50}$ and $Q_L] = (0.6)X(0.2) = 0.12$

and using the "total probability law" the Probability $P[D_{50}]$ is given by the sum or total of these joint probabilities,

$P[D_{50}] = O + 0.08 + 0.12 = 0.20$

which is the total hazard of a damage ratio in excess of 50%.

Next, the provider performs similar calculations for the P[D] of successively higher damage ratios such as 60%, 70%, 80% ; and then by interpolation between the results that bracket the 0.10 Probability value, the particular PL_T value of D could be found that has the 10% risk of being exceeded and the 90% confidence of not being exceeded in T =50 years. For example, suppose that total hazard of a damage ratio in excess of 70% = 0.05, then by interpolation:

$PL_T = 70\% - (70\% - 50\%)(0.10 - 0.05) / (0.20 - 0.0.05) = 63\%$

ESSENTIAL INFORMATION AND RELATIONS REQUIRED FOR DAMAGE LOSS EVALUATION

Site Seismic Hazard The site seismic hazard curve is a graph with horizontal axis giving the range of all possible values of levels of a given ground motion measure (such as PGA, EPA, or MMI) and vertical axis giving the corresponding probability of exceeding a given level during a specified time period (such as 1, 20, or 50 years). This hazard curve can be converted into a probability density function or a descrete probability mass function for the ground motion values. For example, if a descrete level "i" were to be $PGA_i = 0.40g$, then the probability could be found by the area under the density function between 0.35g and 0.45g.

Damage Predictor A relation giving a central or mean damage ratio (SEL) in terms of: a measure of the building class or system damage factor , the level of the measure of ground motion, and possible site-structure vibration effects. This relation should have some description of the scatter of actual random damage ratio about the predicted mean, or preferably provide the damage distribution function.

Damage Distribution Function This is the probability function for the damage states of a given building type due to a given level of earthquake ground motion. Actual damage to a building is random because: actual future ground motion as represented by a given measure and level is not completely described by that representation, and a particular building has its own resistance or fragility characteristics that are not completely described by the building structural system type.

This probability function allows the evaluation of the conditional probability of the building having a given damage state (a given range of damage ratios such as 25% to 50%) due to a given level of ground motion along with the SUL having the 90 percent chance of not being exceeded.

DESCRIPTION OF LEVELS OF DAMAGEABILITY ASSESSMENT:

LO (Screening Assessment) The general architectural and structural characteristics of the building, are determined and the type earthquake lateral load resisting system is identified. The basis for this determination may be either a reported or visual observation of the building and/or a review of available construction documents. The characteristics include: the material and type of structural system, the plan size and number of stories, the building code applicable to the design and construction.
This method uses tabulated values or relations for earthquake loss predictions in terms of standard building size and type and the level of earthquake ground motion. Adjustments may be made to accommodate deviations of the building's characteristics from those of the related standard building type.
The level of earthquake ground motion may be based on the building code seismic zone, or ZIP code hazard maps.
The results of this level have an inherently high level of uncertainty, and this is particularly true when proprietary computer programs in a questionnaire format are used by providers having the minimum level of qualifications. For this latter case it is recommended that the results be used only for the purpose of pre-screening the property for decisions related to further study.

L1 The observation, investigation, analysis and damageability evaluation is to be performed by an engineer with declared qualifications and expertise in seismic resistant design and experience in the seismic assessment of the type of building(s) involved in the study. The specific architectural and structural characteristics of the building are determined and the type earthquake lateral load resisting system is identified. The basis for this determination must be from a visual inspection of the building and a review of available construction documents. The characteristics include: the material,type, and essential details of structural system, the plan size and number of stories, and the building code applicable to the design and construction. If construction documents are not available, the type of structural system and related details shall be determined by inspection. The document review and/or observations shall identify obvious flaws or omissions in the structural system that could lead to increased damageability or loss of stability. It is not intended that a detailed investigation be performed. Any special architectural and/or non-structural conditions related to damageabilty shall be identified. If design calculations are not available, a simple analysis shall be performed to evaluate the general degree of compliance with current code load requirements when the inspection indicates potential weakness in the structural system.
The damageability for given levels of earthquake ground motion may determined from tables or relations for the standard building size and type. Adjustments are to be made to accommodate deviations of the building's characteristics from those of the related standard building type.
The levels of earthquake ground motion may be taken from published maps, available site seismic hazard studies, or from attenuation relationships for specific earthquakes on specific faults or source areas.

L2. Same as for level L1 plus: if construction documents are not available, the type of structural system and related details shall be determined by a detailed and thorough inspection. The document review and/or inspection observations shall identify obvious flaws or omissions in the structural system that could lead to increased damageability or loss of stability. Similarly any special architectural and/or non-structural conditions related to damageabilty shall be identified. If adequate design calculations are not available, a detailed analysis shall be performed to evaluate the degree of compliance with current code

load requirements for the principal structural and non-structural elements that significantly determine the damageability and stability of the building. This code analysis may be replaced by an appropriate element demand/capacity analysis using a ground motion level with 10% probability of exceedence in 50 years (475 year return period.)
The damageability for given levels of earthquake ground motion may determined from relations for the standard building size and type and site soil conditions.. Adjustments are to be made to accommodate deviations of the building's characteristics from those of the related standard building type. There must be a damage probability function for the random scatter of actual damage state about the predicted damage due to a given ground motion level.
The levels of earthquake ground motion must be taken from site seismic hazard studies. There must be a seismic hazard curve or relation to establish the probability of all damaging levels of ground motion.

L3 The observation, investigation, analysis and damageability evaluation is to be performed by an engineer with declared qualifications and expertise in seismic resistant design and related dynamic analysis and experience in the seismic assessment of the type of building(s) involved in the study. The main difference between this level of analysis from that of the lower levels is that it evaluates damage to the major individual components (structural system, exterior shell, interior finish, tenant improvements, mechanical/electrical systems) of the building rather than treating the building as a whole having a particular system type. The major components are identified and their values are established such that their sum equals the total replacement cost of the building. Each component is divided into categories that have damage that is best predicted in terms of the response characteristics of: floor acceleration, inter-story drift, local element deformation demands, etc.; and damage ratios are established either from any available data or published tables, or from judgment coupled with specific detailed cost estimates: the result is a damageability relation or curve that provides the component damage ratio and corresponding cost of repairs for the possible range of response values.

The structure is appropriately modeled and dynamic analyses are performed at selected successive descrete levels of ground motion having known probabilities of occurrence. Response spectrum analysis of the elastic structure model may be used with assumed relations between the elastic and inelastic response. Inelastic time history analysis may be performed to more reliably establish particular demand characteristics. When the response values at each floor and story are determined for a given level of ground motion the damage ratio and corresponding damage cost is found for each component at each floor and story level and the total damage cost for the building is then evaluated as the sum of costs at each floor then summed over all floor levels.
Since the individual component damageability relations are often judgmental with large uncertainties; or at best, based on sparse amounts of data, the actual individual component damage cost and resulting total cost for the building are random for a given ground motion. Feasible representation of this randomness may be expressed by use of low,best, and high damage ratios for each component along with a subjective probability or likelihood such as 25%, 50%, 25% for low, best, and high. Alternatively the best or mean value could be selected along with standard deviation (sigma) of scatter for component damage; then by the central limit theorem, the sum or total damage cost would have a Normal Probability Distribution with mean equal to sum of the component mean costs, and with sigma (assuming independence between components) equal to the SRSS of the component sigmas. For each given scenario level of ground motion, the resulting mean value / Building Cost is the SEL and the SUL = (mean + 1.28 sigma) / Building Cost.

ESSENTIAL ELEMENTS OF PROBABILITY AND STATISTICS

Purpose: The evaluation of the various forms of earthquake loss estimates that fall under the general category of "Damage Loss Analysis" requires adherence to the mathematical concepts of probability and statistics. While it is true that the particular models and procedures employed require the use of assumptions and subjective judgment for the evaluation of the related model parameters; the processing of data, the representation of uncertainty and the combination of the probabilities of events need to conform to established mathematical rules. This is analogous to structural analysis where assumptions and judgment are required for material properties and loads, but the procedures must follow the laws of mechanics. The purpose of this section is to provide the necessary rules and relations for the probabilistic portion of loss estimation.

Reference: Jack R. Benjamin and C.Allin Cornell, "Probability, Statistics, and Decision for Civil Engineers", McGraw-Hill Book Company, 1970.

Symbols and Notations

General: A capital letter such as X denotes a random variable, and a lower case such as x denotes a specific value of X.

Continuous Valued Random Variables X and Y

$P[X \le x]$ = Probability of $X \le x$

$f_X(x)$ = probability density function = PDF

$F_X(x) = P[X \le x] = \int^{x} f_X(x)\,dx$ = cumulative distribution function = CDF

$f_{X,Y}(x,y)$ = joint PDF

$F_{XY}(x,y) = P[(X \le x) \cap (Y \le y)] = \int^{x} \int^{y} f_{XY}(x,y)\,dx\,dy$ = Joint CDF

$f_{Y|X}(y, x)$ = conditional PDF of Y given (X=x)

m_X = mean value of $X = \int x\, f_X(x)\,dx$

σ_X^2 = variance of $X = \int x^2 f_X(x)\,dx - m_X^2$

σ_X / m_X = coefficient of variation of X

A constant multiple $C_o X$ has mean = $C_o m_X$ and variance $C_o^2\, \sigma_X^2$

Discrete Valued Random Variables X and Y

$p_X(x) = P[X=x]$ = discrete probability mass function = PMF

$p_{X,Y}(x,y) = P[(X=x) \cap (Y=y)]$ = joint PMF

$p_{Y|X}(y, x) = P[(Y=y) |(X=x)]$ = conditional PMF

m_X = mean value of $X = \sum x \, p_X(x)$

σ_X^2 = variance of $X = \sum x^2 p_X(x) \, dx - m_X^2$

A constant multiple $C_o X$ has mean = $C_o m_X$ and variance $C_o^2 \sigma_X^2$

Sum of Random Variables X and Y

The random variable sum $S = X+Y$ has the following parameters,

$$m_S = m_X + m_Y$$

$\sigma_S^2 = \sigma_X^2 + \sigma_Y^2 + 2\rho_{XY} \sigma_X \sigma_Y$, where ρ_{XY} is the correlation coefficient $(0 \le \rho_{XY} \le 1)$

Sum of N Independent Random Variables X_i

Given N independent (no correlation) random variables X_i each with mean m_i and variance σ_i^2 ,
the sum ΣX_i can be assumed (for loss estimation purposes) to have a Normal probability distribution with
mean = Σm_i and variance = $\Sigma \sigma_I^2$. This is a result of the Central Limit Theorem, and has useful applications for portfolio loss estimation.

Specific Random Variables for Loss Evaluations

A , a = measure of the level of earthquake ground motion, such as PGA, EPA, or MMI.

R , r = damage ratio

S, s = damage state in terms of a defined interval of damage ratios,
such as $(75\% < r \le 100\%)$

C_o = replacement cost of a building, this is a constant non-random value.

C , c = damage cost = $C_o R$, $C_o r$

$H_1(a) = P[A>a]_1$ = annualized seismic hazard for a one year period

$H_T(a) = P[A>a]_T$ = seismic hazard for a future T year period of exposure, such as 50 years.

$F_A(a)$ = CDF for A = $P[A \le a]_T = 1 - H_T(a) = [1 - H_1(a)]^T$, for a T year period of exposure.

$f_A(a)$ = PDF for A = derivative of $F_A(a)$ with respect to "a"

Evaluation of Loss Parameters using the Discrete Valued Random Variable Formulation

Seismicity

Given the site seismic hazard curve $H_T(a)$, construct the PMF $p_A(a)$ by selecting intervals Δ_j of "a" with centroid values a_j such that

$p_A(a) = H_T(a_j - \Delta_j/2) - H_T(a_j + \Delta_j/2)$, for $j = 0$ to M,
where a_o creates negligible damage, and a_M is the judged maximum capable level.

