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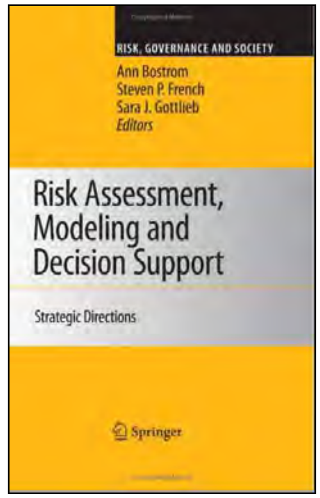

A Brief History of Seismic Risk Assessment

Charles Scawthorn, S.E.

Professor and Head, Earthquake Disaster Prevention Laboratory
Department of Urban Management
Kyoto University
Kyoto 606 Japan
cscawthorn@att.net

Summary

Seismic risk is the potential or probability of a loss due to the occurrence of an earthquake, and is the combination of ***earthquake hazard*** (the physical effects on the natural environment), ***assets at risk*** (ie, the value that is threatened by the earthquake), and ***vulnerability*** of the assets to the effects of the earthquake. A fourth aspect is the mathematical and theoretical ***methods*** by which the three elements are combined to more or less rigorously and accurately estimate the risk. Seismic risk analysis is not an end in itself – rather, the risk must then be judged or ***assessed*** as to its acceptability, relative to social norms, and to other priorities. Seismic risk assessment is still not the end – rather, it is the foundation for seismic risk management, the appropriate and efficient allocation of resources for reducing the risk to acceptable levels.

The history of seismic risk assessment is a long and rich confluence of seismology, earthquake engineering, probability and other fields. This paper addresses developments in seismology, engineering and related fields narrowly, and only to the extent that the development of seismic risk assessment was directly affected. We stop at seismic risk assessment, and do not discuss seismic risk management. The history shows that the rational analysis and mitigation of risk due to natural and other hazards is founded on a large body of work developed over the last 150 years.

A list of key events might include: (1) Mallet – his investigations and founding of seismology in the UK about 1850, (2) Milne – his arrival in Japan in 1880 and development of seismology and training of seismologists in Japan, development of the first practical seismograph, and the founding of the Seismological Society of Japan; (3) Freeman – in the few short years of about 1927 to 1932, his strong encouragement of earthquake engineering in the USA, and role in founding the US strong motion program; (4) Caltech, where Millikan in the 1920s assembled a team who have the credit for development of a robust seismograph network (Wood, Anderson, 1920s), research and education in earthquake engineering (Martel), the Earthquake Magnitude scale [Richter, 1935], magnitude-frequency relation log N = a – b M [Gutenberg-Richter, 1941], and invention of the response spectra [Biot, 1933; Housner, 1941]; (5) the theory of plate tectonics [Wegener, 1913; Hess, 1962; Coats, 1962; Wilson, 1965; Morgan,, 1967; Isacks et al, 1967; Le Pichon, 1968]; (6) Cornell's 1968 BSSA paper on engineering seismic risk analysis; (7) the Finite Element Method (Argyris, Turner, Clough et al, 1940s to 60s), and development of associated structural analysis software (eg, Wilson, 1960s to now); (8) Karl Steinbrugge, Ted Algermissen and the group around them [McClure, Lagorio et al] for focusing on the goal of assessing and reducing the risk (1960s to 80s); (9) the SDDA project at MIT (1973-78, Whitman, Cornell, Vanmarcke, Veneziano et al); (10) ATC-13 (1985) for developing a consistent open set of vulnerability functions (Rojahn, Sharpe, Kiremidjian et al).

Surrounding and channeling these events were broader social and technological influences, such as the rise of nuclear power in the 60s, a sea change in risk attitudes during the same period, and the rise of the personal computer in the 80s. Today seismic risk assessment is well established, with useful tools like HAZUS. However, fundamental improvements are still needed.

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1 Introduction

Seismology and earthquake engineering have rich histories, perhaps due to the fact that earthquakes tend to affect almost *everything* around us – after all, one can take shelter from a storm, but not from an earthquake. Great minds – Aristotle, Plato, Da Vinci and Kant to name a few – have grappled with the problems of earthquakes. When issues of *risk* are added to those of earthquakes, the field and history are further enriched (think of adding Pascal, Fermat, Bernoulli, Keynes…), and the challenge of writing a history increased commensurately. The task is daunting – Housner in 1984 observed:

> *Earthquake engineering is a 20th Century development, so recent that it is yet premature to attempt to write its history…Although 1984 is too soon to write a definitive history, it is an appropriate time for an historical view of earthquake engineering development to see where we were, where we now are, and where we are going….*

This writer agreed entirely when he heard those words in 1984, but two more decades later the perspective is greatly improved. In fact, as we shall see, in many ways we were just on the verge of seismic risk analysis and assessment in 1984, whereas today we have very significant capabilities.

This paper addresses developments in seismology, engineering and related fields narrowly, and only to the extent that the development of seismic risk assessment was directly affected. We stop at seismic risk assessment, and do not discuss seismic risk management. We begin by defining selected terms, since some confusion still lingers in that regard, and provide a very brief overview of seismic risk assessment. We then get to the heart of the matter – the key historical events, developments and influences by which seismic risk assessment came into being. This discussion is broadly structured according to Hazard, Vulnerability, Assets, and Methods. Following is a summary assessment, selected references, tables and figures. An extensive bibliography was compiled but is omitted due to length.

1.1 Terminololgy

Seismic risk is the potential or probability of a loss due to the occurrence of an earthquake. The risk is the combination of three main elements – the ***earthquake hazard***, the ***assets at risk*** (ie, the value that is threatened by the earthquake), and the ***vulnerability*** of the assets to the effects of the earthquake. Figure 1 depicts this conceptually. While earthquake hazard has a relatively narrow scope of simply the physical effects (faulting, shaking, liquefaction, landsliding, tsunami etc) of the earthquake event on the natural environment, whether defined deterministically or probabilistically, the elements of assets at risk and vulnerability need explanation. Assets at risk is used here in the broadest sense – it includes not only those physical items that have financial value, but also non-physical items that can still be valued financially (eg, business interruption, reputation) and very importantly, those items more intangible yet of great value, such as social cohesiveness and peace, public confidence, political union, education, mental health and so on. There are not a few instances of governments overthrown due to their inadequate response to a great earthquake (eg, 1755 Lisbon, 1972 Managua). Vulnerability is the susceptibility of the asset to the hazard, so that vulnerability is defined here just as broadly as asset, although in most usage throughout this paper a somewhat narrower more technical meaning is employed.

The process of analyzing the risk involves a fourth crucial aspect – the mathematical and theoretical ***methods*** by which the three elements are combined to more or less rigorously and accurately estimate the risk. Seismic risk analysis is not an end in itself – rather, the risk must then be judged or ***assessed*** as to its acceptability, relative to social norms, and to other priorities. Seismic risk assessment is still not the end – rather, it is the foundation for seismic risk management, the appropriate and efficient allocation of resources for reducing the risk to acceptable levels.

While we begin by defining some terms, and other terms where used, we assume a knowledgeable reader:

- **Earthquake**: Tectonic movements of the earth's crust resulting in propagating broad-banded vibratory motion (volcanic earthquakes and human-induced events such as blast are not considered here).
- **Assets**: the humans, animals, property, business operations and other items of value whose reduction in value (loss) is a concern. In general, the economy and built, social and natural environments that may be affected by an earthquake. Similar terms include exposure, inventory, and portfolio. Note that assets include intangibles such as intellectual property, reputation, etc.
- **Damage**: Death, collapse, physical injury or other degradation in condition of assets.
- **Seismic hazard**: The phenomena and/or probability of an earthquake-related agent of damage, such as fault rupture, vibratory ground motion (i.e., shaking), inundation (e.g., tsunami, seiche, dam failure), various kinds of permanent ground failure (e.g., liquefaction, landsliding), fire, or hazardous materials release..
- **Seismic Intensity:** A metric of the effect, or the strength, of an earthquake hazard at a specific location, commonly measured on qualitative scales such as MMI, MSK, and JMA.
- **Loss**: the decrease in asset value resulting from damage. Loss may be direct, or indirect (the terms 'direct' and 'indirect' loss are used variously - see
- Table **3** for an example, and concordance of usage).
- **Vulnerability** generically refers to the probability of damage given the occurrence of a hazard. If damage is defined as the median damage, the relation with hazard is termed a vulnerability function or curve. In some cases damage and loss are combined, so that vulnerability can be the probability of loss given the hazard. Note also that in the social domain vulnerability has a somewhat different meaning, referring more to the lack of capacity of populations and social systems to cope with disasters.
- **Fragility:** complementing vulnerability is the concept of fragility, which is the probability of being in a damage state (eg, "1%" damage, or "light" damage) given the hazard.
- **Seismic risk**: potential or probability of a loss due to the occurrence of earthquakes and associated hazards.
- **Risk analysis:** Systematic use of information to identify sources and to estimate risk. Information can include historical data, theoretical analysis, informed opinions, etc.
- **Risk assessment:** Overall process of risk analysis and risk evaluation.

- **Risk evaluation:** Process of comparing the estimated risk against given risk criteria to determine the significance of the risk. Risk evaluation may be used to assist in the decision to accept or to mitigate a risk.
- **Risk management:** the process and acts to reduce risk in an orderly, efficient and desirable manner.

Table **3** provides an example of some of these terms, and other terms, and also shows that there is still some confusion in terminology in the indirect loss arena.

1.2 Overview of seismic risk assessment

As shown in Figure 1, seismic risk analysis is the combination of three main factors – hazard, vulnerability, and asset value.

Seismic hazard is the result of a process combining the probabilistic occurrence of one or more earthquakes (the 'source'), with the estimated effects of the earthquake at a site ('attenuated' to the site via the 'path'), considering the specific conditions at the site ('site-effects').

While the hazard is what 'nature does', assets are generally what humankind 'puts in the way of nature', although even the natural environment will be disturbed by an earthquake and may lose 'value' from a scenic or other perspective. Assets are people, buildings, contents, communications, organizational operations, etc. Any asset will have many relevant attributes, such as the age, health and income of a person, the location, age, size, materials of construction, lateral force resisting system and occupancy of a building, the location, age, size etc, nature and criticality of operations, and redundancy, of a financial data center, or water or other lifeline system.

Vulnerability or fragility functions are developed for each asset based on the general or specific seismic resistive characteristics of the asset. In general, one or both of two methods are employed, Figure 2:

(a) *empirical*, in which observations of the performance of similar assets are implicitly or explicitly assessed. Empirical sources can further be divided into three important sub-classes:

1. Field survey data – that is the qualitative and statistical record of observed damage in actual earthquakes.
2. Experimental and laboratory data, derived from tests of components and/or small scale models (although recently full scale model testing is becoming more feasible).
3. Expert opinion-derived, which is the estimate by knowledgeable persons with first-hand experience observing earthquake performance of structures. The expert opinions may be derived and expressed by more or less rigorous methods.

(b) *analytical*, in which the properties of the asset are analyzed using a theoretical model based on a mechanics of materials or other theoretical framework. Ideally, the two methods should agree, or be used in conjunction in a

If empirically-derived data are employed to calibrate an analytically-based model, the result is termed a *hybrid* model. Relatively few hybrid models have been developed.

Seismic risk assessment takes the results of a sra and compares it against societal, organizational or personal norms. These norms vary with each situation –they may be legally mandated, or may be decided on the basis of more or less rational decision making criteria, such as benefit cost analysis.

2 A brief chronology of selected events in seismic risk assessment

Table 1 presents a chronology of selected events key to the development of seismic risk analysis. The column headings Hazard, Vulnerability, Assets and Risk are rubrics, intended generally to refer respectively to developments in the Earth Science, Built Environment and Socio-Economic spheres, and to those developments that contribute to integrating or analyzing those three spheres into an assessment of the likelihood of loss – that is, seismic risk.

Many events cut across more than one of these spheres. An example is seismic intensity - quantification of damage can be a measure of shaking intensity, or a measure of structural integrity, depending on what one regards as the independent variable. That is, one measures the strength of shaking at various sites by observing damage to similar construction at those sites (intensity is the independent variable), or one takes the intensity of shaking as given (dependent variable), and judges the relative seismic resistiveness of structures (damageability is the independent variable) subjected to the same intensity. Historically, and confusingly, seismic intensity has been used both ways – isoseismals are mapped and earthquake magnitudes thereby estimated, and damage is estimated based on intensity (eg, ATC-13). There is a significant although not complete tautology in this usage – the tautology is diluted in that human reactions and natural phenomena (eg, liquefaction) are also used in estimating intensity, but not typically vice-versa. In Table 1, developments with respect to intensity cut across Hazard and Vulnerability. By allocating the space in the table in this way, large empty swaths show lagging development.