Building Damageability

For the specific building structural system, select a damage state prediction function that can provide the conditional PMF and its parameters for damage state S given ground motion level $A = a_j$:

$p_{S|A}(s,a)$ for damage states s_i , for $i = 0$ to N,
where s_i is a given interval Δ_I of damage ratios "r" having centroidal values r_i , and where s_o is a negligible to low damage state, and s_N is the high to complete damage state.

By substitution of r_i for s_i in $p_{S|A}(s,a)$ the conditional PMF for R is
$p_{R|A}(r,a)$ in terms of the discrete values r_i , for $i = 0$ to N.

Scenario Loss for a selected scenario ground motion level $A = aP$:

Compute the conditional PMF parameters given A=aP, where aP is a selected value of the discrete a_j values (such as the PGA value having 10% risk in 50 years);

$$m_{R|aP} = \sum r_i \, p_{R|A}(r_i, aP) \quad , \text{ summed from } i = 0 \text{ to } N.$$

$$\sigma^2_{R|aP} = \sum r_i^2 \, p_{R|A}(r_i, aP) - m^2_{R|aP}$$

The conditional parameters $m_{R|aP}$ and $\sigma^2_{R|aP}$ are needed for the the evaluation of the scenario loss for a portfolio of buildings.

The Scenario Expected Loss SEL = $m_{R|aP}$

The Scenario Upper Loss SUL = 90% upper confidence limit on the scenario loss is the value of r_{90} such that the discrete CDF equals 0.90,
$\sum p_{R|A}(r_i, aP) = 0.90$, where the summation is from r_o to r_{90} , and it may be necessary to interpolate between successive r_i values to find r_{90}.

Probable Loss PL_T

This is the upper 90% loss due to the hazard of any of the damaging ground motion levels a_j that could occur during the time period of T years.

Given $p_A(a)$ and $p_{R|A}(r,a)$ for a building, compute the joint PMF,

$$p_{R,A}(r,a) = p_{R|A}(r,a)\ p_A(a)$$

and then the marginal PMF for R,

$$p_R(r) = \sum p_{R|A}(r,a_j)\ p_A(a_j)\text{, summed for all } a_j \text{ from } j = 0 \text{ to } M.$$

Probable Loss PL_T is the value r_{90} such that

$\sum p_R(r_i) = 0.90$ where the summation is from r_o to r_{90}, and it may be necessary to interpolate between successive r_i values to find r_{90}

Evaluation of Loss Parameters using the Continuous Valued Random Variable Formulation

"Scenario" Loss for a selected scenario event $A = aP$

Given the seismic hazard curve $H_T(a)$ with its corresponding PDF $f_A(a)$ and the building damageability $f_{R|A}(r,a)$, the conditional probability parameters for the scenario event

of $A = aP$ are:

$$m_{R|aP} = \int r\ f_{R|A}(r,aP)\ dr$$

$$\sigma^2_{R|aP} = \int r^2\ f_{R|A}(r,aP)\ dr\ -\ m^2_{R|aP}$$

These conditional probability parameters are needed for the evaluation of the "scenario" loss for a portfolio of buildings.

The SEL = $m_{R|aP}$

The SUL is the value of r_{90} such that the CDF equals 0.90,

$\int f_{R|A}(r,aP)\ dr = 0.90$, where the integral is from 0 to r_{90}

Probable Loss PL_T

This is the upper 90% loss due to the hazard of any of the damaging ground motion levels "a" that could occur during the time period of T years.

Given $f_A(a)$ and $f_{R|A}(r,a)$ for a building, compute the joint PDF,

$$f_{R,A}(r,a) = f_{R|A}(r,a)\, f_A(a)$$

and then the marginal PDF for R,

$$f_R(r) = \int f_{R|A}(r,a)\, f_A(a)\, da$$

The PL_T is the value r_{90} such that

$$\int f_R(r)\, dr = 0.90$$ where the integral is from 0 to r_{90}

Evaluation of Loss for a Portfolio of Buildings

"Scenario" Loss for a Portfolio of Buildings

Given a portfolio of K Buildings, where each building k with replacement cost C_{Ok} is subject to a "scenario" ground motion aP_k having a common hazard such as 10% in 50 years; compute the conditional parameters $m_{R|aPk}$ and $\sigma^2_{R|aPk}$ for each building (using either the discrete or continuous probability formulation). Since each building will have a random damage ratio $R|aP_k$ due to the ground motion represented by aP_k the corresponding damage cost $C_k = (C_{ok})R|aP_k$ is a random variable with parameters,

$$m_k = C_{0k}\, m_{R|aPk}$$

$$\sigma^2_k = C^2_{0k}\, \sigma^2_{R|aPk}$$

According to the central limit theorem, that states that a sum of random variables tends toward the normal probability distribution, the total "scenario" portfolio random loss cost $C_K = \sum C_k$ for the K buildings is approximately a normal random variable with parameters,

$$m_K = \sum m_k$$, summed from k=1 to K,

$$\sigma^2_K = \sum \sigma^2_k$$

With the total portfolio value $C_t = \sum C_{ok}$,

Portfolio SEL = m_K / C_t

Portfolio SUL = $[m_K + 1.28\sigma_K] / C_t$,

where the factor 1.28 is the 90% upper bound value for the standardized normal variate.

EXAMPLE FOR A SINGLE BUILDING

The following example will employ the procedure and relations given in the following EERI reference: Thiel and Zsutty, "Earthquake Characteristics and Damage Statistics", Earthquake Spectra, Vol. 3, No. 4, 1987. The definitions, equation and table numbers referred to in this example correspond to those given in this reference. The purpose for using the particular method given in this Spectra paper is not meant to be exclude other procedures but only to provide definite examples of a damage predictor, the related damage distribution function, and the numerical calculation procedures using real numbers. Other methods are valid and applicable as long as: they are based on the experience and knowledge obtained from observed and/or analytical predictions of the performance of structures, the procedures do not violate the rules of probability and statistics, and the resulting damage loss evaluations are fully defined

The SEL and SUL are to be found for the scenario10% risk/50 year ground motion along with the PL_T value for the following building and site seismic hazard conditions.

A 200'X400' concrete tilt-up wall building with a plywood sheathed wood frame diaphragm is located on a firm soil site in South San Francisco. The structure has wall ties and continuous tie elements. The wall ties are PAT connectors, and the continuous glu-lam girder tie elements do not have sufficient splice connection resistance at two locations. Wall settlement tilting due to eccentrically loaded footing has caused spalling at the girder supports at four locations. A seismic hazard curve is available for the site.

The SEL may be evaluated by two ways; each of which will provide essentially the same answer. The first would be the formally defined method of finding the centroid $m_{R|aP}$ of the damage state PMF $p_{R|A}(r_i, aP)$, the second involves the use of the following empirical predictor of the centroid of the damage state PMF,

$$d = 0.554\ (b\ m\ s)(a)^{0.63} \qquad \text{Spectra Eqn (11-2)}$$

where:

b = Building vulnerability factor representing the damageability of the building construction type as referenced or compared to the damageability of a low rise building with unreinforced masonry bearing walls which is assigned the standard value of b = 1.00. Building types having more resistive systems are assigned b less than 1.00, and buildings with a lessor amount of damage resistance have b greater than 1.00. The individual building type b values were assigned to provide the best agreement with available damage data and expert opinion: the results are given in the Spectra Table 8-3.

m = Spectrum modification parameter representing harmonic amplification due to the possible similarity of the periods of vibration of the building and the seismic ground motion.

s = Site response spectrum parameter representing the relative response of the site referenced to that of a standard firm soil site condition, in the range of vibration periods near to that of the building. The effects of long duration of shaking due to earthquakes having large magnitude can also be represented by this parameter.

a = Peak ground acceleration for a given level of earthquake ground motion at the site. It provides the measure of the intensity of the ground motion and is associated with a given probability of being exceeded during a given building life; such as 10% in 50 years.

The particular description and method of evaluation of the above listed parameters for the building are given in the following sections. The resulting values will also be used for the determination of the shape parameter "p" for the damage state PMF.

Building Vulnerability "b"

The general configuration and details, most appropriately conforms to structure system 21 given in Spectra Table 8-3, with a standard value of b = 0.41. The diaphragm connections and tie details are similar to the Pre-Northridge Earthquake construction as represented by system 21. There is increased damage potential due to the weak tie element splices and spalled girder seats; these deficiencies will be represented by a penalty factor of 1.5 applied to the standard b value giving b = 1.5(0.41) = 0.62. (note here that the quality of knowledge and experience of the engineer comes into play for both the identification of deficiencies and the assignment of the appropriate penalty factors or credits for conditions that are worse or better than the standard).

Site and Source Response "ms"

For the purposes of this example the separate m and s factors are combined to a single "ms" factor to represent the possibility of harmonic response amplification due to the matching of the building and ground motion vibration frequencies. For relatively stiff buildings located on a relatively firm soil type, the standard level of amplification is represented by "ms" = 1.25 for earthquakes having Richter Magnitude of about 7.0. However, since the nearby San Andreas Fault could produce an event in the Magnitude 8.0 range, the possible long duration of shaking and harmonic response amplification due to the relatively long (400') diaphragm spans will be represented by "ms" = 1.5 for the 10%/50 year earthquake. Other values will be assigned for the smaller and larger events in the Probable Loss PL evaluation.

Effective Peak Acceleration "a"

A site specific seismic hazard curve H_T (a) for T= 50 years has been provided for the building site This hazard curve gives a Peak Ground Acceleration (PGA) of 0.50g for the 10% / 50 year earthquake and this will be used for the "a" value. This value is the scenario "aP". Other values and their probabilities will be taken from this curve for the smaller and larger events as required for the PL evaluation.

MEAN DAMAGE AND RELATED DAMAGE STATE PROBABILITIES

With the assigned values of "b", "ms", and "a", the SEL can be determined by

$$d= 0.554\,(bms)(a)^{0.63}\times 100\% \qquad \text{Spectra Eqn (11-2)}$$

and the shape parameter "p" that defines the damage state PMF necessary for the evaluation of the SUL is given by

$$p= 0.651\,(bms)(a)^{0.606} \qquad \text{Spectra Eqn (10-1)}$$

which when entered into Spectra Equations (4-4) with e = 1/6 gives the PMF = probabilities for the damage states S_i:

P_0 for State S_o in the $0 < r \leq 5\%$ range = $(1-p)^4$
P_1 for State S_1 in the $5 < r \leq 25\%$ range = $4p(1-p)^3(5/6)$
P_2 for State S_2 in the $25 < r \leq 50\%$ range = $(2/3)p(1-p)^3 + 6p^2(5/6)(1-p)^2$
P_3 for State S_3 in the $50 < r \leq 75\%$ range = $p^2(1-p)^2 + 4p^3(1-p)(5/6)$
P_4 for State S_4 in the $75 < r \leq 100\%$ range = $(1/2)p^3(1-p) + p^4(5/6) + (1/6)p^3$

These probabilities P_i can be used for the conditional PMF for the discrete damage ratio R, $p_{R|A}(r_i, aP)$ where the r_i are the damage state centroid values:
$r_o = 2.5\%$, $r_1 = 15\%$, $r_2 = 37.5\%$, $r_3 = 67.5\%$, $r_4 = 87.5\%$

SEL due to the 10% Risk in 50 year Ground Motion

Using b = 0.62, ms = 1.5, and a = 0.50 = aP, the Spectra Eqn (11-2) gives

$SEL = 0.554(0.62)(1.5)(0.50)^{0.63} = 0.333 =$ 33 percent

SUL due the 10% Risk in 50 year Ground Motion

$$p = 0.651(0.62)(1.5)(0.50)^{0.606} = 0.40$$

Giving from Spectra Eqns (4-4): $P_0 = 0.13$, $P_1 = 0.29$, $P_2 = 0.35$, $P_3 = 0.18$, $P_4 = 0.05$

The SUL is the damage level r_{90} having a 90% chance of not being exceeded due to the scenario 10% / 50 year level of earthquake ground motion (having aP = 0.50g) is found by interpolation within the P_3 damage interval:

$$SUL = 0.75 - (0.25)(0.10 - 0.05) / (0.18) = 0.68 = \text{68 percent}$$

Scenario Mean and Variance

With the damage ratio PMF $p_{R|A}(r_i, aP)$ for $r_o = 2.5\%$, $r_1 = 15\%$, $r_2 = 37.5\%$, $r_3 = 67.5\%$, $r_4 = 87.5\%$, given by the corresponding damage state probabilities P_i for the scenario aP = 0.50g, the mean and variance values are given by,

$$m_{R|aP} = \sum r_i \, p_{R|A}(r_i, aP) \text{ , summed from } i = 0 \text{ to } 4.$$

$$\sigma^2_{R|aP} = \sum r_i^2 \, p_{R|A}(r_i, aP) - m^2_{R|aP}$$

Computations are as follows:

i	P_i	x_i %	$P_i x_i$	$P_i x_i^2$
0	0.13	2.5	0.3	0.8
1	0.29	15.0	4.4	66.0
2	0.35	37.5	13.1	491.2
3	0.18	67.5	12.1	816.8
4	0.05	87.5	4.4	385.0
	--------		--------	--------
	Σ=1.00		Σ=34.3	Σ=1759.8

$m_{R|aP} = 34.3 = 34$ percent

(Note that this is the formal definition of the SEL and it is essentially equal to the value of 33 percent given by the Spectra Eqn (11-2).)