Table 1 Brief Chronology of Seismic Risk Assessment

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
1755	**Lisbon Earthquake** – structural, urban planning and other mitigations developed, but don't spread				
1783	Schiantarelli quantifies damage (**Calabria earthquake**, soon after Lisbon and with greater losses, spurs some attention to earthquakes				
1811-12	New Madrid (US) earthquakes – no advances				
1828	seismic intensity quantified by Egen (Belgian earthquake), not much used however				
1850s	**Ft. Tejon** (US), **Edo Ansei** (Japan) earthquakes – no advances				
1850	Mallet's Map – lays out bands of seismicity, shows plate boundaries and regions of high risk at a glance. Well-known in seismology, doesn't seem to have had any effect related to risk				
1867			D.A. Sanborn National Insurance Diagram Bureau established in New York City – growth in development of fire insurance maps		
1874	Rossi (Italian), defines intensity scale				
1881	Forel (Swiss) combines his scale with Rossi's, for Rossi-Forel Scale, with ten degrees of intensity (first scale to be widely used internationally)				
1880	Milne, Ewing, Gray arrive Japan, build first good seismograph; Seismological Society of Japan founded (world's first)				
1883	Giuseppe Mercalli (1850-1914) improves Rossi-Forel scale but still keeps ten degrees				
1886	**Charleston (US) earthquake** – good documentation including sand blows and building damage, but not much advancement of				

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
	science or mitigation				
1887	Mt. Hamilton and Berkeley Seismological Observatories established (first in western Hemisphere)				
1891	Lawson maps San Andreas fault (but believes it's a thrust fault)				
1891	**Nobi earthquake** – establishment of Imperial Earthquake Investigation Committee (multidisciplinary); Fusakichi Omori (1868-1923) surveys overturned stone-lanterns etc, draws acceleration isoseismals, develops seven degree intensity scale, fore-runner of today's JMA scale.				
1880s-1890s		Increasing seismic design in San Francisco, use of bond iron, high-rise buildings (q.v.. Tobriner)			
1892	Seismological Soc.Japan dissolved				
1902	Adolfo Cancani extends Mercalli scale to twelve degrees, with estimated ground acceleration values but poor qualitative descriptions, resulting in the Mercalli-Cancani scale.				
1905	Anderson defines normal, reverse and strike-slip faulting modes			NBFU survey of San Francisco, identifying great fire risk	
1906	**San Francisco Earthquake and Fire** Isoseismals mapped by Wood,; significant detail in the city of San Francisco itself, using ad hoc intensity scale (Lawson, 1908)	Structural effects documented (USGS, 1907), finding that engineered buildings not substantially damaged by the earthquake or fire, if reasonably well fire-protected to begin with.		Founding of Seismological Society of America; Japanese engineers visit and investigate effects; Emphasis on fire, and downplaying of earthquake by City (and engineers). Areas of 'infirm ground' noted and used by the San Francisco Fire Department in subsequent construction of special high pressure water system	

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
1908 - 1909	**Messina (Italy) earthquake**	Italian committee develops equivalent lateral force (ELF) for seismic design; T. Sano (Japan) independently develops ELF method			
1908				Construction of SFFD AWSS	
1911	Hugo F. Reid (1859-1944) expounds *elastic rebound theory* (Reid, 1911), based on studies of 1906 earthquake				
1912	Sieberg provides full descriptions of each degree of Mercalli-Cancani scale. Mercalli-Cancani-Sieberg or MCS Scale twelve-degree scale still in use in Southern Europe.				
1913-1915	Wegener propounds "*Origin of Continents and Oceans*" (ie, plate tectonics). Is ignored.				
1920s	Modern Caltech and its Seismo Lab established; Wood and Anderson develop and deploy standard torsion seismograph; Richter joins in 1925.			Frank Knight publishes *Risk, Uncertainty and Profit*, a classic in risk management.	
1923	**Tokyo earthquake and Fire**				
	IEIC becomes Earthquake Research Institute (Suyehiro first director)	Naito's buildings undamaged; Japanese seismic building code using Sano seismic coefficient method (aka, ELF, equivalent lateral force)			ASCE sends team to investigate
1923-24	Bailey Willis series on "Earthquake Risk in California" in BSSA				
1925	**Santa Barbara (US) earthquake**			Insurance industry earthquake losses, J.R. Freeman takes interest	

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
1926		Palo Alto seismic code		John von Neumann presents first paper on theory of games, at University of Göttingen,.	
1926	Prof. R. Martel (Caltech) attends Earthquake Conference in Japan, to learn from 1923 events.				
1927		UBC seismic code, emulates ELF approach from Japanese code			Mississippi floods
1929	Seismological Soc. Japan re-established J.R. Freeman attends World Engg. Conf. in Tokyo, meets Martel and Suyehiro				
1930	Freeman (BSSA, 1930) presents plan for strong motion network and other concepts; subsequently lobbies vigorously.				
1931	Wood and Neumann publish MMI (1931) Gutenberg joins Caltech				.
1932	(a) Strong Motion instrumentation authorized for US Coast and Geodetic Survey, NBS builds instruments with assistance from MIT and U. Va., instruments deployed in California; (b) USC&GS performs ambient and forced vibration surveys of buildings in California, leading to rule for building natural period (T = 0.1 N, where N is number of stories).			Freeman publishes *"Earthquake Damage and Earthquake insurance"* Suyehiro invited to US, lectures at Berkeley, Stanford, Caltech and MIT, great interest and appreciation	
1933	**Long Beach Earthquake**: First strong motion recording (27 individual components); PGA	Field and Riley Acts (California) require seismic design for schools and other buildings, respectively.			
1933	Structural response spectra (Biot, 1933; Housner, 1941)				
1935	Richter defines earthquake *magnitude* (Wadati)				

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
1936				Federal Navigation Act of 1936 requires U.S. Corps of Engineers carry out projects for improvement of waterways *when total benefits of a project to whomsoever exceed the costs of that project*. Beginning of Benefit-Cost Analysis.	
1939	Trace amplitude-frequency relation identified (Ishimoto-Iida), approximately equivalent to Gutenberg-Richter (1956)				
1941	Gutenberg and Richter "*Seismicity of the Earth*", log N = a-bM				ENIAC, First electronic general-purpose computer
1942	Gutenberg and Richter (1942) on earthquake magnitude, intensity, energy				
1945				McCarran-Ferguson Act, gives states regulation of insurance companies, fragmenting the industry	
1946	First (Bikini) and subsequent nuclear test provide precise seismo data.				
1949	Earthquake Engineering Research Institute (EERI) founded as an outgrowth of the Advisory Committee on Engineering Seismology of the US C&GS, to encourage research in the field of earthquake engineering.				
1951	Kawasumi probabilistic acceleration map of Japan Seismic "probability" map of US (US C&GS, actually not probabilistic)			Start of Nuclear Power: (1951) first generation, Arco ID; (1954) first power grid generation, Obninsk, USSR; (1956) first commercial, Calder Hall, England; (1957) first full-scale in the US, Shippingport (PA).	

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
1952	Housner publishes *Intensity of Ground Motion During Strong Earthquakes* (Caltech report) – probabilistic mapping method, with results for California (published as ONR report, doesn't seem to have attracted much attention)	**Kern County earthquakes** – Steinbrugge, Moran et al document damage; ASCE *Lateral Forces of Earthquake and Wind* ("Blue Book" forerunner)		H. Markowitz, publishes "Portfolio Selection," (*Journal of Finance*), 1990 Nobel Prize	IBM 701 computer
1953		Mogami and Kubo publish experiments on sands, coin term *liquefaction*		John von Neumann and Oskar Morgenstern publish *The Theory of Games and Economic Behavior*	
1956	Richter revises MMI scale of 1931 but retains 1931 reference;			Gallagher publishes "*Risk Management: A New Phase of Cost Control*," (Harvard Business Review),	World Conference on Earthquake Engineering (Berkeley)
1957					Fortran released by IBM
1958	Housner publishes *Mechanics of Sandblows* (BSSA) but not appreciated ("even by him")				
1959		*Recommended Lateral Force Requirements and Commentary, Seventh Edition,* Seismology Committee,			

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
		Structural Engineers Association of California ("Blue Book"			
1960	**Chile earthquake**, first instrumental identification of rupture release along fault				2WCEE (Japan) with World Conferences about every four years thereafter
1960s	Emergence of Plate Tectonic theory: Hess (1962), Coats (1962), Wilson (1965), Morgan, (1967), Isacks et al (1967), Le Pichon (1968)		Decline of Sanborn Company and insurance fire maps; Ian McHarg, ESRI and start of GIS	Don Friedman moves to Travellers Insurance Company from MIT, develops Hurricane Risk Models	IBM 1620; Design and construction of numerous nuclear power plants (through early 1980s);
1961	WWNSS global seismological network established;				
1962				Douglas Barlow, insurance risk manager for Massey Ferguson (Toronto), develops idea of "cost-of-risk," Rachel Carson publishes *The Silent Spring*, starting environmental movement and shift of US to risk aversion.	
1963	Founding International Assn. Earthquake Engg.;			Founding Disaster Research Center, Ohio State U. (Dynes, Quarantelli, start of social science research)	
1964	**Prince William Sound (US) Earthquake** and **Niigata (Japan) earthquakes** Major liquefaction, ground failures			Hydrologic Engineering Center (HEC) formed by US Army Corps of Engineers – develops and	

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
	and building collapses – draws widespread attention; subsequent widespread investigations of liquefaction, esp. by H. Seed, R.V. Whitman and T.L. Youd in US, and T. Iwasaki and others in Japan.			distributes ***HEC-1*** and later free flood hazard and risk software (http://www.hec.usace.army.mil/)	
1965				Moore's Law: *computing power doubles every 18 months*	
1966	*Earthquake Engineering* (Wiegel, 1966) published			The Insurance Institute of America creates "*Associate in Risk Management*,", first move towards professionalism in insurance industry Ralph Nader publishes *Unsafe at Any Speed* , consumer movement,, rise of punitive damages	
1968	Cornell BSSA paper *Engineering Seismic Risk* (BSSA) – breakthrough publication, everyone gets it. Paradigm shift in earthquake engineering			*Earthquake Hazard in the San Francisco Bay Area : A continuing Problem in Public Policy* (K.V. Steinbrugge) one of the first reports to translate what is known by scientists into public policy recommendations	
1969	Probabilistic hazard map of Canada (Milne and Davenport) First revision of US hazard map since 1949 (Algermissen et al, but not probabilistic)		Algermissen, Steinbrugge, McClure begin development of loss studies, with Studies in Seismicity, for US Coast and Geodetic Survey		
1970s	Birth of paleoseismology, lead by Wallace et al; late 70s Sieh finds several prehistoric Ft. Tejon type events at Pallett Creek, near Los Angeles				
1970		Wilson develops general purpose structural analysis program (SAP)		US EPA (Environmental Protection Agency) established, leading to many analytic advances in response to environmental regulations.	

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
1971	**San Fernando (US) earthquake** and aftershocks increases US SM records from 741 to 1,758; Seismic gap concept identified (Sykes)	San Fernando (US) earthquake stimulates research in lifelines, lead by C. Martin Duke		CDI Rule 226 and PML requirement; JH Wiggins (and W. Petak) assess damage – data used (in part) by Whitman for damage probability matrices (DPM) for SDDA project (q.v. 1973). Ed O'Connor (Long Beach City Official) initiates URM regulation effort;	
1972	The Alquist-Priolo Earthquake Fault Zoning Act (California) requires mapping of earthquake faults, and special geological investigations in defined zones around those mapped faults.		Algermissen, Steinbrugge et al perform first regional loss study: *A Study of Earthquake Losses in the San Francisco Bay Area*, for Office of Emergency Preparedness, NOAA, Washington, D.C.		
1973	Whitman starts Seismic Design Decision Analysis Project at MIT (to 1977) – many innovations, esp. DPMs, developed in part from data, and in part by use of Delphi process. JH Wiggins Co. (Wiggins, Petak, Gordon et al) through 1978 analyze US earthquake, wind and flood losses, funded by NSF's RANN program (C. Thiele, program manager). Summary published in Petak, and Atkinson. 1982. Wiggins Co. (esp. Petak) analyzes AIG California portfolio for earthquake, penetrates insurance market.				1973 Geneva Assn. established, linking risk management, insurance and economics
1974	Uniform hazard spectra (McGuire)	Statistical Analysis of Building Damage (Scholl, 1974) *Peace of Mind in Earthquake Country* published (Yanev, 1975)		As a result of 1971 San Fernando earthquake, C. Martin Duke founds ASCE TCLEE, focus on seismic performance of lifelines	
1975			WASH-1400 Reactor Safety Study ("Rasmussen Report") published – encourages wider use of probabilistic methods; Brown's Ferry NPP fire, major damage, near melt-down; Risk and Insurance Managers Assn. (RIMS) created.		
1976	Probabilistic hazard map of the US (Algermissen)			Start of Assn. State Flood Plain Managers (ASFPM)	
1977	Moment magnitude M_w (Kanamori; also Hanks and Kanamori, 1979)			Wiggins / Petak study of national natural hazards risk	First PC (Apple II)

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
1978	Tokai (Japan) earthquake forecast (Ando) and subsequent creation of special zone for broad mitigation effort Tangshan (China) earthquake – 250,000+ killed, no apparent effect			ATC 3-06 model building code; McGuire ***FRISK*** Program; Canvey Island study (process safety, UK)	
1979				VisiCalc Spreadsheet; Three Mile Island NPP – partial core meltdown	
1980				Society for Risk Analysis formed	
1981		First base isolated building: William Clayton Building, Wellington, New Zealand		EQE Inc. founded to offer seismic risk reduction services[1]	First IBM PC
1982		First probabilistic model of fire following earthquake; First research into hazardous material releases in earthquakes			
1983	Estimation of earthquake losses in Los Angeles : damage scenarios under varying earthquake research effort (Dames & Moore)			William Ruckelshaus speech on "Science, Risk and Public Policy" to US National Academy of Sciences, putting risk management on national political agenda.	
1984	Characteristic earthquake (Schwartz and Coppersmith)	F. Press proposes International Decade of Hazard Reduction (8th World Conference on Earthquake Engineering)			
1985		*ATC-13 Earthquake Damage Data in California;* first base isolated building in US (Foothills Justice Center, Rancho Cucamonga, CA)			Mexico City earthquake;
1986	Increasing insurance portfolio analysis projects for Dames & Moore, EQE and other companies			Chernobyl NPP explosion, widespread contamination	
1987	*Pre-Earthquake Planning for Post-Earthquake Recovery (PEPPER)* Project, Los Angeles (Spangle et al)			Applied Insurance Research (AIR) founded;	

[1] Other engineering firms (J.A. Blume, H.J. Degenkolb, Dames & Moore, J.R. Benjamin) offered these services but this was not their focus.

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
				EQE develops ***EQEHAZARD***	
1988				***IRAS*** model (Kim, Dong, Shah et al)	
1989	**Loma Prieta (US) earthquake**; spurs mitigation in California, Pacific Northwest			Risk Management Solutions (RMS) founded[2]	Hurricane Hugo (US)
1990	IDNDR inaugurated by UN				
1991	Global map of seismic gaps (Nishenko)	*Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States*, FEMA 1991. development of ***LLEQE*** (LifeLine EarthQuake Engineering)			
1992	Increasing utilization of loss estimation software (Law, 1997), due to experiences in 1989 (Loma Prieta and Hurricane Hugo) and Hurricane Andrew; HAZUS development starts (Schneider and Schauer, 2006)				Hurricane Andrew (US)
1994	**Northridge (US) earthquake**: real-time estimation of isoseismals (EQE); same day estimation of losses (Wall St. Journal, 1994), modeling companies estimates of insurance losses are poor compared with results development ***EPEDAT*** (Eguchi et al, 1997; Nigg and Eisner, 1997)				Northridge Earthquake
1995	**Kobe (Japan) earthquake;** increase in interest in seismic risk management in Japan				
1997	***HAZUS*** Initial Release (Kircher, 1997a, 1997b)				
1998	***ShakeMaps*** (Wald et al)				
1999				Popularization of risk concepts with Peter Bernstein's book *Against the Gods: The Remarkable Story of Risk*	
2000		***NEES*** (George E. Brown, Jr. Network for Earthquake Engineering Simulation) development begins			
2000	***EXTREMUM*** Disaster Management Technology (Russia) release Rapid Global estimation of natural hazards losses (see also *QUAKELOSS*, a derivative of EXTREMUM, at http://www.wapmerr.org/quakeloss.html)				

[2] RMS website says 1988 but interview with Hemant Shah (Reactions, 2004) says 1989.

Date	Hazard	Vulnerability	Exposure	Risk	Event/Comment / Other
2003	***HAZUS*** – MH release				
2004	***LESSLOSS*** (EU project for Risk Mitigation for Earthquakes and Landslides)				
2006	***NERIES*** – EU 10 year project to develop new generation of earthquake hazard and risk assessment tools				

3 How we got here

In his Keynote speech to the 1984 8th World Conference of Earthquake Engineering in San Francisco, George Housner also noted "*…there are still many people that remember relevant information and would be severe critics of a history. To write an acceptable history, it is necessary to wait till most of the poorly known facts have disappeared from memory and literature, then, with a coherent blend of fact and fiction, history can be written.*" So, let us attempt a coherent blend of fact and fiction, knowing full well that *there are still many…critics of a history*.

3.1 Hazard and some related matters

3.1.1 Early days

The history of seismology, and earthquake engineering, begins with Mallet. His interest was two-fold – the pursuit of pure knowledge, but also the reduction of death and destruction. He embodied the complementary natures of the scientist *and* the engineer. His map and works foresaw truths painfully learned much later – plate tectonics, seismic zones, microzonation, seismic risk. He was followed by Rossi, Forel, Mercalli, who in the same spirit developed scales that serve to both measure the size of the natural event, and the effects of that event on humankind. Milne went to Japan, experienced an earthquake and never went back to geology. With Ewing and Gray he immediately developed excellent seismographs and the network infrastructure they demand, and founded the Seismological Society of Japan (his perspicacity can be judged by the fact that the SSA was not founded until 25 years later). Japan was fertile ground, not only in its seismicity but in the expansive energy of a people recently released from feudal bonds. Spurred by the Nobi earthquake, within a few years a large cadre of solid scientists and engineers (Omori, Suyehiro, Sano…) had built a solid understanding of earthquake mechanics and seismic design. (It should be noted that the Seismological Society of Japan was dissolved in 1892, the year after the Nobi earthquake, perhaps due to the establishment of the Imperial Earthquake Investigation Committee. SSJ was re-established in 1929).

The 1906 San Francisco earthquake was not the seminal event it should have been. Much storied and gloried, it allowed Reid to recognize elastic rebound, but not much else of value – seismological, engineering or seismic risk – emerged. SSA was established, but it had been *the fire*, and seismic considerations did not make their way into San Francisco's, or any US, building code. This is particularly ironic given the solid risk management that was emerging in the fire insurance field – since the civil war, Sanborn and others had been developing detailed risk data, and US cities, tired of their conflagrations, were spending big money to build special high pressure water systems. The1908 Messina (Italy) earthquake, with 70,000 dead, was much more of a seminal event. The Italians appointed an excellent commission, who developed principles of seismic design still in use today (the Japanese did the same contemporaneously and independently).

It was in Southern California where the next progress was made. In 1920 there was no seismological observatory in Southern California. Harry Wood was brought to Caltech by Robert Millikan to fill that vacuum. Wood was a pragmatic fellow who was more interested in studying earthquakes in his backyard rather than from thousands of miles away, since the local events were potentially damaging. He and John Anderson immediately built a practical seismograph which began to generate good quality data which Charles Richter, when he arrived in 1925, began to analyze.

In 1923 the Tokyo earthquake had motivated Japan to adopt a rational seismic design procedure in its building code, using the Equivalent Lateral Force (ELF) method developed by Sano early in the century (and independently, by the Italians). The 1925 Santa Barbara earthquake, combined with a seminal series of papers in 1923-24 by Stanford professor Bailey Willis in the Bulletin of the Seismological Society of America, lead to adoption in 1927 of a similar provision in the first Uniform Building Code. The Italians, Japanese and American engineers all agreed that an ELF of about 10%, adjusted for soils and transient stresses, should suffice, due in part to the successful performance of buildings in the 1923 Tokyo earthquake that had been designed in this manner by T. Naito.

Independently, insurance companies had 'taken a beating' in the 1925 Santa Barbara earthquake, which caught the attention of a remarkable engineer and insurance executive named John Ripley Freeman. Space does not permit telling of the full story, but suffice it that Freeman looked into the situation and was shocked:

> *The American structural engineer possesses no reliable accurate data about form, amplitude, or acceleration of the motion of the earth during a great earthquake to withstand which he must design a structure. Notwithstanding there are upward of fifty seismograph stations in the country and an indefinitely large number of seismologists, professional and amateur ; their measurements of earthquake motion have been all outside of the areas so strongly shaken as to wreck buildings…Most of the prominent American textbooks on theory of structures say nothing about earthquake-resisting design.* (Freeman, 1930)

Freeman decided the US needed a strong motion program, started with the local officials and went up the ladder to the Secretary of Commerce and even President Hoover. The National Bureau of Standards was put on the job, and designed and built a standard instrument for the US Coast and Geodetic Survey, who deployed it, all within a year or so and just in time to catch the strong motions from the 1933 Long Beach earthquake. Engineering seismology was born, a prerequisite for seismic design. The maximum PGA recorded in 1933 was 280 gals, several times greater than the recently promulgated ELF requirements in the UBC and Japanese codes. Inexplicably given this evidence, California passed the Riley Act, requiring buildings to be designed for a minimum lateral force (quite small, in practice). Also passed was the much more influential Field Act, which required all K-12 public schools in California to be designed under the supervision of the State Architect.

Following 1933, the growth in strong motion observations was very slow, from 27 in 1933 to a total of about 1,000 in 1971, when the total was doubled by the 1971 San Fernando earthquake. Figure 4 shows the global growth since – today, there are an estimated 150,000 records worldwide (author's estimate), which have shown that PGA of 0.7g is not unrealistic for sites close to a fault in a large earthquake. Figure 5 shows the distribution of those records – Japan's strong motion programs today dwarf those of most of the rest of the world, and Japan has recorded about 60% of the global archive[3].

In 1935 Richter, who had been struggling with the growing body of data that the Wood-Anderson seismographs were generating, read a paper by Wadati which suggested that the maximum amplitude of a seismograph correlated with the size of an earthquake. This lead to Richter defining earthquake magnitude as the maximum amplitude of the Wood-Anderson seismographs at a standard distance. The concept of magnitude, although simple and borrowed from astronomy, was very powerful, not only for communicating to the public but also as a simple measure that could be employed in statistical studies. By 1941 Gutenberg and Richter had accumulated enough data to sort out global seismicity and publish "*Seismicity of the Earth*", on the basis of which they could state a power law for earthquake occurrence – the well-know Gutenberg-Richter magnitude-frequency relations $\log N = a - b\,M$, where N is the number of events greater than magnitude M[4]. They had also developed relations between magnitude, energy, acceleration and intensity, which allowed estimation of the strong motion given the magnitude and distance, and estimation of the the intensity given the acceleration[5]. Wood and Neumann in 1931 had modified the Mercalli Scale for US construction, so that a correlation between intensity and damage was also now at hand.

Therefore, by about 1940 seismology was able to instrumentally estimate the size of earthquake on a defined scale (magnitude), and estimate the probability of various size events in a future period ($\log N = a - b\,M$, with a and b defined for different regions). There were about 100 strong motion recordings which had been used to develop estimates of acceleration, and intensity, as a function of magnitude and distance. And, intensity defined damage. Therefore, all the elements were at hand for estimating the probability of damage. However, perhaps due to World War 2, no one seems to have made that leap.

About the same time, also at Caltech, Biot and Housner developed the concept of response spectra, which was immediately recognized as of great value as it permitted consideration of multiple modes in earthquake response.

3.1.2 1950

During most of the 40s, not much seems to have happened, undoubtedly due to the War. Following the War, the Earthquake Engineering Research Institute (EERI) was founded in 1949 to promote research.

Research <u>was</u> needed – in 1948 the US Coast and Geodetic Survey issued the first national seismic 'probability' map , although the map was not probabilistically based . Rather, it was a mapping of the maximum observed intensities, clustered into 'zones'. The map had problems – Zone 3 was contiguous with Zone 1 in some places, Zone 2 with Zone 0 – but its main problem seems to have been resistance to designing for earthquakes. The map was revised the next year ,

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[3] Actually, there is no single global archive, although COSMOS and NOAA's National Geophysical Data Center are relatively large useful international archives.

[4] Ishimoto-Iida (1939) had independently found a comparable relation, but it wasn't widely known.

[5] They noted the possibility, but declined at that time, to define magnitude in terms of total event energy. That would wait for Kanamori (1978), and Hanks and Kanamori (1979), to define moment magnitude.

so that Charleston SC moved from Zone 3 to Zone 2, and then the following year the map was withdrawn . As Beavers (2002) relates:

> *"…the USCGS made the following official statement: 'The Seismic Probability Map of the United States, SMC-76, issued by the US Coast and Geodetic Survey in 1951, has been withdrawn from circulation because it was found to be subject to misinterpretation and too general to satisfy the requirements of many users.'*
>
> And, quoting a 1996 study (Mittler, as quoted in Beavers):
>
> *'. . . the United States Geodetic Survey retracted a map in the 1950's because business and scientific interests applied pressure on the grounds that the map (like all science) was subject to misinterpretation.' There also appears to have been resistance by the public and other federal agencies to design buildings and facilities to earthquake loads where earthquakes were not generally known to occur.*

Nevertheless, the map was adopted for the 1949 edition of the UBC, and served as the national seismic zonation map until 1970.

In contrast, in Japan in 1951 Kawasumi put the elements of earthquake magnitude, frequency and strong motion attenuation together, to produce a probabilistic acceleration map of Japan, Figure 6. In his paper, Kawasumi stated:

> *and if we want to know, for example, expectancies of … total amount of damage in current price or number of casualties etc., they may be determined from this mean frequency, since these damages are respectively functions of the intensity of an earthquake. These expectancies themselves also serve as the practical indices of earthquake danger. It is also to be noted that we can also derive a physical index of earthquake danger.*

It is interesting to compare seismic hazard maps in use in the Japan and the US in 1951, Figure 6 and Figure 7. The Japanese map is probabilistically based and offers substantial detail, clearly reflecting significant variation in seismic hazard. The US map, not probabilistically based, divides California, roughly the same size as Japan, into three zones, with Zone 3 covering more than half of the state.