$\sigma^2_{R|aP} = 1759.8 - (34.3)^2 = 583.3$

$\sigma_{R|aP} = 24.2 = 24\%$

These scenario parameters will be used in an example dealing with the scenario SEL and SUL evaluation for a given portfolio of buildings.

Probable Loss PL_T

The SEL and SUL values are conditioned to be due to the scenario 10%/50 year earthquake. However since other lower or higher levels of earthquake ground motion could occur and cause damage during the future 50 year period, it is useful to consider the total hazard probable loss PL_T defined as the damage ratio having a 90 percent chance of not being exceeded due the total exposure of any damaging level of earthquake that could occur during the 50 year period.

The building site hazard curve $H_{50}(a)$ provides the following probabilities $P[PGA>a]_{50}$ for the time period T=50 years:

PGA = a	$H_{50}(a)= P[PGA>a]_{50}$	j	a_j
0.0g	1.00		
		0	0.05g
0.1g	0.98		
		1	0.20g
0.3g	0.50		
		2	0.40g
0.5g	0.10		
		3	0.60g
0.7g=max.	0.00		

The discrete earthquake events a_j are defined as the mid-point values of the intervals between the tabulated Peak Ground Acceleration PGA = a values.
Here it is assumed that the damage PMF resulting from the use of the discrete value a_j is essentially the same as that resulting from any of the "a" values in the interval represented

by a_j. The accuracy of this assumption improves with the reduction of the size of the intervals and resulting increase in the number M+1 of a_j values used. For this example, M+1 = 4. The event Probabilities $P[a_j]$ are found as follows:

$a_0 = 0.05g$ for [0<PGA< 0.1g], $P[a_0] = 1.00 - 0.98 = 0.02$; Assume a_0 causes negligible damage.

$a_1 = 0.2g$ for [0.1g<PGA< 0.3g], $P[a_1] = 0.98 - 0.50 = 0.48$

$a_2 = 0.4g$ for [0.3g<PGA< 0.5g], $P[a_2] = 0.50 - 0.10 = 0.40$

$a_3 = 0.6g$ for [0.5g<PGA< 0.7g = Max. Value], $P[a_3] = 0.10 - 0 = 0.10$

Any of the events a_j could occur during the 50 year period.

TOTAL HAZARD PROBABLE LOSS

Find conditional hazard:

			Damage State Probabilities from Spectra Eqns (4-4)					Conditional Hazard due to a_j: $P[R>50\% \mid a_j]$	$P[R>75\% \mid a_j]$
a_j	ms	p	P_0	P_1	P_2	P_3	P_4	$=P_3+P_4$	$=P_4$
0.05g	---	---	1.00	0	0	0	0	0	0
0.2g	1.25	0.19	0.43	0.34	0.19	0.04	0.00	0.04	0.00
0.4g	1.50	0.35	0.18	0.32	0.32	0.15	0.03	0.18	0.03
0.6g	2.00	0.59	0.03	0.13	0.32	0.34	0.18	0.52	0.18

Compute total hazard:

a_j	$P[a_j]$	$P[R>50\% \mid a_j]$	$P[R>50\% \mid a_j]\cdot P[a_j]$	$P[R>75\% \mid a_j]$	$P[R>75\% \mid a_j]\cdot P[a_j]$
0.2g	0.48	0.04	0.02	0.00	0.00
0.4g	0.40	0.18	0.07	0.03	0.01
0.6g	0.10	0.52	0.05	0.18	0.02
			Total = 0.14		Total = 0.03

Total Hazard of damage ratio R >50% in 50 years = 0.14 = 14 percent

Total Hazard of damage ratio R >75% in 50 years = 0.03 = 3 percent

By interpolation, the damage ratio r_{90} having a total hazard of 10 percent in 50 years is 59%, such that P[R >59%] = 10 percent and P[R < 59%] = 90 percent. This damage ratio of 59% is termed as the Probable Loss PL_{50}.

EXAMPLE FOR A PORTFOLIO OF BUILDINGS AT DIFFERENT SITES

The scenario SEL and SUL are to be found for a portfolio of K=3 buildings at different sites, where the scenario earthquake ground motion is the PGA having a 10% risk/50 years at each particular site. The buildings are: Building 1 is the tilt-up in South San Francisco used for the single building example; Building 2 is a medium rise steel moment frame in San Jose; and Building 3 is a two-story wood frame condominium in San Diego, California. The replacement costs C_{ok} (in millions of dollars), the computed conditional scenario mean and variance parameters, and required calculations are:

Bldg k	C_{ok}	$m_{R\|aPk}$	$\sigma^2_{R\|aPk}$	$m_k = C_{0k}\, m_{R\|aPk}$	$\sigma^2_k = C^2_{0k}\, \sigma^2_{R\|aPk}$
1	6.4	34.3%	583	220	23880
2	15.4	18.2%	225	280	53361
3	5.6	12.6%	160	71	5018
	------			-------	---------
	C_t = 27.4			571	82259

The total scenario portfolio random loss cost C_K for the K buildings is approximately (by the central limit theorem) a Normal random variable with parameters,

$$m_K = \sum m_k = 571$$

$$\sigma^2_K = \sum \sigma^2_k = 82259$$

$$\sigma_K = 287$$

Using the 90% upper bound value of the standardized normal variate =1.28, the 90% upper bound for C_K is,

$$C_{90} = m_K + 1.28\sigma_K = 571 + 1.28(287) = 938$$

In terms of damage loss ratios,

Portfolio SEL = $m_K / C_t = 571/(27.4) = 20.8 = 21\%$

Portfolio SUL = $C_{90} / C_t = 938/(27.4) = 34.2 = 34\%$

POSSIBLE APPLICATION OF DAMAGE LOSS ESTIMATES TO PERFORMANCE-BASED DESIGN

Because building design clients may relate more directly to the cost of damage repair and restoration for their new building in the event of a scenario earthquake rather than to a performance expectation such as "Life Safe" or "Moderate Damage" and the corresponding amounts of deformation, yielding, and cracking, the SUL values corresponding to the performance levels could be provided. For example, using the SEAOC Vision 2000 Performance ratings:

Rating	Performance Expectation	Anticipated Damage	SUL Range
9 to 10	Fully Operational	Negligible	0 to 5%
7 to 8	Operational	Light	5% to 25%
5 to 6	Life Safe	Moderate	25% to 50%
3 to 4	Near Collapse	Severe	50% to 75%
1 to 2	Partial to Total Collapse	Complete	75% to 100%

The related damage probability distribution function with its related sigma σ and SUL could provide the much needed description of the uncertainties and variabilities inherent in performance prediction that can be understood by both the designer and the building owner.

Los Angeles Tall Buildings Structural Design Council Conference
Los Angels, California, May 7, 1999

THE ASTM STANDARD GUIDE FOR ESTIMATION OF BUILDING DAMAGEABILITY IN EARTHQUAKES

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Abstract

ASTM has developed a Standard Guide for the Estimation of Building Damageability in Earthquakes. It is intended for use on a voluntary basis by parties who wish to estimate damageability from earthquakes to real estate. The Guide was developed by a group of providers, users and public members. Procedures are given for conducting an estimate of earthquake loss study considering the user's due-diligence requirements and risk tolerance level. The Guide provides requirements for five different types of earthquake loss studies intended: building stability, site stability, building damageability, contents damageability, and business interruption. Four levels of investigation from 0 to 3, are given to serve the particular varied purposes for which the results of a given type of study are desired: Level 0 is termed a screening level of investigation, while Level 3 is the most exhaustive investigation. Definitions are provided for terms commonly used in damageability analysis. These include: Scenario Loss (SL) and Probable Loss (PL) as replacements for the term Probable Maximum Loss; the latter is no longer recommended for use. SL is the loss with a specified probability of exceedance determined for a specified earthquake or ground motion. PL is a loss with a specified probability of exceedance in a given time period from all possible earthquake occurrences, weighted by their probability of occurrence. Contents Damageability and Business Interruption assessments are recommended to be based on a SL assessment. The Guide provides reporting as well as other administrative and qualifications requirements. The Guide has an extensive commentary.

Introduction

Lenders, insurers and equity owners in real estate are giving more intense scrutiny to earthquake risk than ever before. The 1989 Loma Prieta earthquake, which caused more than $6 billion in damage, accelerated an already established trend for improved loss estimation in California; the 1994 Northridge event with over $20 billion in damage has completed the process—loss analysis is now an integral part of the real estate financial decision making process. Financial institutions are in need of specific and consistent measures of future damage loss for this decision process. The long used notion of "probable maximum loss" (PML) has become, for many, a catch phrase to encapsulate all earthquake issues into a simple number that can be used to qualify or disqualify a potential commitment. Unfortunately, there has previously been no industry or professional consensus on what PML means or how it is computed.

ASTM has developed a *Standard Guide for the Estimation of Building Damageability in Earthquakes* that is now nearing completion of balloting. The purpose of an estimate of earthquake loss study is to provide the user with an adequate measure of possible earthquake losses than may be expected during the anticipated term for holding either the mortgage or the deed. This paper reviews the Guide. It uses and interprets text from the Guide to give the reader an understanding of its contents and intent.

This Guide presents specific approaches, which the real estate and technical communities can use to characterize the earthquake vulnerability of buildings. It recommends use of new terms, Probable Loss (PL) and Scenario Loss (SL) in the future to make specific the type of damageability measures used. The term Probable Maximum Loss (PML) is not encouraged for future use.

The financial criteria used to evaluate a property should address three distinct issues:

- *Life-safety threat posed by the building or portions of the building;*
- *Likelihood of failure of the site, for example fault ruptures passing through foundations, significant settlement, or liquefaction of the supporting soils; and/or secondary hazards affecting the site, for example flood waves from ruptured dams, tsunamis and seiches; and,*
- *Financial measures of possible damage due to effects of earthquakes on the building(s) directly or indirectly related to physical damage.*

The first issue is simply one of characterizing circumstances where the possibility of life endangering damage or failure of the building is sufficiently high that it poses an unacceptable liability to the owner and his debt holders. Such cases generally entail local or global failure of the structural system that supports gravity loads. This is addressed by the Building Stability assessment below. The second is to identify circumstances where there are preventive measures in building design and construction that can be or have been taken to avoid a major loss when there is a possibility of site failure or inundation. This is addressed by the Site Stability assessment below. The third is to assess the possible damage and loss of use that characterize the financial risks (for example, upper bound losses, expected annualized loss, maximum insurance loss) from earthquakes. This is addressed by the Damageability, Contents and Business Interruption assessments below.