Housner in1952 developed an approach for probabilistic seismic mapping similar to Kawasumi's, in a report for the Office of Naval Research which however doesn't seem to have been widely used or published.

Liquefaction had been noted in many earthquakes (eg, by Dutton in the 1886 Charleston event) but it was only in the 1950s that Mogami and Kubo (1953), noting the virtually total loss of strength of vibrated sands, coined the term *liquefaction*, and Housner (1958) wrote a beautiful analysis of the 'mechanics of sand blows'. However, as Housner noted in 1997 in reference to his own paper "*neither I nor anyone else…seemed to grasp the practical significance of the phenomenon*….". When buildings overturned in the 1964 Niigata (Japan) earthquake, liquefaction was 'discovered' and became the subject of intensive and extended research

An outgrowth of the organization of EERI was the *World Conference of Earthquake Engineering*, held at Berkeley in 1956. While the 1929 *World Conference of Engineering* in Tokyo had had the 1923 earthquake as one of its foci, the 1956 conference was the first conference focused solely on earthquakes. Forty papers were presented, and the participants found the event very valuable. It lead to a series of World Conferences of Earthquake Engineering, the 13th of which was held in Vancouver, B.C. in 2004. Figure 10 shows the growth in World Conference contributed papers.

Starting with work at Stanford and Caltech in the 1920s and 30s, earthquake structural dynamics had developed in the US to the point where John Blume, Henry Degenkolb and other leading engineers wanted to introduce those concepts into the design practice. A group gathered in San Francisco and in 1952 produced "Lateral Forces of Earthquake and Wind" which by the end of the decade had developed into the SEAOC "Blue Book" (*Recommended Lateral Force Requirements*), which for the next 40 years was the earthquake section of the UBC, used by virtually most of the rest of the world (excepting Japan and the Soviet bloc). The Blue Book was a good code, influential and representing the best thinking of the time. Not in the Blue Book itself, but contained in its supporting materials was a statement that structures designed in accordance with the Blue Book should:

- *Resist minor earthquake shaking without damage*
- *Resist moderate earthquake shaking without structural damage but possibly with some damage to nonstructural features*
- *Resist major levels of earthquake shaking with both structural and nonstructural damage, but without endangerment of the lives of occupants*

This came to be known as the life-safety criterion and it became knowledge among engineers, but not the public, that the intent of the code was to protect life safety, and that it did not prevent damage or protect investments or operations – that therefore the code was a minimum standard.

The writer should note at this point that the first time he read this statement, about 1973, he was immensely struck with its absurdity. The statement was one of the primary reasons his career shifted from structural design to risk analysis. The third bullet in the Blue Book philosophy provides for life-safety. However, it also provides for the situation that, if all buildings in a major city (like San Francisco) are designed per these provisions, then <u>all</u> buildings – <u>the entire city</u> – would sustain structural damage when subjected to major levels of earthquake shaking. What was the basis for that decision? How would an entire city cope with all buildings being damaged? Why design for that to happen? There were no satisfactory answers.

And, other issues and questions were emerging – during the 50s and 60s society were being fundamentally transformed[6]:

- The digital computer had come into existence (see Table 1 for some key dates), allowing increased analytic capability.
- Like the digital computer, Operations Research had been developed during World War 2, and its statistical, probabilistic and structured approach was seeping into many areas of technology.

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[6] The points that follow are entirely US-centric, due to the writer knowing only the cultural history of his own country (if that!). However, the US had enormous influence at this time, particularly in the technological arena, so that these culturally-specific events to some extent had global influence. It of course would be interesting to compare contemporary influences in Japan, Europe and elsewhere.

- Another product of the war, atomic power, was being converted to ‘atoms for peace’. In the 50s only a few nuclear power plants were built, but construction accelerated quickly in the 60s, Figure 8.
- The 1927 Mississippi and other floods had lead to the Navigation Act of 1936, which introduced benefit cost analysis, including the discounted cost of damage, into engineering and federal thinking (but in the flood arena, not seismic). There had been a hiatus during the War, but by the 50s flood protection was a major effort, and had to be justified. To support this, the US Army Corps of Engineers formed the Hydrologic Engineering Center in 1963, to develop tools for estimating flood probability and avoided damage.
- The fire insurance industry, which had lead the way in accumulating detailed accurate exposure data (and loss statistics) since the Civil War, came to the conclusion that their loss statistics were probably adequate for future underwriting, and the legions of surveyors compiling Sanborn maps were no longer necessary.
- Also in the insurance industry, Thomas F. Malone and Don Friedman were bring the science of meteorology and risk analysis to Travellers Insurance, to model hurricane losses for the insurance industry. They had come to Hartford from MIT to develop data and probabilistic estimates with enough rigor for the actuaries.
- Ian McHarg was teaching ‘design with nature’ at the University of Pennsylvania. He and urban planners everywhere were struggling with how to rationally and efficiently process the many factors they recognized as important. Towards the end of the 60s, Geographic Information Systems emerged, with the development of *Canadian GIS* in 1967, and the founding of ESRI in 1969.
- Vance Packard wrote *The Hidden Persuaders* (1957) showing the manipulative tactics of Madison Avenue; Jane Jacobs in *The Death and Life of Great American Cities* (1961) critiqued isolated, unnatural urban spaces; Rachel Carson’s *Silent Spring* (1962) gave birth to the environmental movement; the outrageous demolition of New York’s Penn Station (1964) spawned the conservation movement; and Ralph Nader’s *Unsafe at Any Speed* (1965), started the consumer movement. These statements and the heartfelt public responses were indicative of an erosion of faith in US institutions and their ‘trust me’ paternalism, and of an aversion to risks that unconsidered growth was creating. There arose a demand for demonstrable safety, which Carson, Nader and others were showing Americans weren’t getting.

Technical demands – the risk of nuclear power, investment in offshore platforms – and a growing consciousness that *explicit* consideration of risk was both possible and desirable combined to set the stage for a new model. Steinbrugge (1968) spoke for the earthquake community in a landmark monograph *Earthquake hazard* (sic) *in the San Francisco Bay Area; a continuing problem in public policy*, which brought the discussion of earthquake risk into the public forum.

The changing focus was signaled by the creation of the first center to provide research into the social science aspects of disasters, the Disaster Research Center at Ohio State University founded by Russell Dynes and E.L. Quarantelli in 1969.

3.1.3 1968

And then, in 1968, there appeared Cornell's paper *Engineering Seismic Risk Analysis*. In the field of seismic risk, no paper has the impact that Cornell's did. Perhaps Richter's definition of magnitude had a similar impact on seismology in 1935. It was a breakthrough publication – everyone got it, the paradigm shift in earthquake engineering to a probabilistic way of thinking. Although it appeared to come out of the blue, it hadn't. At UNAM, Esteva and Rosenblueth (where Cornell had been a visiting professor) were working on similar lines, Kawasumi had produced *national maps* 17 years earlier, and Housner had been there, in a 1952 paper. In fact, Cornell in the first sentence of the paper cites Blume, 1965; Newmark, 1967; Blume, Newmark and Corning, 1961; Housner, 1952; Muto, Bailey and Mitchell, 1963; and Gzovsky, 1962. But the Cornell paper nailed it. The next sentence goes on to say *"The engineer professionally responsible for the aseismic design of a project must make a fundamental trade-off between costly higher resistances and higher risks of economic loss"*. Simply put, the paper laid out a transparently clear, reproducible algorithm for integrating the probabilistic contributions of any number of faults ('sources'), to determine the total 'risk' at a site – that is, the probability distribution of ground motion (an irony of the paper is that the *risk* in Cornell 1968 refers to *hazard*, as commonly used today). While the paper strives to provide a closed form solution, in general it couldn't do that, and to this day virtually all seismic hazard estimates are developed via numerical integration using special purpose codes (discussed further below).

Others soon followed – Milne and Davenport in 1969 used a similar methodology to develop a complete seismic hazard mapping of Canada, similar to Kawasumi's mapping of Japan (Milne and Davenport submitted their paper seven months after Cornell, but before his appeared. This writer does not know if they were aware of Cornell's work. However, while their paper is very good, it's an application, and doesn't read with the same clarity and impact as Cornell's).

Also in 1969, Algermissen, in the first sentence of his paper on page one of the 4th World Conference of Earthquake Engineering, observed *"The zoning of the United States for seismic risk has not received the attention…that the subject has enjoyed in other parts of the world, notably in countries such as Japan, the U.S.S.R and New Zealand*." His paper went on to present a "seismic risk map" [Algermissen's quotes] of the United States, Figure 11, which however he was careful to point out was not frequency (ie, probabilistically) based and which was an interim map – more work was in the offing. Nevertheless, it was quickly adopted by the UBC, replacing the 1949 'withdrawn' map. In 1976 a fully probabilistic map was released , Figure 11, using attenuation equations for hard rock developed by Schnabel and Seed in 1973, modified for slower attenuation in the Eastern and Central US. The level of detail for California shown in the inset in Figure 11 (not unlike the detail of Kawasumi's 1951 map), when compared with the 1970 map, shows the analytical capability the Cornell method provided.

3.1.4 To Today

From the early 70s to today, the seismic hazards field has generally been one of consolidation, with much effort on more and better data, and refinement of concepts and models. The basic elements for seismic hazard analysis are sources (derived from geological and seismological data), strong ground motion attenuation, site effects, and methods to analytically integrate the data. We summarize source, attenuation and analysis here, omitting site effects due to space.

3.1.4.1 Source

Source data availability has advanced enormously since Cornell's paper. Plate tectonics emerged in the 60s and that framework has guided much source identification. Kanamori and Hanks reduced the plethora of magnitude scales that had developed following Richter in 1935, to the moment magnitude scale, M_w, that is increasingly the international standard. Global catalogs have been compiled from the various national catalogs, and much work has been done to remove duplicate entries and correct other errors. "The *International Seismological Centre* is a non-governmental organization charged with the final collection, analysis and publication of standard earthquake information from all over the world. Earthquake readings are received from almost 3,000 seismograph stations representing every part of the globe. The Centre's main task is to redetermine earthquake locations making use of all available information, and to search for new earthquakes, previously unidentified by individual agencies." (http://www.isc.ac.uk/).

An issue for probabilistic hazard estimates like Milne and Davenport's or Algermissen's is how complete and homogeneous is an earthquake catalog? In 1972 Carl Stepp developed a useful test for catalog homogeneity, which has improved the quality of seismic hazard estimates. The problem is that a catalog may contain large events from long ago, but smaller events from that far back in history will likely be missing, due to lack of instrumentation, or simply lost records. For more recent periods, larger events will likely not yet have occurred. These gaps in the record result in underestimates of seismicity, relative to the long term record.

To fill these gaps, many of the most famous names in seismology, such as Mallet, Comte Montessus de Ballore and Davison to name a few, have pored over historical documents to document ancient earthquakes. One of the most diligent of modern investigators in this regard has been Prof. Nicholas Ambraseys of Imperial College (UK) who since the 60s has carefully research the historical record, particularly in the Trans-Alpide belt (ie, from the Mediterrean through to the Himalayas) . Careful examination of ancient documents can date an event and, by ascribing intensities to the descriptions, draw approximate isoseismals from which earthquake magnitude for the event can be back-calculated. The result of the effort of the many investigators doing this work is that the historical record of seismicity now dates back about 3,000 years, albeit very incompletely in the early period. To go back beyond the historical record, beginning in the 60s Wallace and co-workers began using paleoseismological techniques to extend earthquake catalogs back to prehistoric times . Examples of such techniques include dating of C_{14} deposits in ancient liquefaction sites, or in drowned forests, and dendrochronology (dating of tree rings). In 1984 these techniques were dramatically rewarded when evidence was found near Los Angeles by Kerry Sieh of repeated Ft. Tejon-like earthquakes going back a millennium .

Another effort has been the patient mapping of earthquake faults by geologists over many decades. The result is that many regions now have detailed fault maps (http://earthquake.usgs.gov/regional/qfaults/ for the entire US; http://unit.aist.go.jp/actfault/english/products/index_e.html for parts of Japan).

3.1.4.2 Strong motion

A large amount of effort has been spent on building strong motion networks – the first as discussed above was in Southern California in 1933, and the Japanese followed in the 1950s. Networks were established in the 1960s in Mexico, Europe, New Zealand, India, and in the 1970s in Turkey, Iran, the Philippines and Taiwan (where a very large amount of data was recorded in the 1999 ChiChi earthquake), and exist in many other countries. Figure 5 shows the growth in number of recordings, and Figure 9 shows two of the larger strong motion networks in Japan, which, in sheer number of instruments, appear to dwarf networks anywhere else.

With increasing numbers of strong motion recordings, better and better attenuation equations have emerged. A relation developed by Donovan (1973) was one of the first to use the data from the 1971 San Fernando earthquake, and was widely used until well into the 80s. Douglas cites 121 relations developed between 1969 and 2001 for PGA, and 76 for spectral ordinates – key workers in this field have been Esteva, Blume, Donovan, Ambraseys, Trifunac, McGuire, Idriss, Milne, Faccioli, Campbell, Joyner, Boore, Bolt, Abrahamson, Crouse, K. Sadigh, Annaka, Somerville, Youngs, Yamazaki, Bommer, and Bozorgnia, approximately ordered according to their earliest contribution.