ASTM Task Group E06.25.55

ASTM established the Task Group in 1996. Gary Varum and Charles Thiel were asked to co-chair the Group, hereafter called the Committee. The membership of the Committee was selected from interested individuals from the provider community, users and public. The members are:

- Richard Belyea, Home Savings of America[1]
- Judd Bernstein, Chase Manhattan Bark
- John Brazeau, GE Capital Commercial Real Estate
- Carl DeStefanis, IVI International
- John Egan, Geomatrix Consultants
- Jeff Haskell, Trowbridge Kieselhorst and Company, Mortgage Bankers
- Tony Hitchings, EQE International[2]
- Marshall Lew, Law/Crandall
- James Lord, LFZ Associates
- Barry Schindler, John A. Martin and Associates
- Kevin Schmitt, Cigna Investment Management
- Charles C. Thiel Jr., Telesis Engineers
- Steve Toth, Teachers Insurance and Annuity Association
- Gary S. Varum, Telesis Engineers[3]
- Ted Zsutty, Consulting Engineer

The Committee is a Task Group of ASTM Sub-Committee E6.25, *Whole Buildings and Facilities*, chaired by Wayne Meyer. Gerald Davis serves as the chairman of the Committee E6, *Performance of Buildings*. All of the members participated in the development of the Guide. The materials reported herein are the product of the whole committee's effort, not just those of the authors.

The Committee developed the Standard Guide over a period of 18 months. As a part of this process, over 300 earthquake loss reports prepared by a broad range of providers for a broad range of users were reviewed. These provided a basis for understanding the breadth of both needs and common commercial practices. The Guide was developed to respond to the different needs of users and not to restrict performers, except for technical issues in building assessment and reporting. The draft Guide has been completed and approved by the Task Group and Sub-Committee E6.25. In both cases all the ballots were affirmative; there were neither negative nor acceptance with reservation ballots cast. The ballot of Committee E6 was completed before presentation but after completion of this manuscript.

ASTM has a rich tradition in the construction industry of developing voluntary standards for a wide range of building materials, products, professional practices, and building evaluation. Task Group E50.02.07, *Property Condition Assessment*, chaired by Carl DeStefanis and Barbara Salk, is in the final stages of preparing a Standard Guide on property condition assessment reports. An earlier Standard Guide on environmental assessment of buildings and building sites has been widely used.

Purpose

The *Standard Guide for the Estimation of Building Damageability in Earthquakes* is intended for use on a voluntary basis by parties who wish to estimate damageability from earthquakes to real estate. Procedures are given for conducting an estimate of earthquake loss study for a specific user considering the user's due-diligence re-

[1] Now Washington Mutual Bank

[2] Now with Bay Area Rapid Transit District.

[3] Formerly with Interactive Resources, Inc.

quirements and risk tolerance level. The objectives of the Guide are to:

- synthesize and document good commercial, customary practice for the estimation of probable loss to buildings from earthquakes for real estate improvements;
- facilitate standardized estimation of probable loss to buildings from earthquakes;
- ensure that the standard of site observations, document review and research is appropriate, practical, sufficient, and reasonable for such an estimation;
- establish what can reasonably be expected of and delivered by a loss estimator in conducting an estimation of probable loss to buildings from earthquakes;
- establish an industry standard for appropriate observations and analysis in an effort to guide legal interpretation of the standard of care to be exercised for the conducting of an estimation of probable loss to buildings from earthquakes, and,
- establish the requirement that a loss estimator communicates his observations, opinions, and conclusions in a manner meaningful to the user and not misleading either by content or by omission.

The Guide provides requirements for the performance of five different types of earthquake loss studies intended to serve different financial and management needs of the user: building stability, site stability, building damageability, contents damageability, business interruption. Four levels of investigation, from 0 to 3, are given to serve the particular varied purposes and degrees of accuracy for which the results are desired: Level 0 is termed a screening level of investigation, while Level 3 is the most exhaustive investigation.

The Guide is organized in 13 sections with an associated commentary. It will be available from ASTM as soon as it is approved. The Appendix provides a Table of Contents of the Guide.

Principles

The following principles are an integral part of the Guide and are intended to be referred to in resolving any ambiguity or exercising such discretion as is accorded the user or the loss estimator in estimating loss to buildings from earthquakes. It is also to be used in judging whether a user or loss estimator has conducted appropriate inquiry or has otherwise conducted an appropriate estimation of the loss to buildings from earthquakes.

- *Uncertainty not eliminated.* No estimate of earthquake loss from earthquakes to buildings can wholly eliminate uncertainty regarding damage resulting from actual earthquakes. The successive levels of study of this Guide are intended to reduce, but not to eliminate, uncertainty regarding the estimation of damage resulting from actual earthquakes in connection with a building, or a group of buildings, and the Guide recognizes the reasonable limits of time and cost, related to a selected level of study.
- *Not exhaustive.* There is a point at which the cost of information obtained or the time required to gather it outweighs the usefulness of the information and, in fact, may be a detriment to the orderly completion of transactions. One of the purposes of this Guide is to strike a balance between the competing goals of limiting the costs and time demands inherent in performing an estimate of earthquake loss to building(s) and the reduction of uncertainty about unknown conditions that may result from the acquisition of additional information.
- *Level of study.* Not every property will warrant the same level of earthquake loss assessment. Consistent with good commercial or customary practice, the appropriate level of estimate of earthquake loss to buildings from earthquakes will be guided by the type of buildings subject to assessment, the resources and time available, the expertise and risk tolerance of the user, and the information developed in the course of the inquiry.

Significance and Use

The Guide is intended for use on a voluntary basis by parties who wish to estimate damageability from earthquakes to real estate. The Guide outlines procedures for conducting an estimate of earthquake loss study for a specific user considering the user's due-diligence requirements and risk tolerance level. The specific purpose of the estimate of earthquake loss study is to provide the user with an adequate measure of possible earthquake losses that may be expected during the anticipated term for holding either the mortgage or the deed.

The Guide provides that a user only can rely on the estimate of earthquake loss for the specific purpose that such study was commissioned and that point in time that the loss estimator's observations were conducted. It is recognized that a loss estimator's opinions and observations are often impacted or contingent on information, or the lack thereof, that was readily available to the loss estimator at the time of conducting an investigation. For instance, a loss estimator's observations may have been impacted by building occupancy load, or the availability of property management to provide information, including, but not limited to original construction documents, at the time of the estimate of earthquake loss study.

The Guide is site-specific in that it relates to estimation of earthquake loss to building(s) located at a specific site.

While a study prepared in accordance with this Guide may reference or state that it complies with this Guide provided that it identifies any extraordinary exceptions to same, no implication is intended that a person must use this Guide in order to be deemed to have conducted an inquiry in a commercially prudent or reasonable manner in any particular transaction. Nevertheless, this Guide is intended to reflect a commercially prudent and reasonable inquiry.

Terminology

The Guide provides definitions of a wide range of words and terms used in damageability analysis, 68 in total. Among these are:

Maximum Capable Earthquake: The earthquake that can occur within the region that produces the largest average ground motion at the site of interest. All faults and features for which there is reasonable professional basis within engineering seismology and geology to assign a maximum earthquake to the fault or feature are to be assessed. The ground motion at the site is determined by application of an appropriate attenuation relationship determined from those available that best represent the specific seismic and tectonic setting of the immediate region. This is sometimes termed the maximum credible earthquake.

Probable Loss (PL): The earthquake loss to the building(s), not including contents or equipment, that has a specified probability of being exceeded in a given time period from earthquake shaking. PL values are expressed as a percentage of building replacement construction cost (current). The PL estimates are to include, in a statistically consistent manner, the probability distribution functions of the possible ground motion levels at the site and the probability distribution function for the building's damageability due to each possible level of ground motion. Ground motions are determined from a site-specific evaluation of the seismic exposure and are represented by a probability distribution function. Building damageability and seismic performance depends on the level of study and shall recognize the dynamic response characteristics of the building(s). The building damageability distribution is determined from past performance data, expert estimates of performance, and/or detailed analysis at specific ground motion levels. PL values are given either as a value(s) with a specified return period(s), PL_N, or as the value that has specified probability of exceedance (from 1% to 50%) in a given time period (1 to 50 years). The most common return periods used are 72, 190 and 475 years, that correspond to a 50% probability of exceedance in 50 years, and a 10% probability of exceedance in 20 and 50 years, respectively. The most commonly used probability of exceedance is 10%, and the most common time periods are 20 and 50 years.

<u>PL Values for Groups of Buildings</u> must be determined in a statistically consistent manner that fully recognizes the probabilistic damage distributions for the individual buildings and the possible correlations between the buildings' damageability. Where the buildings in a group are located at nearby sites with common expected ground motions, the ground motions for each building's damageability determination may be fully correlated such that the damageability distributions are based on the same ground motions. Where the sites are significantly separated, or the buildings' site soil conditions are different, then the damageability determination must consider the degree of correlation in ground motions for the separate sites and/or site conditions as part of the PL determination.

PL_N Abbreviation for probable loss with a return period of N years.

Return Period: The return period of a particular value of a random variable is the inverse of the annual probability that the value is equaled or exceeded. It is **not** the time period between occurrences of the value, but is the long term average of the random times between occurrences. Often return period is interpreted to mean that if the value was realized in 1994, and the return period is 100 years, then the next occurrence will be in 2094; this is completely wrong. For example, earthquake occurrences are usually considered as Poisson distributed random variables, that is, ones where the probability is near constant from year to year, and the probability of an occurrence this year is independent of what happened last year. For a Poisson random variable, the probability that the value will be equaled or exceeded in its return period term is 63%.

Scenario Loss (SL): The earthquake loss to the building(s), not including contents or equipment, resulting from a specified scenario event on specific faults affecting the building, or specified ground motions. The specific damageability and ground motion characterizations are to be specified. SL values are expressed as a percentage of building construction cost (current replacement cost). The ground motion used for determination of the SL can be specified in a variety of ways, which must be clearly stated in the report, including:

a. ground motion in the maximum capable earthquake (MCE) for the building site;
b. ground motion specified as the design ground motion in the applicable building code for the building site;
c. ground motion from specific earthquake(s) likely to affect the building site with a specified probability of exceedance, using an accepted attenuation relationship for the seismic setting and with the uncertainty of the estimate clearly indicated; such maximum scenario events are prescribed for various faults based on paleoseismic evidence;
d. ground motion with a specified return period as determined from a probabilistic ground motion seismic hazard analysis;
e. a selected maximum Modified Mercalli Intensity (MMI) for the site determined from published maximum value maps; or
f. the Modified Mercalli Intensity for the site as estimated from peak ground acceleration values.

The probability of the SL value being exceeded in the scenario must be stated in the report. The term SEL is used when the reported value is the expected value, while SUL is used when the probability of exceedance is 10%. Other values may be specified by the user.

<u>SL Values for Groups of Buildings</u> must be determined in a statistically consistent manner that fully recognizes the probabilistic damage distributions for the individual buildings and the possible correlations between the buildings' damageability. Where the buildings in a group are located at nearby sites with common expected ground motions, the ground motions for each building's damageability determination may be fully correlated such that the damageability distributions are based on the same ground motions. Where the sites are significantly separated, or the buildings' site soil conditions are different, then the damageability determination must consider the degree of correlation in ground motions for the separate sites and/or site conditions as part of the PL determination.

Scenario Expected Loss (SEL): The expected or mean value loss in the specified ground motion of the scenario selected. Since the damage probability distribution is usually skewed, rather than symmetrical, it should not be inferred that the probability of exceeding the SEL is 50%; it can be higher or lower than this amount.

Scenario Upper Loss (SUL) The scenario loss that has a 10% percent probability of exceedance due to the specified ground motion of the scenario considered.

Uncertainty Tolerance Level: The amount of uncertainty in financial exposure that can be incurred by a user resulting from the cost to remedy earthquake damage associated with potentially hazardous conditions not identified by an estimate of probable loss. This is influenced by such factors as initial acquisition cost or equity contribution, mortgage underwriting considerations, specific terms of the equity position, projected term of the hold, etc.

Use of the term PML is discouraged: The Committee examined the use of the term Probable Maximum Loss (PML). It is widely used to characterize building damageability in earthquakes. It has had a number of significantly different explicit and implicit definitions as used by many individuals and organizations, and in many reports remains undefined. It is recommended that the term not be used in the future. The term may be used for non-technical purposes, but not as a term to specify a precise value of analysis procedure. The terms probable loss (PL) and scenario loss (SL), whose definitions are precise, should be used to characterize the earthquake damageability of buildings and groups of buildings in the future.

PL and SL values for the same building(s) are fundamentally different measures of damageability. SL considers a building's damageability due to a specific scenario earthquake ground motion. PL values simultaneously consider the uncertainties in both ground motion due to all-possible earthquakes, and the building's damageability in these ground motions in a statistically consistent manner.

When a damageability analysis is completed using a specific ground motion, say a 475-year return period ground motion or a maximum MMI intensity, then the analysis is a SL result, not a PL result.

PL and SL values are intended to serve different risk management or fiduciary purposes and are not strictly comparable. PL values are expected to be most useful when the financial decisions are to be made for the individual building or group of buildings under consideration. SL values (with varying definitions of the specific scenario(s) considered) are expected to be most useful when it is desired to compare the expected performance of a particular building with the performance of other buildings in a portfolio. Thiel, in series of papers presented to the *Tall Buildings Structural Design Council* has explored the differences in results between different PL and SL analysis approaches using the same site seismicity and building damageability, [*Thiel, 1997, Thiel and Hagen, 1997, Thiel and Rosidi, 1998, Thiel, 1999*]. Great care needs to be exercised in choosing between PL and SL to assure that the needs of the user are well served and consistent with the user's fiduciary responsibilities.

Types and levels of investigation

The Guide provides requirements for the performance of five different types of earthquake loss studies intended to serve different financial and management needs of the user.

- *Building Stability:* Assessment of the likelihood that the building will remain stable in earthquakes.
- *Site Stability:* Assessment of the likelihood that the site will remain stable in earthquakes, that is, not be subject to failure through faulting, liquefaction, landsliding or other site response that can threaten the building's stability or cause damage.
- *Damageability:* Assessment of the damageability of the building to earthquake ground motions and the degree of damage expectable over time. In performing the damageability assessment either a probable loss or a scenario loss assessment, or both, can be completed.
- *Contents Damageability:* Assessment of the damageability of the building's contents to earthquake ground motions.
- *Business Interruption:* Assessment of the implications for continued use or partial use of the building for its intended purpose due to earthquake damage to the building, contents, equipment.

These are described in the following sections, with specific details given only for the damageability assessment. The Appendix gives a Table of contents of the Guide. Following is a detailed discussion of the building damageability assessment.

The Committee recognized that the needs of users might require different intensities of evaluation, depending on purposes. The estimate of earthquake loss may consider any level of investigation from 0 to 3 that serves the particular purposes for which the results are desired. Level 0 is termed a screening level of investigation and requires the least effort and yields the least confidence, while Level 3 is the most exhaustive investigation yielding the highest confidence.

An earthquake damageability assessment may be performed for an individual building or a group of buildings. When an earthquake damageability assessment is performed under this Guide, it should at the minimum always include an assessment of building stability (BS), and site stability (SS). It may also include a damageability, contents damageability and/or business interruption assessment.

TABLE 1. Recommended minimum levels of inquiry based on seismic zone of the property and the acceptable level of uncertainty of the user. The seismic zones are those of the 1994 edition of the Uniform Building Code. BS refers to the Building Stability assessment, SS to the Site Stability assessment, and D to the Damageability Assessment; the number following the abbreviation is the level of investigation; i.e., BS0 is a Building Stability Level 0 assessment.

Acceptable	Seismic zone per UBC-94		
uncertainty level	Zones 0, 1, 2A, 2B	Zone 3	Zone 4
Very low	BS0, SS0, D1	BS1, SS1, D1	BS2, SS2, D2
Low	NA	BS1, SS1, D1	BS1, SS2, D2
Moderate	NA	BS0, SS0, D0	BS1, SS1, D1
High	NA	NA	BS0, SS0, D0

For buildings in UBC seismic zones 3 and 4, the user may select any level for these investigations (0 through 3), but must perform a Building Stability and Site Stability assessment to meet the requirements of the Guide.

Because of its minimal effort the uncertainty in the result of a Level 0 study is very high, while the uncertainty in the result of a Level 3 effort is considerably less uncertain, but still not certain, since earthquake occurrences and structural response have residual uncertainties that cannot be eliminated in the current state of the art or knowledge. Generally, the quality of the results, and their associated reliability, will be largely determined by the experience and quality of effort of the loss estimator, not just the level. The argument can be made that the lower the level of investigation the more important is the experience, expertise, and knowledge of the performer.

The selection of the level of the investigation performed should be guided by the level of uncertainty in the result that is acceptable to the user. The matrix of Table 1 is offered as a guide to selection of the levels of investigation to match the acceptable level of uncertainty. The zone references are from the map of seismic zones as it appears in the 1994 edition of the Uniform Building Code. The acceptance levels are not defined, but are given to reflect the progression of investigation levels with changes in acceptable uncertainty.

The damageability portion of the assessment may report a Probable Loss (PL), with specified probability of exceedance and time period or return period for exceedance, and/or a Scenario Loss (SL), where the specific scenario and the probability of exceedance are given, usually as the expected value or mean (SEL) or the 10% probability of exceedance value, the so-called Scenario Upper Loss (SUL).

The use of interactive computer programs developed specifically to assess the damageability of buildings and requiring only *general* information about the building and site should be limited to screening level (Level 0) damageability assessments. Investigations at higher levels require the professional skills of an experienced loss estimator to determine conditions and weigh influences.

When a new investigation is performed that is consistent with this Guide and has a higher level than a prior investigation, then the new investigation supersedes the former one.

The following subsections review the contents of the Standard Guide for different types of vulnerability assessments. First, since they all require a characterization of the earthquake environment, the ground motion hazard assessment procedure is reviewed.

Probabilistic ground motion hazard assessment (G)

A characterization of ground shaking hazard is required for PL evaluations of damageability, and can have applications in some SL studies, Building Stability, and/or Site Stability assessments. The objective of ground motion assessment is to characterize the earthquake ground motions at the site having a specified probability of being exceeded in a given time period for the assessment. The ground motion level of inquiry should always be at least as high as the level of the inquiry its results are used in, except for Level 3, which may use a Level 2 ground motion assessment.

Building stability assessment (BS)

The purpose of the building stability assessment is to determine if the building is stable under earthquake loadings. A building is deemed stable if it is able to maintain the vertical load-carrying capacity of its structural system under the inelastic deformations due to the earthquake ground motion prescribed for the structure and site by the current edition of the Uniform Building Code. A group of buildings is deemed stable if each of the buildings in the group is deemed stable. There are four levels of inquiry in Building Stability Assessment: Level BS0, Level BS1, Level BS2, and Level BS3. The level of the assessment shall be the same as that used for the damageability assessment, if such is performed.

Site stability assessment (SS)

The objective of the site stability assessment is to determine if the building is located on a site that may be subjected to site instability due to earthquake-induced hazards that induce surface fault rupture, liquefaction, seismic settlement, land sliding, tsunami, seiche, etc. There are four levels of inquiry in Site stability Assessment of real estate: Level SS0, Level SS1, Level SS2, and Level SS3. Three basic types of earthquake impacts are considered:

- *Active earthquake fault zone*: If the building is located within a zone determined for a generally recognized active earthquake fault as identified by any Federal, State, or Local Governmental Agency, or other authoritative source.
- *Potentially active earthquake fault zone:* If the building is located within a zone determined for a generally recognized potentially active earthquake fault as identified by any Federal, State, or Local Governmental Agency or other authoritative source.
- *Other significant earthquake hazards:* Determine if the building is located such that its seismic exposure to other earthquake-related hazards is deemed significant, including, but not be limited to, liquefaction, land sliding, tsunami, and seiche.

Building damageability assessment (D)

The objective of the damageability assessment is to characterize the building(s) expected seismic losses by performing a sufficiently detailed engineering analysis and evaluation of the damageability characteristics of the buildings at given levels of earthquake ground motions. The analysis includes architectural, non-structural, and mechanical components of the building other than the building's primary gravity and lateral load resisting systems and foundations that would not be classified as contents and furnishings. Damageability may be expressed as the probable loss (PL) or the scenario loss (SL). The results may be reported as either the expected or mean of the value (SEL) or the value with a given upper confidence, say 10% (SUL).

There are four levels of inquiry in damageability assessment: Level D0, Level D1, Level D2, and Level D3.

The damageability analysis for all levels of investigation shall consider all earthquakes that can potentially impact the site that have magnitudes greater than 5.0, and that have PGA values greater than 0.05g at the site, except where other magnitude and ground motion values are justified by characteristics of the specific building(s) and conditions.

Level D0 inquiry (Screening Level) shall consist of, but not be limited to, the following:

- Determine the general architectural and structural characteristics of the building and its seismic resistance systems.
- Evaluate the building's stability by determining the building code to which it was designed, the type, condition and age of the structure, and its gross characteristics (for example, configuration, continuity of load paths, compatibility of system deformation characteristics, redundancy of load paths, strength of elements and systems, toughness of elements and connections, and physical condition).
- Determine the PL or SL values from tables or an equivalent procedure for a basic building type representative of the building, possibly completed with the aid of an interactive computer program. Adjustments should be made to accommodate deviations of the specific building's characteristics from that of the standard or tabulated building type.
- The impacts on damageability of possible site stability are not included in the assessment.
- This level analysis has an inherently high uncertainty in result.

Level D1 inquiry shall consist of, but not be limited to, the following:

- Visit the building to determine its condition, structural characteristics, and quality of construction.
- Cursory review of the original construction documents, if available.
- Evaluate the seismic loads and capacities of selected systems and elements and connections.
- Identify potential flaws in the lateral load-resisting systems that contribute to the building's damageability without performing a detailed investigation. Non-structural conditions are identified that may contribute to the damageability of the building.
- Estimate ground motion characteristics by a Level G1 or higher inquiry.
- Determine PL or SL values from tables or equivalent procedures for a basic building type, possibly completed with the aid of an interactive computer program, but not solely on such a basis.
- The impacts on damageability of possible site failure are not included in the assessment.
- This analysis has an inherent moderate uncertainty in its result.

Level D2 inquiry shall consist of, but not be limited to, the following: In addition to the requirements of the Level D1, investigation, evaluate the condition of the building, and quality of construction, including significant modifications since original construction.

- Examine the original construction documents, or conditions deduced from observation if they are not available, and perform selected calculations to verify demand/capacity characteristics of the building's expected seismic response.
- Determine the seismic response characteristics of the building by assessing those issues likely to dominate its performance, including configuration, continuity of load paths, compatibility of system deformation characteristics, redundancy of load paths, strength of elements and systems, toughness of elements and connections, and physical condition.
- Estimate damage ratio due to representation of each of all possible levels of ground motion at the site, and compute the PL or SL values for corresponding probabilities of occurrence.
- PL or SL values shall not be determined from tables or equivalent procedures for a basic building type, nor from use of an interactive computer program.
- Consider the impacts on damageability to the building(s) due to possible site failure.