The great majority of strong motion attenuation relationships developed to date have an empirical basis. In the 80s and 90s a few attenuation relations were developed based on theoretical / analytical considerations (eg, relations by Boore, Nuttli, McGuire), and there is now an increasing trend toward analytical models.

3.1.4.3 Analysis

In 1976 McGuire, a student of Cornell's and then at the USGS, published open source software (McGuire, 1976, 1978) which greatly facilitated the numerical integration of the Cornell methodology. The freely available *FRISK* (Fault Risk) code was quickly used by many researchers and engineers around the world as the core of numerous computer codes, and greatly stimulated high quality seismic hazard analyses. To this day, pieces of the *FRISK* code are buried deep within many codes.

The HAZUS software (discussed in more detail below) is free GIS-based software available from FEMA that permits the estimation of seismic intensities for scenario events anywhere in the US. The project to develop the current US National Seismic Hazard Maps developed a new generation of software (http://earthquake.usgs.gov/research/hazmaps/publications/docmaps.php), and there is now a project led by Ned Field at USGS to develop an open source distributed hazard software code, *OpenSHA* (http://www.opensha.org/).

Many advances in seismic hazard analysis arose from the needs of the nuclear and offshore industries for state-of-the-art analyses. With the ability to better quantify seismic hazard, the US National Regulatory Commission (NRC) realized that there were many unknowns with the increasing number of nuclear power plants, particularly after WASH-1400 (discussed below), the 1975 Brown's Ferry near-disaster and the 1979 Three Mile Island disaster. From 1981 to 1989, the NRC funded the Lawrence Livermore National Laboratory (LLNL) to develop a Probabilistic Seismic Hazard Analysis (PSHA) method for the eastern United States, which was paralleled by a utilities sponsored study . A key development was more rational and accurate treatment of uncertainties, beginning by distinguishing between epistemic and aleatory uncertainties. Epistemic or 'modeling' uncertainties are based on a lack of scientific understanding that may be reduced in the future, and typified by different results from two models using the same basic data. Aleatory or "random" uncertainties are typified by the inherent variability in seismicity or other phenomena, and cannot be reduced for all practical purposes (NAP, 1997). The use of large logic trees simplified the task of treating uncertainties, such as whether a traditional Gutenberg-Richter or other magnitude-frequency relation (eg, "characteristic earthquake") was most appropriate.

3.1.4.4 Coda

In a sense, Cornell's paper marked the end of one chapter, and the beginning of the next. The chapter that 'ended' was that of seismic hazard, which in another sense had just begun. This may sound contradictory, but with Cornell's paper the problem of determining the probability distribution of the hazard had been solved, particularly given the concurrent emergence during the 60s of the theory of plate tectonics. The earth sciences now had a complete framework, of sources (ie, faults), ground motion and the theoretical framework to link them. The next several decades saw exciting work, as better ground motion models, magnitude-frequency relations, other work and data, data, data filled in the framework. The ground motion modeling was largely empirical, and it was only in the 90s that analytical strong ground motion modeling began to emerge. The US seismic hazard mapping program continued its development to where today it is by far the most advanced in the world. During the 90s, an international team (key members included D. Giardini, H. Gupta, K. Shedlock, G. Grunthal, M. Garcia, B. Iben Brahim, D. Slejko, C. Pannonian, R. Musson, S. Balassanian, V. Ulomov, M. G. Ashtiany, K. Atakan, I. Nyambok, P. Zhang, K. McCue, E. Engdahl, R. McGuire, and D. Mayer-Rosa) developed a global seismic hazard map (GSHAP, 1998), Figure 3. The effort not only produced the first consistent global estimate of seismic hazard, but had many derivative positive effects in promoting international cooperation and enhancing standards and capabilities. It is based on 150 years of hard work and advances in the seismological, geological and other sciences.

And yet, Mallet's map comes off rather well. The difference is we now understand, at least to a better extent, many of the things that Mallet could only see as a glimmer.

3.2 Vulnerability

The chapter that now began had to do with Vulnerability. This is ironic, in that most people's expectations, including the expectations of those in earthquake engineering, is that the engineers can analyze structures to an infinitesimal degree, whereas it's the earth scientists that are always in the 'discovery' mode. And yet, in a very real sense and from the perspective of seismic risk analysis, we know more about the earth than about what humankind has built.

A note on the rubric Vulnerability – first, it refers to both *vulnerability* functions (ie, functions directly relating hazard to final loss or consequence, such as a curve of repair cost as a function of MMI for a selected structural type), and *fragility* functions (which provide a damage state conditioned on hazard, such as Heavy Damage as a function of PGA – the fragilities can then be related to consequences, such as business interruption). Second, we also include under the heading of Vulnerability advances contributing to vulnerability and fragility function development, particularly structural engineering analytical techniques, although we keep discussion of the contributing advances as brief as possible.

Just as with ground motion and many other phenomena, there are two fundamental approaches to vulnerability – analytical, and/or empirical. Ideally, the two approaches are employed in a complementary manner to arrive at a hybrid model, but in seismic risk this has rarely been attempted.

Regarding the analytical approach, consider what is involved if one is asked to estimate the seismic risk of a building:

- In a few moments, for any site in the US, one can access the USGS website[7] and obtain key points on the site's hazard curve, in terms of PGA, spectral acceleration, etc. If the site is not in the US, there is still an extensive global literature of earthquake faults, as well as earthquake catalogs, which can be employed in *FRISK* or other codes to estimate the hazard. Or, admittedly with less confidence, one can access GSHAP and obtain an approximate estimate of the hazard. In either of the above cases, the hazard will need to be adjusted for site specific soil conditions but readily available geologic maps for most of the US and many other localities often will provide sufficient information for at least a preliminary adjustment.
- However regarding the building structure, if the engineer is lucky drawings will be available. Even with drawings, the engineer will still have to make a site visit to ascertain if the building today is the building the drawings show – every engineer has had the experience of finding seismic bracing cut for a new door. The drawings will provide limited information on the nominal material strengths but, for structural analysis material samples (particularly of the concrete) will typically be taken, as well as non-destructive confirmation of reinforcing bar location (similar investigations would be made for wood or other structural materials).
- With the drawings, all that an engineer can do at first is identify whether a lateral force resisting system (LFRS) was incorporated by design. If there is no LFRS, then in a sense the job is easy – the building can probably be judged to be a high risk, and the engineer can proceed to design of strengthening (or other measures) to reduce the risk. However, if an LFRS is found to exist, by design or imputed, then the engineer has several choices – several increasingly complex ELF type analyses, or increasingly complex dynamic structural analysis.

The decision as to what level of analysis to employ depends on the client's need for accuracy and confidence, and the potential liability involved in rendering a professional opinion. However, any analysis involves a considerable level of effort. To begin with, there is the data acquisition and reduction effort – the masses of parts of the structure must be estimated, and the structural stiffnesses of each structural member must be determined. When this data is compiled, it must be built into a structural model, and that model analyzed. Until the 1960s a dynamic structural analysis was infeasible for ordinary practice . The advent of the Finite Element Method (FEM), which had its roots in the 1920s but didn't develop into a usable tool until the 1960s , and the advent of a modicum of computing power, permitted the development of software that made linear dynamic structural analysis feasible, particularly with the invention of the Fast Fourier Transform. However, generally speaking, linear analysis is not an analysis for structural damage which by definition is an excursion of the structure into the nonlinear range. Nonlinear dynamic analysis, typically performed in the time domain, only became feasible in the late 80s, and is still today an advanced method infrequently employed.

Today, commercial software such as *ETABS, SAP2000, ANSYS, STRUDL, RISA3D, STAAD* and *MULTIFRAME* permit linear and nonlinear analysis and are integrated packages with visualization, Figure 12, section properties, CAD and other features. There are a surprising number of free software packages available (see http://www.structural-

[7] http://eqint.cr.usgs.gov/eq-men/html/lookup-2002-interp-06.html

engineering.fsnet.co.uk/free.htm for an extensive list). *OpenSees (* http://opensees.berkeley.edu/) is a free open-source software developed by the Pacific Earthquake Engineering Center (PEER) to simulate the performance of structural and geotechnical systems subjected to earthquakes. The Mid Americas Earthquake Center (MAE) has developed *ZEUS-NL* a free 3D static and dynamic analysis platform for earthquake engineering applications (http://mae.cee.uiuc.edu/software_and_tools/zeus_nl.html).

So, while seismic hazard is available literally at one's finger tips today (at least for the US, via the USGS website), the determination of the potential damage given that hazard (ie, the vulnerability) of a structure is still a time-consuming process, with substantial effort for data acquisition and preparation, and still significant effort for analysis, in which substantial approximations are more the norm than the exception.

And, the above discussion has been for one defined building where the engineer has access to all the available information. If a vulnerability estimate of a *portfolio* (ie, a collection of facilities, such as all the schools in a city), or of a region (ie, just a larger portfolio, but involving all the buildings, plus perhaps some or all other infrastructure such as water, wastewater, power, transportation, telecom etc, collectively referred to as *lifelines*) is required, then the determination of vulnerability using traditional detailed structural engineering techniques is often impractical (for a portfolio), and simply not possible at the regional scale. Other means for development of vulnerability functions must be resorted to. Thus, there are two approaches for development of vulnerability functions – empirical, and analytical. We next briefly review (non-exhaustively) some key events in the development of each.

3.2.1 Empirical Approaches

Empirical development of vulnerability functions involves the collection of damage observations and data for variety of structures or other assets at risk, the organization before or after collection of the variety of assets into some schema, and the processing of the observations and data for each category within the schema to determine a relation for vulnerability as a function of a measure of hazard.

As noted earlier, vulnerability is a general term – when used in the specific, measures of vulnerability are one of the three D's (*deaths, dollars or downtime* – that is, human injury, financial loss, or temporal disruption). The general term vulnerability also refers to fragility, meaning a relation for damage state (Light, Heavy, Collapse, etc) as a function of a measure of hazard. Measures of hazard range from qualitative intensity (MMI, JMA…) to quantitative (PGA, Sa, Sv, etc).

The first empirically-based vulnerability functions were the intensity scales themselves, as developed by Rossi, Forel, Mercalli and others although as discussed above there is some circular reasoning in their usage.

The investigations following the 1906 San Francisco earthquake and 1923 Tokyo Earthquake included detailed examination of structures but this data does not appear to have been processed in any manner for development of a vulnerability function. Freeman (1932) presents some general estimates of damage based on a review of the 1906, 1923 and other events for several categories of buildings, Figure 13. Chick in 1934 presented very similar ratios following the 1933 Long Beach Earthquake. Martel in 1936 investigated "if significant differences in damage [in an earthquake] resulted from differences in the building's subtype, occupancy, or adjacency to other buildings" by looking at 1,261 unreinforced-masonry buildings (UMBs) in Long Beach, CA, and a number of woodframe residences in Compton, CA, shaken by the 1933 Long Beach.

Following World War 2, Japanese investigators and the US Army documented the 1948 Fukui (Japan) earthquake, but the data doesn't seem to have been employed for any statistical purposes. The 1952 Kern County (California) earthquakes seem to have been the first US field investigation of earthquakes since the 1933 Long Beach earthquake, and involved a 'new generation' of investigators (eg, Steinbrugge, Degenkolb, Moran), who did a good job of documenting the earthquake and its aftershocks .

However, the 1964 Prince William Sound (Alaska) was extensively documented (US Coast and Geodetic Survey, 1966-1969. A number of engineers from California (Henry J. Degenkolb, Karl V. Steinbrugge, among others) surveyed the damage to modern construction , and were shocked:

> *I know when I came from Alaska, I figured from now on we're designing buildings as if the earthquake is going to happen in another five years, and we're going to have to answer for all the mistakes. It sure stiffens up your back.* (Degenkolb, EERI, 1994)

The next year Karl V. Steinbrugge wrote *Earthquake Hazards in the San Francisco Bay Area: A Continuing Problem in Public Policy* (Steinbrugge, 1968). That publication was very influential – it caught the attention of State Senator Alfred E. Alquist and contributed to the establishment of the California Seismic Safety Commission, for example. However, from our perspective, it started a series of investigations into what a large earthquake might do in a US urban center. A small group including Karl Steinbrugge, Frank McClure, Henry Lagorio, Henry Degenkolb and others were motivated to develop loss estimates for US urban areas (discussed below). In the first of numerous studies on earthquake damage and potential losses , they laid the basis for probabilistic earthquake hazard estimation and, particularly Frank McClure in Chapter III of that report, gathered dollar value loss, by class of construction, for 1,139 buildings that were reported as damaged by the M7.6 Kern County earthquake of July 21, 1952, and its aftershocks. The objective was to estimate the fraction of all structures, by class of construction and "amount of lateral bracing," that were demolished, repaired, or undamaged as a result of the earthquake. A matrix relating 24 dwelling construction classes with the 12 Modified Mercalli intensities is used; each of the boxes in this 24 x 12 matrix contains a damage ratio (cost of repair as a percent of replacement cost) and a damage factor (the percentage of buildings of this class and located in that intensity zone that would actually experience the specified damage ratio).