This analysis has moderately low uncertainty.

Level D3 inquiry shall consist, of but not be limited to, the following:

- In addition to the requirements of the Level D2 investigation, perform a full engineering analysis of the building's expected performance, for example, by modeling to determine story accelerations and inter-story displacements, including possibly both three-dimensional and non-linear methods to estimate the expected damage.
- Where appropriate, consider the soil-foundation-structure interaction.
- The user should consider implementing peer review to assure acceptable technical performance.
- The building's seismic performance is correctly characterized at the minimum uncertainty level.

Contents damageability assessment (C)

The objective of the damageability of contents assessment is to perform an analysis of the earthquake performance of furniture, fixtures, equipment and contents within the building that are not part of the permanent structure, non-structural components, architectural finishes, or equipment. Analyses are recommended to be performed only on a scenario loss basis, with the specific scenario fully described. Performance of the contents assessment requires that the same level damageability assessment be completed for the same specified scenario, so that there is a common basis of understanding building and contents damageability. There are four levels of inquiry in contents damageability assessment: Level C0, Level C1, Level C2, and Level C3.

Business Interruption assessment (BI)

The objective of the business interruption assessment is to perform an analysis of the site, building, equipment, inventory systems, infrastructure, interdependent businesses, and all other relevant parameters to determine one or more of the following:

- If the facility will suffer business interruption from on-site effects, such as direct damage to buildings and equipment, or loss of critical supplies.
- If the facility will suffer business interruption from off-site earthquake damage to the infrastructure, such as transit systems, power and telecommunications utilities, and water supply and wastewater and treatment facilities.
- If the facility will suffer business interruption from earthquake damage to interdependent facilities (not necessarily owned or operated by the owner).

In addition to its own unique lines of inquiry, the evaluation of business interruption will draw upon other related aspects of the probable loss or scenario loss analyses, including building damageability, site failure, building stability, and secondary impact. A business interruption assessment should not be performed unless a damageability assessment has been performed.

Analyses are recommended to be performed only on a scenario loss basis, with the specific scenario fully described. Performance of the business interruption assessment requires that the same level damageability and contents assessments be completed for the same specified scenario, so that there is a common basis of understanding earthquake impacts on the building(s).

There are four levels of inquiry in Business Interruption Assessment: Level B0, Level B1, Level B2, and Level B3. Damageability evaluations that include level B2 or B3 evaluations should clearly state what effects are included and excluded in the evaluation process.

Qualifications

The estimation of earthquake losses to building(s) may be conducted by either an agent or employee of the user or wholly by a contractor. No practical standard can be designed to eliminate the role of judgment and the value and need for experience by the party performing the inquiry. The user should retain to conduct estimate of earthquake loss studies only those who have the requisite knowledge and experience to perform such studies in a reliable manner for the level of investigation specified. There are two main qualifications that bear on the ability of the loss estimator to reliably give professional opinions on the earthquake hazard posed by a site and the damageability of a building:

- Knowledge of the current state of knowledge and practice of the underlying professional and scientific disciplines that bear on the particular practice;
- Experience in application of the specific professional skills required for seismic evaluation to the specific buildings and conditions of the subject site or building;

The user shall evaluate the qualifications of the performer (loss estimator) before the performer is retained to complete a study. The following issues are ones for which the user should seek information on qualifications:

The skills and experience of the individuals performing the assessment must be given by task assignment. Evidence should be provided of the knowledge of the technical, analytical and mathematical concepts required for the performance of the level of inquiry undertaken.

- Professional registration
- Design experience
- Research and professional practice development experience
- Loss estimation experience
- Earthquake damage investigation experience

The following guidance is given on setting of acceptable qualifications. It should be noted that the qualifications for Building Stability and Damageability Assessments are similar, but different from those for Ground Motion, Site Stability, Contents damageability, and Business Interruption. It is seldom that one individual will have sufficient expertise and experience to perform all of these types of investigations for Level 2 or Level 3 inquiries.

Qualifications should be determined of those individuals performing the majority of the work, as well as the principal-in-charge who reviews and possibly signs the work. The fewer the number of individuals involved, the more important is the experience and qualifications of the person(s) doing the work and making the professional judgments.

Level 0 investigations have no specific requirements. However, it is advisable that the individual performing the assessment be a registered professional and that they declare in their report their competence in the related area of the assessment.

Level 1 investigations require the highest general experience in professional practice and evaluation, because usually there is little oversight or review of the work product and conclusions. Professional experience in the specific professional area of more than 20 years and in performing loss evaluations of more than 5 years is appropriate. Specific experience in the characteristics of the particular site or structural system is not required, but useful. Experience in field investigation of earthquake response in four or more damaging level earthquakes is desirable.

Level 2 investigations require substantial understanding and experience in the specific technical issues that pertain to the particular type of site or structure. Professional experience in the specific professional area of more than 10 years and in performing loss evaluations of more than 3 years is appropriate. Specific experience in the characteristics of the particular site or structural system is not required, but useful. Experience in field investigation of earthquake response in two or more damaging level earthquakes is desirable.

Level 3 investigations require demonstrated, substantial understanding and experience in the specific technical issues for the specific type of site or structure.

Evaluation and report preparation

The Guide addresses what the report of the assessment should include. The report of findings arrived at in the process of conducting an earthquake loss estimation assessment should be presented in a written document following the format provided by the user.

The report should include documentation (for example, references, key exhibits, and photographs) to support the analysis, opinions, and conclusions found in the report. All sources, including those that revealed no findings, should be sufficiently documented to facilitate reconstruction of the research at a later date.

The report shall present the technical basis for the specific conclusions on damageability reached and provide full technical details of the methods and procedures used to determine the damageability values in sufficient detail that a peer reviewer can validate the appropriateness of the technical decisions and procedures used.

It is important that any building for which an estimation of earthquake damageability is made be reviewed for all its characteristics that can impact its seismic performance, including at a minimum, the following seven:

- *Compatibility:* All building elements and their material properties should be able to sustain the maximum deformation without destructive interference. For example, stiff and brittle in-fill wall elements should not interfere with the deformation of the more flexible framing elements and columns.
- *Condition:* How the building has been maintained. Is there evidence of deterioration, decay, damage, settlement, or unauthorized modifications to the structure?
- *Configuration:* Are there irregularities in the building elevation or plan that could lead to concentration of excessive deformation or stress, such as soft or weak stories, or torsion due to eccentric location of resisting elements. These conditions may be caused by the non-compatible installation of rigid non-structural elements such as panels or in-fill walls.
- *Continuity:* There must be a continuous load path of structural elements and connections to carry gravity loads to the foundation, and to carry seismic inertial loads from the horizontal diaphragms to the lateral load-resisting shear elements, for example, shear walls, braced frames, and/or moment frames, etc., and then to an adequate foundation.
- *Redundancy:* The presence of a series of resisting elements or an additional backup system can provide extra assurance against collapse where the possible failure of a single element can occur due to design error, condition or construction weakness; the load initially taken by the failed element can be redistributed to the other elements in the lateral load-resisting system.
- *Strength:* The existing lateral load-resisting capacity should be high enough to prevent sudden brittle failure or excessive inelastic yield distortion.
- *Toughness:* Specific detailing should be provided to prevent excessive strength degradation of structural elements and connections due to the actual cyclic loading that leads to the maximum seismic deformation response.

FEMA-310, when used with caution, provides useful guidance in assessing in evaluation of existing buildings, [FEMA 310].

An Appendix to the report shall present the technical details of the methods used to determine the PL or SL values.

The report shall name the loss estimator(s) involved in preparing the report, indicate their qualifications and expertise in earthquake building performance evaluation, and a description of their experience that is specific to the earthquake performance issues addressed for the particular building(s). This includes not just the principal in charge, but the individuals performing the site visit, if conducted, and all others who participated in the assessment, with an indication of the proportion of the total time they committed to the evaluation.

If a computer software assessment tool was used in the damageability assessment the report shall specify the software used, the vendor, edition, date of the data files utilized, the criteria used, limitations, and the preparer's qualifications.

- *The specific edition of the software and issuance date of any data files used.*
- *The identity and experience of the person providing the input to the program, and the reviewers' names and experience, if appropriate.*
- *Identification of the primary assumptions made that could significantly change the results. Discussion of the primary contributing factors that caused the result to be high (low).*
- *Whether a more detailed analysis recommended and the reasons why.*
- *Any specific limitations or exclusions that limit conclusions presented in the report.*

The report shall have a findings and conclusions section that states the following:

> "I (We) have performed an estimate of probable loss to building(s) from earthquakes in conformance with the scope and limitations of ASTM standard Guide for the Estimation of Building Damageability in Earthquakes [number], edition dated [date], for the property located at [insert address or legal description]. The assessment was performed at ASTM level [specific types of assessment and levels]. {Any exceptions to, or deletions from, this Guide are described in Section [direct to section] of this report. (Include this statement only if there are exceptions.)} The estimated values of damageability and earthquake impacts to the building (group of buildings) are as follows [insert results of analysis with reference to the type of result, for example, SUL, or PL_{190}]."

Where the report is expressly for the purposes of evaluating the suitability of the property to act as the security for a loan, then the report shall contain a limitations language statement:

> "This report is addressed to (client name), such other persons as may be designated by (client name) and their respective successors and assigns."

and any special conditions limiting or allowing its use.

All deletions and deviations from the Guide (if any) shall be listed individually and in detail and all additions should be listed.

The person(s) responsible for the estimate of probable loss to buildings from earthquakes shall sign the report and stamp it as appropriate.

Closing

The ASTM *Standard Guide for the Estimation of Building Damageability in Earthquakes* has set out as its goal the establishment of good and consistent practices for the evaluation of the financial impacts of earthquakes on a building or group of buildings.

The Committee's review of typical reports provided to a variety of users clearly indicated that there is great inconsistency in the use of damage assessment terms, techniques of analysis, and representations of the work completed.

There is little doubt that there is a need for a Guide to provide a consistent basis for users and performers of earthquake loss assessments. The needs appear to be greatest with the users. The Committee discussions with a broad cross section of users indicated that they were often not sure that the criteria and report requirements they were using meet their specific needs. They were particularly concerned that different providers of loss estimation reports appeared to use inconsistent methods and make inconsistent claims for completeness. They was a uniform desire for a standard that provided a basis for consistent practice and use of terms.

The Guide includes recommendations on qualifications of providers for the simple reason that almost all surveyed users wanted it. This point was particularly made by the reviewers, that is, secondary users, of loss reports.

There was a clear distinction between the needs of the users for a specific statement for reliance and the desire of providers to be careful in specifying such a statement. The case was successfully made by the users that standardization of reliance language was vital if the Guide was to yield both technically and administratively useful reports.

The Guide is expected by the Committee to be a living document, with revisions periodically issued as conditions warrant.