Seed investigated the July 29, 1967 Caracas Venezuela earthquake (M6.4), in which four 10- to l2-story buildings totally and one l2-story building partially collapsed (over 200 lives lost). Basic finding was that damage could be approximately correlated with spectral velocity normalized by the buildings lateral design coefficient.

The 1971 San Fernando (California) earthquake then occurred and caused a significant amount of damage to low- and high-rise buildings, collapsing the Veterans and new Olive-View hospitals. McClure did a detailed study of 169 single-family dwellings in the epicentral region of the 1971 San Fernando earthquake (ie, PGA 0.25g to 1.0g), and almost all of which experienced damage in excess of $5,000 (1971$). Hafen analyzed the 1971 San Fernando earthquake for low and high-rise damage data, correlating it with Blume's Engineering Intensity Scale. Rinehart estimated earthquake losses to single-family dwellings based on a detailed empirical basis. Scholl examined the 1971 San Fernando earthquake and several underground nuclear explosions to correlate low-rise building damage with an envelope of spectral accelerations in the 0.05 to 0.2

second range (this being the range of natural periods of USA low-rise buildings). Whitman developed the DPM based on the 1971 San Fernando (and other) data. These correlate discrete damage states with MM1 (which are discrete ground motion states). Part of the same SDDA project later attempted correlations of the San Fernando damage experience with response spectral measures, finding spectral acceleration or velocity to be satisfactory, though no measure of the correlation is given. Algermissen employed MMI, 5 classes of buildings, oval isoseismals and judgmental intensity-loss relations to develop an estimation methodology for mid-rise buildings. This last study was probably most significant for its use of a detailed building inventory.

The MIT Seismic Design Decision Analysis (SDDA) project deserves special mention, as it was an extensive integrated approach to the entire issue of seismic design. Lead by R.V. Whitman, it produced at least 33 reports over five and a half years (Table 2). The program's contributions went beyond the topic of this subsection, and included more sophisticated seismic studies , introduction of Damage Probability Matrices (DPM), seismic design cost studies, incorporation of incident losses (eg, lives lost, business interruption), and the introduction of multi-attribute decision making. Many of the project's studies continued the practice of using MMI as the intensity parameter (but not all – Wong used response spectra) while recognizing that more objective measures would be better. Overall, the project was a very significant step forward in many areas, including seismic risk analysis.

In Japan, an extensive literature has been built up describing earthquake damage.. Mochizuki surveyed existing structures in Tokyo and related these to damage ratios providing a good match with the 1923 Kanto earthquake. Shiga , for 1 to 5 story Japanese RC buildings, related damage in the 1968 Tokachi-oki earthquake to wall ratio and nominal shear stress in columns and walls, providing a probabilistic estimate for building damage.

In 1985 the Applied Technology Council (ATC) published ATC-13, *Earthquake Damage Evaluation Data for California*, which has been a major influence ever since. The study used a modified Delphi process for expert opinion elicitation to poll 85 experts on their estimates of damage to 78 different classes of buildings and infrastructure. Building stock was categorized by material of construction (eg, W = Wood) and lateral force resisting system (eg, W1 = single family dwellings, S5 = low-rise light metal steel buildings). Derivatives of this categorization, not changed very much, have continued through two decades of work in the US, including HAZUS, and are the model building types (MBT) likely to continue in use for much longer. The expert's opinions were fitted to beta distributions and presented in the form of Damage Probability Matrices. The resulting ground motion-loss vulnerability functions were not explicitly derived from statistical data, but were still empirical in that they were based on the observations of the experts. Substantial guidance was given on compilation of building inventories and related matters. The ATC-13 report has stood the test of time very well. Key persons leading the effort included Chris Rojahn, Roland Sharpe, Anne Kiremidjian, Roger Scholl and Richard Nutt, and the Project Engineering Panel consisted of Milton **A.** Abel, , J. Marx Ayres, John A. Blume , George E. Brogan , Robert Cassano, Ted M. Christensen , Henry J. Degenkolb , Homer H. Given, Henry J. Lagorio, Le Val Lund, Ferd F. Mautz, and James L. Stratta.

Following the 1994 Northridge earthquake, a project (ATC-38) gathered data on 530 buildings located within 300 meters of strong-motion recording sites that were strongly shaken by the earthquake, with the goal "to correlate the relationship between recorded ground shaking". The resulting data did not achieve its purpose of developing new correlations, in part due to the relatively light damage of many of the buildings in the vicinity of the seismographs. One lesson that was learned is that the placement of seismographs needed to be reviewed, so as to place more in areas of anticipated higher damage. Schierle also examined woodframe dwelling losses of the 1994 Northridge earthquake, with the objective to create seismic vulnerability functions for six categories of dwelling, but with similar lack of dramatic new findings.

The above discussion has focused on buildings, and lifelines will be discussed below. A third important class is equipment, since industrial and critical facilities are often more dependent on their equipment functionality than building functionality (short of collapse). A major effort to develop empirically-based equipment fragility functions was funded by the nuclear industry's Seismic Qualifications Utility Group (SQUG) during the 80s and 90s. Yanev summarized the extensive database of the observed seismic performance of industrial equipment and nonstructural components that was developed under the auspices of the Electric Power Research Institute (EPRI). The focus of the database is on facilities related to electric power, including power plants, electrical-distribution substations, oil refineries, and natural-gas processing and pumping stations. There are also extensive entries related to the earthquake performance of water-treatment and pumping facilities, large commercial facilities, hospitals, and conventional buildings. By 1990, the database reflected equipment performance at more than 100 major facilities, many smaller facilities, and hundreds of buildings that experienced strong motion (typically peak ground acceleration of 0.15g or greater). Surveys at that time included experience in 42 events since the 1971 San Fernando Earthquake.

3.2.2 Analytical Approaches

Until very recently, there have been fewer attempts at developing analytically-based vulnerability functions, for some of the reasons discussed above, and due to the recognition that empirically-based functions would more likely reflect actual built conditions and have more credibility. Blume et al in 1975 summarized and compared three damage prediction techniques: the spectral matrix method (an analytical probabilistic method), the seismic element method (*'an eclectic method using a theoretical basis but modified to include observed behavior'*) and the decision analysis method (empirical) finding advantages in each, depending on application. Czarnecki for the SDDA project at MIT, found that building component energy absorption over energy capacity roughly measured damage. Design level didn't seem to affect the damage level greatly. Kuribayashi in 1978 have used an average seismic coefficient dividing elastic from elastoplastic behavior, together with a normal distribution, to provide a damage estimator, although not relating it to the structural system. Sakamoto in l974 used a trilinear force-displacement curve together with standard displacement response spectra to determine a maximum acceleration for wooden houses.

Scawthorn et al in 1981 developed relatively simple but nonlinear dynamic models for low- and mid-rise buildings in Japan, and used empirical data from the 1978 Miyagiken-oki and other earthquakes to calibrate the models, marking one of the first attempts at a hybrid model. Kustu, Scholl and co-workers at J.A. Blume and Associates employed a similar technique but de-aggregating the building into its sub-components . Most recently, Porter has extended that approach and developed the Assembly Based Vulnerability

(ABV) method, which is the first fully rational approach to vulnerability. It consists of a detailed nonlinear dynamic analysis of a building, the results of which are employed to determine damage states for the structural and all significant non-structural components (eg, gypsum wall board, windows, suspended ceilings, mechanical and plumbing). Detailed cost data is then used to estimate all contributing repair costs for each component. While it can be applied to an individual building, it also can be used for classes or model building types, by defining ‘index buildings’ – in this mode it was used to examine the benefits and costs of retrofitting wood frame construction in California . The methodology is used by the California Earthquake Authority (ie, the state insurance company).

The HAZUS software uses a semi-hybrid approach, in that it employs the Capacity Spectrum method developed by S. Freeman in 1998 to estimate the non-linear behavior of the structure, to determine a fragility curve for the structure. Many of the parameters for the structural capacity however can be traced back to ATC-13, which means the methodology has an empirical basis. The translation from fragility to cost is at the overall structural, not component, level, although the method could easily be extended to the component level.

Lastly, for equipment, it should be mentioned that analytical techniques have also been developed, which are mostly applied in nuclear power and other applications where high reliability is required. Kennedy, Ravindra, Campbell, Short, Hardy, Reed and co-workers have lead the field in developing these methods .

3.2.3 Lifelines

The foregoing discussion has focused on building structures. Lifelines are much more varied than buildings, and space does not permit a review of all the work done in that regard – suffice it to say that lifelines emerged as a separate seismic field following the 1971 San Fernando earthquake, due in particular to efforts by Prof. C.M. Duke at UCLA, who was instrumental in founding ASCE’s Technical Council on Lifeline Earthquake Engineering (TCLEE). TCLEE has lead the field in the US since that time. Key leaders of TCLEE have included Hall, Schiff, Lund, Eguchi, T.D. O’Rourke, M. O’Rourke, Taylor, Tang, Werner, Elliott, Cooper, Ballantyne and Shinozuka, Kiremidjian, and many others (see http://www.asce.org/community/disasterreduction/tclee_home.cfm).

Most non-US contributions in the lifelines area have come either from New Zealand and especially Japan, where Kubo, Toki, Kameda, Katayama, Hamada, Sato and Takada have been key leaders. A noteworthy venue for developments in this arena has been a series of US-Japan meetings since about 1980 on the topic of lifelines seismic risk, lead by the above-named Japanese and US persons.

Three specific studies regarding lifelines vulnerability functions are worth noting:

- Lund and Schiff in 1991 developed a database for recording and compiling pipeline damage records. The database is composed of records, one record for each pipe failure. Each record consists of 51 data fields, indicating the associated earthquake, the pipeline owner, pipe break location, soil condition, details of construction and installation, and nature of the break. The database, which contains information about 862 pipe breaks in the 1989 Loma Prieta earthquake, is defined to facilitate appending pipe-break data from future earthquakes. Similar, larger, databases have been developed in Japan by Takada, Hamada and others.

- Recently, the American Lifelines Alliance (ALA) has developed a body of work on lifelines vulnerability .

3.2.4 Special Vulnerability Relations

The above discussion has focused on vulnerability of typical engineering topics – buildings and infrastructure. Because earthquakes affect virtually all aspects of society, a number of relatively specialized vulnerability relations have been developed, dealing with injuries, ground failure, Fire Following Earthquake, liquefaction and other aspects, for which we highlight some of the key developments.

3.2.4.1 Injuries

The estimation of human injuries is a key task for risk analysis. Steinbrugge had provided estimates of injuries in the USGS and NOAA studies in the 70s, but based only on a simple rule of thumb. Mitchell was one of the first to seriously consider this issue, based on Turkish earthquakes. The 1985 Mexico City earthquake had a particular impact on this topic, due to (a) the large number of high-rise building collapses, resulting in an extended period of search and rescue for the large numbers of trapped victims, with tragically little to show in the end, and (b) the large number of hospitals that had collapsed, doubly compounding the disaster medical response. The US and other countries began to examine issues of search and rescue, and there was a large amount of activity internationally having to do with search dogs and many kinds of technology (infrared, sound, heartbeat detectors, microcameras, etc. FEMA sponsored work on heavy search and rescue (ATC-21), and developed the USAR (Urban Search and Rescue) team concept in place today. Friedman in 1988 developed an estimate of Workers Compensation losses for a "Worst Case" event in Greater Los Angeles, for the insurance industry. Durkin in 1992 collected injury data and examined the damage to health care facilities. Jones, Noji, and Krimgold, convened a key workshop in 1989 on the topic, which was followed a year later on the other coast by a second workshop – these two workshops were the state-of-the-art at the time, although the field was still developing. They were followed in 1992 by an international conference on the topic . The HAZUS software contains an injury module. Most recently, Shoaf, Seligson and co-workers have been working on a complete injury model, including valuing the cost of injuries , and various investigators have been collecting injury-related data.

3.2.4.2 Liquefaction

While a large effort has been spent on liquefaction since its ‘discovery’ in the 1964 Niigata (Japan) earthquake, almost all the effort has focused on either estimating the potential for liquefaction, or mitigating it, for specific conditions. Almost no work has been done on developing functions to estimate the distribution of damage to a class of buildings in a locality given the occurrence of liquefaction. In fact, one might say that most of the liquefaction related work has been at the “hazard” or “micro” scale. The first research this writer is aware of regarding estimation of damage to buildings given the occurrence of liquefaction was by this author (in 1981) who investigated the probability of damage to Japanese low-rise wood buildings given the occurrence of significant liquefaction, finding that about 10% are destroyed and 25% damaged.

3.2.4.3 Fire Following Earthquake

The problem of fire following earthquake is a potentially very serious earthquake problem in regions with large wood building inventories, as the 1906 San Francisco, 1923 Tokyo and 1995 Kobe earthquakes show. The insurance industry had long been concerned about this issue and the problem had been addressed in Japan, although only in piecemeal manner. The problem was unaddressed in the US until the early 80s, when a stochastic model of the Fire Following Earthquake process was developed by Scawthorn. Steinbrugge highly evaluated the model for insurance applications, and it was subsequently widely adopted by the insurance industry .