References

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Appendix

Table of Contents

ASTM Standard Guide for the Estimation of Building Damageability in Earthquakes

Example 2: Probable Maximum Loss Calculations

Presenter: Dick Fallgren
Myers Houghton & Partners

PML Methods and Procedures

Resource Documents

Steinbrugge (1982)

(damage data)

ATC-13 (1985)

(damage statistics)

NCEER-95-03 (1995)

(fragility curves)

Implementation Procedures

ATC-13

Thiel & Zsutty (1987)

REI / Degenkolb

EQE

Dames & Moore

RMS

Figure 1

PML Procedures (1/4)

Methodology	Number of Consultants
Steinbrugge	3
ATC-13	5
Thiel & Zsutty	4
Proprietary (e.g., IRAS)	3

Figure 2

PML Procedures (2/4)

Calculation Procedure	Number of Consultants
Loss for given GM level	13
Combined probability	2

Figure 3

PML Procedures (3/4)

PML Loss Level	Number of Consultants
Median or mean	6
90th percentile	9

Figure 4

PML Procedures (4/4)

Basic Loss Modifiers	Number of Consultants
Used	11
Not used	4

Figure 5

Ground Motion Hazard Levels (1/3)

Probability of Exceedance	Number of Consultants
50% / 50 years	4
10% / 20 years	4
10% / 50 years	13
2% / 50 years	2

Figure 6

Exceedance Probabilities

Average Return Period (yr) - Tr	Probability of Exceedance (%) - Pex							
	Exposure Period (yr) - n							
	10	20	25	30	50	100	200	250
43	21	37	44	50	69	90	99	100
50	18	33	39	45	63	86	98	99
72	13	24	29	34	50	75	94	97
100	10	18	22	26	39	63	86	92
200	5	10	12	14	22	39	63	71
225	4	9	11	12	20	36	59	67
475	2	4	5	6	10	19	34	41
950	1	2	3	3	5	10	19	23
1900	1	1	1	2	3	5	10	12
2500	0	1	1	1	2	4	8	10

Tr = -n/ln (1-Pex/100) or Pex = (1-exp(-n/Tr))*100

Figure 7

Ground Motion Hazard Levels (2/3)

Ground Motion Parameter	Number of Consultants
MMI	10
PGA	7
Not Reported	3

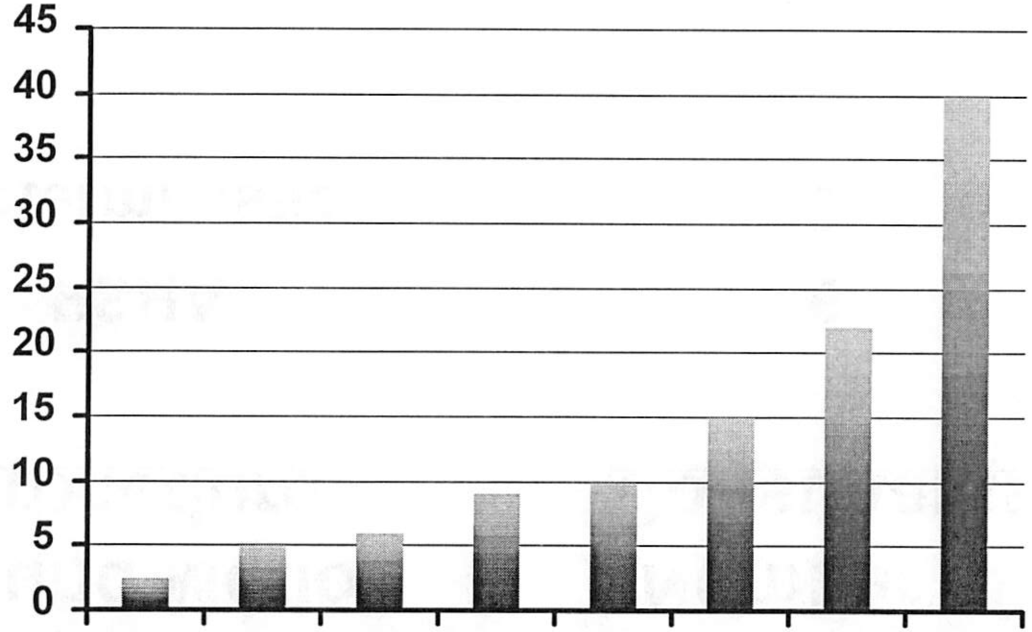
Figure 8

Ground Motion Hazard Levels (3/3)

Ground Motion Procedure	Number of Consultants
PSHA	6
Deterministic	9

Figure 9

Variation in PML by Definition



GM (PGA):	0.2	0.2	0.35	0.35	0.5	0.5	0.7	0.7
GM (P_{ex}):	50 / 50		20 / 50		10 / 50		MCE	
PML Level:	Mean	90^{th}	Mean	90^{th}	Mean	90^{th}	Mean	90^{th}

Figure 10

Example: Building and Site Data

ATC-13 Building Class: Concrete tilt-up, pre-1973
(ATC-13, FC21, standard)

Site Soil Conditions: Holocene alluvium
(97UBC Site Class D)

Ground Water > 10 feet

Ground Shaking Hazard: 10% in 50 years exceedance
(500-year return period)

MMI VIII

Figure 11

ATC Damage Probability Matrix

Facility Class 21

Damage State	Damage Factor Range (%)	Central Damage Factor (%)	Probability of Damage in Percent by MMI and Damage State						
			VI	VII	VIII	IX	X	XI	XII
1 – NONE	0	0	0.3	--	--	--	--	--	--
2 – SLIGHT	0 – 1	0.5	35.2	1.2	--	--	--	--	--
3 – LIGHT	1 – 10	5	64.5	97.7	49.7	8.7	1.2	--	--
4 – MODERATE	10 – 30	20	--	1.1	50.3	85.7	56.6	13.0	0.7
5 – HEAVY	30 – 60	45	--	--	--	5.6	42.0	73.6	40.1
6 – MAJOR	60 – 100	80	--	--	--	--	0.2	13.4	59.2
7 – DESTROYED	100	100	--	--	--	--	--	--	--

Figure 12

ATC-13 Mean Damage Factor

$MDF_I = \Sigma (P_{DSI}) \times (CDF_{DS})$

Summed over all damage states (1-7)

Where:

MDF_I	=	mean damage factor for given MMI
DS	=	damage state
P_{DSI}	=	probability of given damage state for given MMI
CDF_{DS}	=	central damage factor for a given damage state

Figure 13

Fragility Curves - ATC-13 FC 21

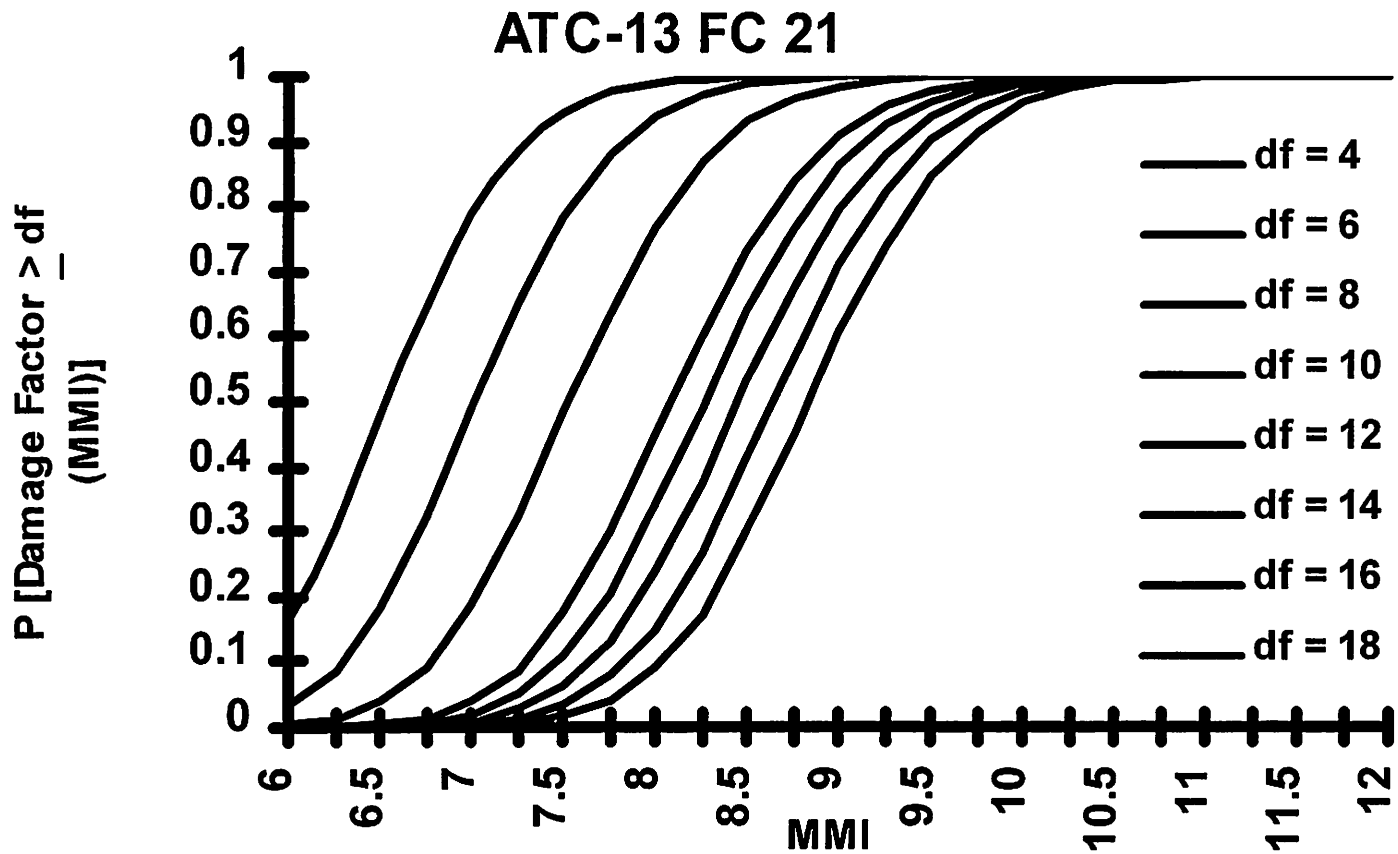


Figure 14

Example: Total Damage Factor

$$MDF(T) = [\, MDF(S)^2 + MDF(FR)^2 + MDF(L)^2 + MDF(LS)^2 + MDF(IN)^2 \,]^{1/2} \leq 100\%$$

where:

MDF(S) = mean damage factor due to ground shaking

MDF(FR) = mean damage factor due to fault rupture

MDF(L) = mean damage factor due to liquefaction

MDF(LS) = mean damage factor due to landslide

MDF(IN) = mean damage factor due to inundation

Figure 15

Example: Ground Motion Hazard

- Peak ground acceleration: (site class B) 0.30g
- Soil amplification factor: 1.2
- Peak ground acceleration: (site class D) 0.36g
- Conversion PGA to MMI:

Table 10.1: MMI to PGA Conversion Table (NIBS, 1997)

MMI	VI	VII	VIII	IX	X	XI	XII
PGA	0.12	0.21	0.36	0.53	0.71	0.86	1.15

- Modified Mercalli Intensity: VIII

Figure 16

Damage Factor Distribution
ATC-13 FC 21, MMI VIII

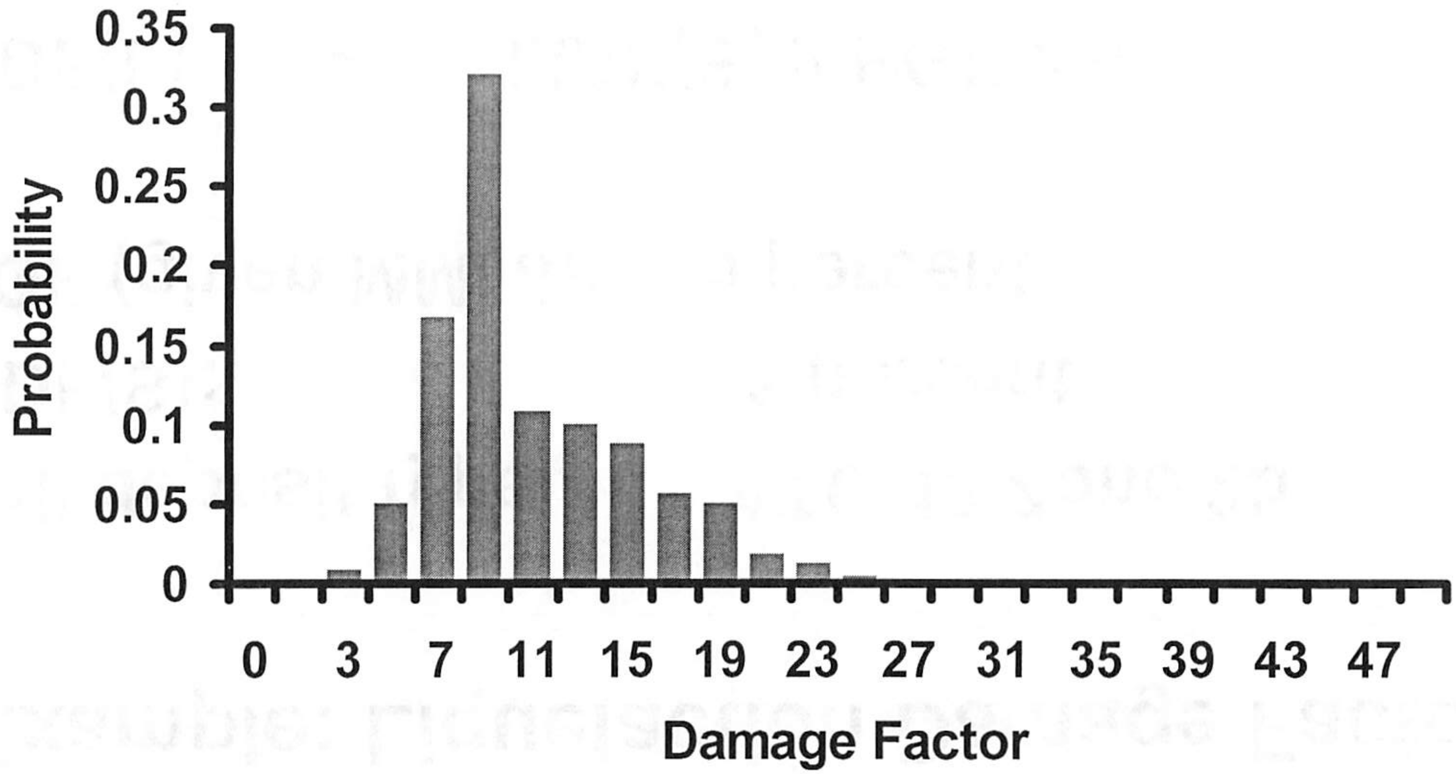


Figure 17

Example: Liquefaction Damage Factor

Soil deposit type:	ATC-13 Zone 2b
MDF(S):	11 percent
PGF (given MMI 8):	5 percent

MDF(L)	=	MDF(S) x PGF x 5
	=	11 x 0.05 x 5
	=	2.75 percent

Figure 18

Example: Building PML

MDF(S):	11.0
MDF(L):	2.75
MDF(T):	11.4
Modifier Factor:	+30 percent

Modified PML:

$$PML = 11.4 \times [\,1 + (+30/100)\,]$$

$$= 15 \text{ percent}$$

Figure 19

Standard PML Definition

"It is critical that a standard definition of PML for individual buildings, as well as a methodology to calculate it, be developed. Individual PMLs, currently developed using a wide range of different techniques, have a tremendous effect on property values."

– **From Earthquake Insurance Basics (EERI April, 1997)**

Figure 20

EXAMPLE: PROBABLE MAXIMUM LOSS CALCULATION

Richard B. Fallgren
Vice President
Myers, Houghton & Partners

Introduction

The methods and procedures available for estimating probable maximum loss (PML) have been discussed by previous seminar speakers (Figure 1). There is no consensus on their use, and individual consultants typically adopt a methodology and interpret and modify it for their application. The purpose of this paper is to share our impressions on which of the methods are most commonly used and describe the approach our structural engineering office has taken.

Survey of Procedures in Use

We are occasionally requested to review, on a confidential basis, PML reports submitted to our clients in connection with property transactions. The scope of the review is generally limited to assisting them in assessing the completeness of the report and interpreting the conclusions with respect to their internal seismic risk policy. These reviews provide an opportunity to draw some conclusions on which of the several available PML procedures appear to be most commonly used by consultants evaluating seismic risk to buildings in California.

Our conclusions are based on about 30 seismic risk assessment reports prepared in the last 3 or 4 years by 15 different consultants. These reports include estimates of earthquake damage loss for over 100 buildings representing a range of sizes and construction types in California. They were prepared by structural engineering and property condition assessment consultants for various lenders and buyers and sellers of commercial and multi-family residential buildings.

A summary of the PML procedures and parameters described by the 15 consultants as their basis for estimating maximum probable loss is shown in Figures 2 through 5. It is apparent that a variety of procedures are favored by the various consultants, although all are based on methodologies derived from the loss data and opinions of Steinbrugge and ATC-13. The definition of PML varies, depending on whether the loss is estimated for a given level of ground motion, or alternatively, the loss value itself is estimated by combined probability. Reporting of the confidence level associated with the PML also varied, with some using a median or mean estimate and others the 90th percentile level. Modifications to the standard loss estimates are made by most consultants, based on building-specific information. While a range of definitions of the PML were used, it should be recognized that the definitions presented may in some cases have been dictated by client requirements, and may not necessarily reflect the consultant's preferred approach.

The ground motion hazard levels used in the reports also vary (Figures 6 through 9). Most consultants based the PML on ground shaking with a 10 percent probability of exceedance in 50 years. Other ground motion levels reported ranged from 50% in 50 years to 2% in 50 years. Ground motions with average return periods ranging from 72 to 2500 years were thus used. When reported, the ground motion was characterized in terms of MMI or PGA (or typically, both). It appeared from the information provided in the reports that most consultants were not using a probabilistic seismic hazard analysis (PSHA) methodology in estimating ground motion.

This brief, limited sample of PML reports gives an indication of the lack of consensus on appropriate procedures and definitions for the PML. This can lead to a wide range of opinion on the PML by different consultants for a given building just due to the procedure used and the definition of PML. Figure 10 illustrates, for a hypothetical building, the effect various combinations of calculational procedure and hazard level can have on the PML. For this example, the PML might be reported as low as 3 percent or as high as 40 percent. Unless the basis of the loss estimate and the level of confidence associated with it are provided, the user of the PML estimate does not really have adequate information on seismic risk to the building.

Example Using ATC-13

Example for illustration: The building under consideration is a concrete tilt-up structure constructed before 1973 located on a level site underlain by Holocene alluvium classified as 1997 UBC Site Class D (Figure 11). Ground water is below a depth of about 30 feet. The site is not subject to earthquake-related fault rupture, landslide or inundation hazards. The PML is to be calculated as the mean damage loss for ground shaking with a 10 percent probability of being exceeded in a 50 year period.

General procedure: The methodology used is that described in ATC-13 (ATC, 1985). Damage probability matrices derived from expert opinion are provided for 40 standard building classes based on number of stories, structural framing type and materials of construction. The general form of the damage probability matrix is shown in Figure 12. Additional "non-standard" and "special" categories for each building class, accounted for in loss estimation by shifting the input MMI levels up and down, respectively, were also developed to account for variations in design or construction practices over time. Each value in the matrices represents the probability that a structure of a specified class will be in a given damage state when subjected to a particular intensity of shaking (MMI). Damage states are defined in terms of ranges of "damage factor", where damage factor is defined as dollar loss divided by replacement value. The mean damage factor for a given shaking intensity is defined as the sum over all damage states of the product of the central damage factor for a given damage state and the probability of being in a given damage state given the shaking intensity (Figure 13). The total mean damage factor is conservatively taken as the sum of the mean damage factor for shaking and mean damage factors for collateral hazards (poor ground, landslide, fault rupture, inundation) estimated using separate methodologies.

Modifications to the ATC-13 procedure: Equivalent fragility curves, transformed from the damage probability matrices for 40 "standard" building classes in ATC-13, are used to represent damage-motion relationships for structures in California (Anagnos, 1995). An example of fragility curves for Facility Class 21 in the damage factor range of 4 to 18 percent is shown in Figure 14. We find the fragility curves are easier to interpret analytically and facilitate comparison of damage probabilities for different building types. In addition, we have adopted the use of the SRSS (square root of the sum of the squares) of the individual mean damage factors as the most likely estimate for the total mean damage factor (Rojahn, 1997) as indicated in Figure 15.

Ground motion hazard: Peak ground acceleration (PGA) at the site is estimated from the USGS National Seismic Hazard maps (USGS, 1996) as 0.30g for Site Class B for ground shaking with a mean return period of 500 years (Figure 16). This value is adjusted for Site Class D conditions using a soil amplification factor F_a of 1.2 (Table 2-13 of FEMA, 1997), resulting in PGA = 0.36g. Since the Modified Mercalli Intensity scale is used as the ground shaking characterization in ATC-13, a conversion from PGA to MMI is necessary. A number of proposed conversion relations are presented in ATC-13, and others can be found in more recent documents. For this example, an equivalent intensity of MMI VIII for PGA = 0.36g is selected.

Mean damage factor due to ground shaking: The damage factor probabilities for MMI 8 are obtained from the fragility curves (Figure 14) as the increment in probability of exceedance between the fragility curves. For example, the probability of damage factor 7 percent given MMI 8 is the difference between the probability of exceeding damage factor 6 and 8, which from Figure 14 is found to be 0.94 - 0.77 = 0.17. This is repeated for all fragility curves crossing the MMI 8 ground motion level such that the sum of the damage factor probabilities is unity. The resulting distribution of all damage factor probabilities caused by MMI 8 ground shaking is shown in Figure 17. The median, mean and 90^{th} percentile damage factor values can be obtained by statistical analysis from the frequency distribution. For this example, the resulting values are 8.5, 11 and 17 percent for the median, mean and 90^{th} percentile, respectively.

Mean damage factor due to liquefaction: The soil deposit type at the site is classified as Zone 2b (Holocene alluvium, water table > 10 feet). The estimated probability of ground failure given MMI 8 ground shaking is 5 percent (ATC-13, Table 8.4). The mean damage factor due to poor ground/liquefaction for surface facilities given MMI 8, including buildings with basements, is estimated as the product of the mean damage factor due to ground shaking , MDF(S), and the probability of ground failure (PGF) times 5 (ATC-13, Equation 8.2a). The mean damage factor due to liquefaction, MDF(L), is thus 11 x 0.05 x 5 = 2.75 percent (Figure 18).

Building PML: The base PML, defined as the total damage factor MDF(T) caused by shaking and collateral hazards, is taken as the SRSS of the individual mean damage factors, MDF(S) and MDF(L), or $[(11)^2 + (2.75)^2]^{1/2}$ = 11.4 percent. The final step is to account for building-specific information on favorable features or unusual earthquake vulnerabilities in the PML estimate. This is accomplished by the use of modifier factors that increase or decrease the base PML as a function of building characteristics differing from the average of its class (Steinbrugge, 1982). Using an assumed modifier factor of +30 percent for this example, the modified PML is 15 percent (Figure 19).

Conclusions

The approach adopted by this office is based on the use of the Steinbrugge and ATC-13 procedures as the starting point, with a large measure of judgement applied on the part of the structural engineer in modifying the base PML to account for specific features of the individual building. We recognize there are limitations to this approach. Desirable improvements would include (1) quantitative definition of ground motion rather than intensity, (2) a presentation that would enhance the user's understanding and acceptance of uncertainty associated with the PML, and (3) an accepted procedure for combining the probability of the ground motion and the loss such that the PML represents a probable loss within a specified time period.

There is currently no standard definition of PML for individual buildings (Figure 20). Several recent activities have great potential for reaching a consensus on the definition and improving the technical process. The first of these is the proposed "Standard Guide for the Estimation of Building Damageability in Earthquakes" by ASTM Committee E06.25.55. This document will be particularly useful in communicating to our clients the degree of reliability of our PML estimates with respect to the level of effort they have authorized us to perform. Finally, the recent developments in earthquake loss estimation in the

HAZUS methodology represent an exciting new approach with the potential for substantially improving the PML process.

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