Fire Following Earthquake modeling in Japan improved dramatically in the 80s, and recent researchers in Japan include Sekizawa , Murasaki and Tanaka , as well as on-going work by the Tokyo Fire Dept. and Japan's National Fire Research Institute. New Zealand is also concerned about the problem, and investigators there include Cousins and the New Zealand Fire Service .

3.2.4.4 Hazardous Materials

Environmental impacts resulting from release of hazardous materials (HAZMAT) in earthquakes have received relatively little attention. Preparedness and response to natural hazards have tended to focus on human casualties, structural damage, and property losses, and environmental impacts have only been reported when they have resulted in major incidents, such as the petroleum fires that followed the 1964 Niigata earthquake. This situation is changing, due to a number of factors, including better recording of HAZMAT incidents in natural hazards (eg, 387 such incidents in the 1994 Northridge earthquake, not to mention the enormous environmental impacts of Hurricane Katrina in New Orleans), and more stringent standards for environmental liability.

Reitherman was perhaps the first in the US to look at the problem of hazardous materials releases in earthquakes, in 1982, and he, Selvaduray and Perkins have developed databases and methods for the problem. The HAZUS project reviewed the state-of-the-art as of 1992 and found three models as of that time . The model developed by Tierney et al.focused on the likelihood of gaseous releases, and its potential effect on surrounding populations. However, it was not found to be suitable for risk assessment efforts by local jurisdiction personnel due to the level of detailed analysis required. The study by Ravindra was very similar to the Los Angeles County Fire Department methodology, and was really intended for seismic vulnerability analysis of individual facilities, requiring significant expert input. The HAZUS model provides a listing and mapping of HAZMAT facilities vs. seismic intensity.

More recently, Steinberg and Cruz have closely investigated the 1999 Marmara Earthquake (Turkey), where a number of hazmat releases occurred.

3.2.4.5 Socio-Economic Impacts and Business Interruption[8]

While estimates of casualties, cost of repair and other 'direct damage' measures come first to mind for most applications, the economic impact of an earthquake on a business, and the economic impact of a great earthquake on the overall regional economy, are important issues. Dacy and Kunreuther in 1969 and Mukerjee in 1971 were probably the first to examine the broader economic impacts of natural hazards, while Cochran in1974 was the first to quantify the economic impacts of a large regional earthquake, in this case the 'coming San Francisco earthquake', for which he found about half the overall economic impact was 'secondary':

> *A reoccurrence of the 1906 San Francisco Earthquake in 1974 would likely cost the Bay area in excess of $13 billion, approximately one half of which would take the form of lost income due to a regional economic recession. The unemployment rolls would be swelled by as many as one quarter million. The probability of such large scale social disruption following an extreme geophysical event signals the need for a broadened perspective in planning for such potentialities, and the need to review the choice of adjustments to mitigate these effects. Concentration on mean annual damages or direct damage ensuing from disaster may not take into consideration the social benefits of measures pursued to affect damage reduction. The importance of these findings lies in the implications for public policy which may need some rethinking if the potential for large scale economic chaos is to be avoided.* (Cochrane, 1974)

The economic aspects received further attention in the 80s, as Rose and co-workers examined the economic costs of loss of infrastructure , and Ellison, Milliman and Roberts examined the regional economic effects of earthquakes and earthquake prediction. Another aspect of considering economic impacts was at the 'micro-scale', where FEMA funded development of methodologies for assessing the benefit-cost of seismic retrofitting . Beginning in the mid-90s, the HAZUS project developed a well-founded model of the regional economic impacts of a large earthquake , which employs a computable general equilibrium model designed to rebalance a region's inter-industry trade flows based on discrepancies between sector supplies and demands.

Modeling of economic impacts, like the other aspects of modeling discussed here, must be based on good data. A number of investigators have collected data from various earthquakes, but two efforts were particularly important:

- Tierney and Dahlhamer performed surveys of disaster-related business impacts of the 1994 Northridge Earthquake (as well as 1993 Midwest floods), focusing on eight aspects related to determining business interruption: business characteristics, nature of physical damage, lifeline service interruption, business closure, business relocation, insurance and disaster-assistance programs, disaster preparedness, and losses. These studies contributed to understanding the particular vulnerabilities in natural disasters of small and mid-sized businesses.
- A study of the Northridge Earthquake by EQE International, Inc., and the Governor's Office of Emergency Services was perhaps the most-thorough effort to collect data and compile a database of the effects of an earthquake. The data included the seismological and geotechnical aspects of the earthquake; the characteristics of the building stock

[8] The author hopes to expand on this section in the final paper.

exposed to strong motion; building damage data including ATC-20 safety evaluations and repair-cost estimates; coroner data on earthquake-related fatalities; relocation and injury data from cities, the Red Cross, and the Salvation Army; and insurance losses reported by the California Department of Insurance.

3.3 Asset Identification and Attributes

The third ingredient for a seismic risk analysis, beyond the hazard and a vulnerability function conditioned on the hazard, is the identification of and attributes of the assets at risk. As noted earlier, over 100 years ago, detailed fire insurance maps were available for all major urban areas of the US – an underwriter literally had at his fingertips up to date information on the size, occupancy, materials of construction and protective features (for fire) for every building in a city. That was lost in the mid 20th Century. Steinbrugge and succeeding investigators trying to develop accurate informative loss estimates from the 70s until very recently have struggled with trying to determine *what is out there*?, and *what are its attributes relative to seismic vulnerability*? (and, *where is it*?). For an individual structure, drawings will typically be available, but for a regional loss study, similar information on the 'portfolio' or 'inventory' is typically so widely dispersed as to be inaccessible. Tax assessor records have been a chimera – they are difficult to acquire, are different in every county, and in most counties don't contain much reliable information on structural attributes. Selected counties' assessor records (eg, Los Angeles, San Francisco) have relatively useful amounts of structural information, but still require significant processing.

Perhaps the only academic pursuing the problem of built inventory in the 70s and 80s was Barclay Jones, at Cornell University, who investigated relationships between population size and techniques for estimating size and characteristics (floor area and height) of building stocks in urban areas –case studies were cities in Colombia and Turkey as well as the boroughs of New York City. Jones in1987 addressed losses from earthquakes, noting that estimating elements at risk had received less attention to date. A complete enumeration of the building stock of a moderate-sized metropolitan area in the United States, Wichita, Kansas, was compared to previous and less complete studies. The number and area of buildings disaggregated by use was given and replacement costs calculated. The spatial distribution of buildings by rings outward from the center was also determined. The techniques developed were shown to approximate existing building stock of a metropolitan area in greater detail than previous work, and regularities in the composition and distribution suggested that the techniques were generally applicable.

In the early 80s, a study by Scawthorn and Gates of earthquake losses was one of the first to develop 'proxy' measures of many attributes , and in 1985 the ATC-13 study provided an excellent survey of practices to date, and guidance for filling in the gaps in data. The FEMA 224 study (1991) benefited from better information on infrastructure. Since that time, GIS has penetrated most municipalities, who are tending towards integrated databases of all facets of their operations. However, the detailed structural attributes desired by risk analysts is still lacking. The insurance industry, under the influence of the modeling companies, have improved their data enormously. Most recently, remote sensing and related techniques hold out some hope of providing automated data acquisition at the regional level.

The one major advance has been the development of a national database of assets at risk, by the HAZUS project. The specific inventory provided for the general building stock are (FEMA, 2006):

- **Square footage by occupancy.** Estimated floor area by specific occupancy (e.g., COM1).
- **Full Replacement Value by occupancy.** Estimated replacement values by specific occupancy (e.g., RES1).
- **Building Count by occupancy.** Estimated building count by specific occupancy (e.g., IND1).
- **General Occupancy Mapping.** A general mapping of the inventory data from the specific occupancy to general building type (e.g., Wood).
- **Demographics.** Housing and population statistics for the study region.

These data were compiled from various sources (Census of Population and Housing, 2000: Summary Tape File 1B Extract; Census of Population and Housing, 2000: Summary Tape File 3; Dun & Bradstreet, Business Population Report aggregated by Standard Industrial Classification (SIC) and Census Block, 2002; Department of Energy, Housing Characteristics 1993 and related 1995 and 1997 data). This data is then mapped to Model Building Types using a pro ration scheme. While proxy-based and no substitute for detailed local information, the resulting inventory data appears reasonably correct in the mean, is consistent across a region, in fact nationally, and is freely and readily available on the HAZUS CDs. The HAZUS database is an enormous advance, at least for a first approximate analysis (useful for determining the overall magnitude and significant of the earthquake risk, and for planning more detailed studies), which is the primary purpose of HAZUS.

Outside the US, the issue of developing a portfolio generally still remains although in selected regions excellent databases have been developed. A surprising number of municipalities in developing economies tend to have relatively sophisticated GIS systems. Some regions (eg, parts of Japan) tend to have better building data (relative to the US). The problem can be tackled head-on – an impressive recent effort was Istanbul, where over one summer, school teachers (who were on summer vacation) were hired, trained and then surveyed every building in the City, to compile a database for earthquake loss estimation purposes (M. Erdik, personal communication). This data was all loaded into an existing high-quality municipal GIS system.

A recent contribution to the problem of asset attributes has been the World Encyclopedia of Housing, developed by a global group lead by EERI members and sponsored by the IAEE. The WHE contains a wealth of information on the construction and seismic resistive aspects of housing and other building types around the world, including information on seismic strengthening of various building types specific to the region, Figure 14.

3.4 <u>Risk Analysis Methods</u>

The fourth aspect of a seismic risk analysis, beyond the hazard, vulnerability and asset attributes, is the mathematical and theoretical ***analysis methods*** by which the three elements are combined to more or less rigorously and accurately estimate the risk. Willis in1923 compiled some loss ratios but Freeman (1932) was probably the first to systematically compile damage data and develop economic loss ratios for a wide variety of building types (reading the literature, it would appear that insurance underwriters had compiled and used loss ratios prior to 1932, but Freeman would have been very familiar with such work, and clearly felt the information he offered in his book was badly needed).

The concept of Probable Maximum Loss (PML, also variously referred to as Maximum Probable Loss, and other variations) has long been used in the fire insurance business, probably since the 19th century. PML is actually one of three 'levels' for consideration while underwriting for fire: Probable Loss, PML, and Maximum Foreseeable Loss (MFL). As of 2006, the Insurance Services Office defines PML for fire as:

> ***PML (Probable Maximum Loss)*** *is an estimate of the largest loss that a building or a business in the building is likely to suffer — considering the existing mitigation features — because of a single fire. The PML is the maximum expected loss, expressed as a percentage of the building's value, when critical protection systems are functioning as expected.*
>
> *The Maximum Foreseeable Loss (MFL) is an estimate of the largest fire loss likely to occur if a key loss-reduction system fails.*
>
> *The PML and MFL percentages depend on many factors, including:*
>
> - *construction of building*
> - *combustibility of contents*
> - *susceptibility of contents (likelihood of damage from fire, smoke, and water)*
> - *private and public fire protection*
>
> *For example, in a fire-resistive building with a fire-division wall between each occupant, chances are the entire building wouldn't burn if a fire broke out. But in a building without adequate protection features, a single occurrence might involve a significant loss, and the probability is high that both the building and its occupants would experience extensive damage in the same occurrence. And occupants such as flower and pet shops can experience severe losses even in small, quickly extinguished fires.* (ISO, 2006)

Guy Carpenter, the leading reinsurance broker offers :

> ***MFL (Maximum Forseeable Loss)*** *The anticipated maximum property fire loss that could result, given unusual or the worst circumstances with respect to the nonfunctioning of protective features (firewalls, sprinklers, a responsive fire department...as opposed to PML (Probable Maximum Loss), which would be a similar valuation but under the assumption that such protective features function normally.*

Other authorities defining PML can be cited – today, it is still a widely used term in the insurance and related industries, for fire.

Regarding earthquake, on the other hand, Freeman (1932) did not use the term, and the concept of PML was long recognized as problematic. McGuiness in1969 observed:

> *The term "PML" or "probable maximum loss" is one of the most widely used terms in property insurance underwriting. But it represents one of the least clear concepts in all insurance. This fact is reflected by the results of a four-year study that involved collecting*

> *the personal and company definitions of PML from over one hundred underwriters and underwriting executives. No two of their definitions fully agree.*

However, despite problems for using the term in regard to earthquake, it was used by McClure in 1969, probably due to the influence of Steinbrugge, who worked in the insurance industry. In the aftermath of the San Fernando earthquake in 1971, concern about the exposure of the insurance industry to earthquakes greatly increased, leading the California Insurance Department to issue Rule 226, which requires all licensed insurers to report each year their insured exposures for earthquake shake damage on residential and commercial structures in California. To assist insurers in complying with Rule 226, the California Insurance Department developed a simple but useful method for insurers to estimate their probable maximum loss (PML). While it was recognized by the Department that definitions of PML varied widely within the industry, the methodology developed by the California Department of Insurance and its consultant K.V. Steinbrugge has been used by the State of California since about 1980 to monitor insurance industry exposure. In that methodology:

- *Building Class PML* (i.e., for an individual building of a specific class, such as wood frame, see Tables 32.3 and 32.4) is defined as the expected maximum percentage of monetary loss which will not be exceeded for nine out of ten buildings, where the building is located on firm alluvial ground, subjected only to the vibratory motion from the maximum probable earthquake (i.e., not astride a fault or in a resulting landslide).
- *Aggregate PML* is the sum of all of the PML values in a PML zone, plus factored PML values for buildings located outside of the PML zone but still within the earthquake underwriting zone. A factored PML is a reduced PML value based on reduced intensity (i.e., damage) with increasing distance away from the causative fault.

Using this methodology, insurance companies in California are required to report their aggregrate PML each year to the California Department of Insurance. This is of interest to the department, as it wishes to assure adequate company surplus to assure payment of claims in the event of a large earthquake.

Almost from the same time, however, others have all strongly discouraged use of the term, with ASTM (1999) stating:

> *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 been no previous industry or professional consensus on what PML means or how it is computed…use of the term Probable Maximum Loss (PML) is not encouraged for future use.*

and have proposed alternative measures .

In the 1970s the SDDA project, discussed above, was developing a fully probabilistic methodology for integrating vulnerability over hazard, accounting for uncertainty. This methodology, in varying forms, is the standard model used today, although all forms don't necessarily derive directly from the SDDA project – that is, the methodology was developed concurrently by others. For example, Oliveira considered the seismic risk of a site and a metropolitan area and determined the final probability distribution of the maximum response of a single-degree-of-freedom (SDOF) system which, when related to damage through a damage ratio function (characterized by random variables yield and collapse) and integrated over the region gave the global loss.

3.5 Assessment

Having traced the history of seismic risk analysis, the next step would be to trace the corresponding development of assessment of the analytical results – that is, the norms and criteria by which the analytical results are assessed. However, space does not permit an adequate discussion of this aspect, so the following thoughts will simply be noted.

First, seismic risk assessment would appear to be a natural development of a society less interested in risk-taking, and more interested in assuring safety. This would appear to be a development paralleled in many fields, such as consumer safety, environmentalism, etc, as briefly discussed above. Whether this is a long-term trend, or a temporary (but influential) movement a la the Progressive Era (ca 1900-1917), remains to be seen.

Second, generally speaking, there would not appear to be any explicit specific norms or standards for seismic risk assessment, in California or, in this writer's experience, anywhere else, with the probable exception of California standards for public K-12 schools, and hospitals. A study of various laws and programs would provide inferences as to patterns of norms and standards for seismic safety. Examples of items for study would include:

- Seismic provisions in the 1927 UBC and subsequent building codes (which were not mandated in the UBC until 1960, and not until later in other model codes)
- 1933 Field and Riley Acts (school standards strict and effective; building standards lax and ineffective)
- 1959 Blue Book (tolerates widespread structural damage)
- 60s requirement for seismic safety elements in California
- 1972: Alquist Priolo Act, requiring Special Studies in fault zones
- 1986: SB 547 (section 8875 of the California Code, setting 'soft' standards for URM mitigation, but ultimately generally effective.
- 1983: California Hospital Seismic Safety Act, SB 1953, and its varied path and effectiveness.
- Caltrans bridge seismic retrofit program – started following 1971 San Fernando earthquake, but it took another two earthquakes to finally complete it (generally speaking).
- Bay Bridge – the delays in retrofitting and replacing these spans deserve a careful study
- Record of the Insurance Industry in California (and elsewhere)
    - 1983 Coalinga earthquake and 'concurrent causation'
    - 1994 Northridge earthquake and the effective industry withdrawal from market due to the requirement for a mandatory offer of earthquake insurance
    - The first attempt at a California state earthquake program under Commissioner Garamendi, and its failure.

- o The second and successful attempt under Commissioner Quackenbush, and the establishment of the California Earthquake Authority.

Perhaps the best attempt by the profession to codify an acceptable standard for seismic performance was the *Vision 2000* report by the Structural Engineers Association of California , in which several performance levels were defined, Figure 16. The Performance-based earthquake engineering tools needed for implementation of Vision 2000 are however still emerging, and the real impact of Vision 2000 still remains to be seen.

Third, there doesn't appear to be any explicit frameworks for assessing seismic risk. Various decision-making frameworks are employed, including benefit cost analysis, life cycle cost analysis , internal rate of return, and least regret. These are all relatively fixed frameworks, and other paradigms are probably more appropriate.

Fourth, seismic risk assessment cannot be seen in a vacuum – there are other developments which directly influence seismic risk assessment – to name a few:

- NRC – the US Nuclear Regulatory Commission has been deeply influential in the development of seismic risk methods and, by its example, in influencing the assessment of the results of those methods in non-nuclear arenas. The nuclear field is currently on the verge of an apparent renaissance – what effects might that have?
- Basel II requires reliability standards for financial institutions, including for natural hazards. The impacts of those requirements or their example on other institutions has not been felt, but may occur in the future.
- Sarbanes Oxley Act of 2002 requires considerable transparency in corporate management. This transparency should extend to management of natural hazards, but doesn't seem to have had an impact yet. Will it?
- Deregulation – the deregulation of the telephone, airlines and electric power industries (with the catastrophic experience in California and with ENRON) raises issues as to their robustness for large natural hazards. How should that be assessed?
- Gramm-Leach-Bliley Financial Services Modernization Act of 1999 repealed Glass Steagall, so that banks, insurance companies and securities firms can cooperate and compete. Does this potential concentration of capital imply greater vulnerability? including to natural hazards. Might standards emerging from these new conditions offer insights for seismic risk assessment and decision-making? Similar questions arise when consumer safety, product liability and transportation safety norms and standards are considered.

That such seemingly distant examples might have influences in seismic risk assessment is not implausible. Conversely, consider examples much closer to home:

- In the earthquake strong motion field, there is a long history of institutional cooperation and archiving of data. COSMOS, NGDC, and the International Seismological Centere are just three of the most prominent examples. Yet, complementing the hazard arena, there is no cooperation or archiving of vulnerability data. Why not? The root cause probably lies in an identified and vital earth sciences agency (the USGS) whiles no comparable national engineering agency. Dishearteningly, in this regard, EERI recently had its reconnaissance funding (the Learning from Earthquakes program) drastically cut.

- In the 1960s the National Flood Insurance Program emerged, as a model coordinated approach to flood mitigation. Communities are provided insurance, but levees and other flood protection measures are required. About the same time, the California Dept. of Insurance began monitoring insurance company exposure via its Probable Maximum Loss (PML) reporting requirements . Recently, the California Dept. of Insurance seems to relaxed its vigilance. Yet, the Florida Hurricane Commission, as compared with California, strictly monitors its insurance companies, and requires full confidential disclosure of all insurance modeling software employed in the state. These disparities need examination.
- Hurricane Katrina is an object lesson in what not to do. The community had been warned many times, with articles about the risk in scientific and popular magazines years and months prior to the disaster. What does this tell us about people's perceptions and attitudes toward natural hazards? About the value of risk assessments? About how to plan for recovery and reconstruction, should San Francisco or Los Angeles be devastated by an earthquake?

4 Current Status

As of this writing (June, 2006), the status of seismic risk assessment is that the US remains the center of innovation and almost the center of application, although that is rapidly changing. The global insurance industry is served basically by the three modeling firms, all of which are based in the US, with some significant contribution from London. These three firms however are fiercely competitive and closely guard their technology, so that while innovation occurs it is closely held and the merit is difficult to judge. This is partially compensated by rating agencies such as Moody's and Standard & Poor's requiring confidential disclosure from the modeling firms, and the Florida Hurricane Commission's detailed inquiries into the hurricane models.

A major development in the US has been HAZUS, which has funded an extensive collation of technology, so that methods for earthquake, hurricane and flood loss estimation are clearly laid out. However, while the software is distributed free of charge, the source code is closed, so that it is regarded as something of a 'black box', and has had limited acceptance. As a result, while to some extent serving risk-based mitigation, HAZUS has also tended to stifle innovation, in that potential supporter of new risk-based software question why they should compete with 'free' software; while at the same time the inaccessibility of the source code precludes its free and open enhancement. This is a typical defect of any attempt to have an 'authorized' version (*viz.* parallels in IBM-Apple, and Windows-Linux).

In contrast, probably the most successful series of risk models anywhere has been the flood frequency and loss estimation software developed by the US Army Corps of Engineers (USACE), at the Hydrologic Engineering Center (HEC). HEC-RAS and similar programs have succeeded by being free, with source code available to many users. Therefore, independent vetting has occurred. It helped that flood modeling was required by the NFIP, and that USACE had something of a monopoly on this, in the US. This situation is now changing however, with DHI's Mike series of software making significant inroads in the US, based on more advanced dynamic flood modeling, versus the 'static' modeling in the HEC software.

Outside of the US, some national authorities have embraced risk-based modeling and the UN's ISDR, the World Bank and other institutions are strongly encouraging a risk-based approach to disaster risk management.

An interesting observation is the place of Japan in this development. Arguably, Japan should be the leader in earthquake engineering worldwide, due to the size of its earthquake risk and its technological capabilities. From 1880 to 1930 it was the leader, which Freeman and Martel very clearly observed in the late 20s, leading Freeman to push for the strong motion program in California, and to invite Suyehiro to lecture at Berkeley, Stanford, Caltech and MIT. From that moment, the US surpassed Japan, developing the first strong motion program, the magnitude scale, the magnitude frequency relation, response spectra and other innovations. Admittedly, many of these innovations were developed independently in Japan about the same time, but their visibility and application were much lower. Following World War 2, Kawasumi published his probabilistic hazard map of Japan (1951), about two decades ahead of its time. But, while many innovations still continued in Japan, Kawasumi's map seems to have been the end of probabilistic and risk thinking in Japan. When this writer was at Kyoto University in the late 70s, some work was being done in Japan on hazard analysis, but risk analysis was almost unknown. As the WASH-1400 report introduced probabilistic analysis to engineers in general, and Wiggins, Blume, Whitman and then Yanev and colleagues, introduced seismic risk management in the US in the 70s and 80s, this writer's casual observations and recollections for the 70s to 90s was that the field was totally ignored in Japan. Seismic design was very advanced in Japan, but it was deterministic in nature, and systems or enterprise risk management approaches just did not exist, despite their burgeoning development in the US. It was only following the 1995 Kobe earthquake and the demonstrated seismic vulnerability of even 'modern' Japanese construction, that interest in risk management in Japan emerged. The first seismic retrofit of a high-rise building in Japan was designed by a US consulting firm, in 1997.

5 Concluding Remarks

The rational analysis and mitigation of risk due to natural and other hazards is founded on a large body of work developed over the last several 150 years. If one were asked to list the top few developments essential to seismic risk assessment, the list might be something like:

1. Mallet – his investigations and founding of seismology in the UK about 1850.
2. Milne – his arrival in Japan in 1880 and development of seismology and training of seismologists in Japan, development of the first practical seismograph, and the founding of the Seismological Society of Japan.
3. Reid's Elastic Rebound Theory (1910) and Wegener's theory of continental drift (1913); however, Wegener's ideas were rejected at the time, and not accepted until the 1960s with the theory of plate tectonics.
4. Freeman – in the few short years of about 1927 to 1932, his strong encouragement of earthquake engineering in the USA, role in founding the US strong motion program, and book laying out building damage experience and reduction of that experience to loss ratios – and Neumann and colleagues for translating Freeman's ideas into actual deployed instruments in time for the 1933 Long Beach earthquake.
5. Caltech – does credit go to Millikan for bringing Wood, Richter, Martel, Gutenberg, Benioff, Housner and Hudson? or do they get the credit for development of the

   a. Magnitude scale (Richter, 1935)
   b. magnitude-frequency relation, log N = a – b M (Gutenberg-Richter, in 1941)
   c. response spectra (Biot, and Housner, 1941)
6. Cornell's 1968 BSSA paper on engineering seismic risk analysis

Items 1-6 are necessary and sufficient for estimation of seismic hazard. Freeman laid the basis for a rational approach to seismic risk assessment, including vulnerability functions. The proper development of vulnerability functions however still required:

7. the Finite Element Method (Argyris, Turner, Clough et al, 40s to 60s), and development of associated structural analysis software (eg, Wilson, 60s to now).
8. Karl Steinbrugge and the group around him, Algermissen, McClure, Lagorio and others, for focusing on the goal of assessing (and reducing) the risk (60s to 80s)
9. the SDDA project at MIT (1973-78, Whitman, Cornell, Vanmarcke, Veneziano et al), for a consistent approach to the entire problem, and
10. ATC-13 (1985) for developing a consistent open set of vulnerability functions (Rojahn, Sharpe, Kiremidjian et al)

These and selected other developments are shown in Figure 17, overlaid on a background of the global growth in natural hazards loss estimation.

While much more remains to be done, recent developments in information technology permit leveraging of this body of knowledge in ways not previously possible. Key to enhanced seismic risk mitigation is dissemination of the capability to analyze risk, in an open and transparent manner, and better doctrine on using the results.

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Acronyms

ANSI	American National Standards Institute.
ANSS	Advanced National Seismic System
ASCE	American Society of Civil Engineers. Producer of the standard ASCE 7, Minimum Design Loads for Buildings and Other Structures.
ATC	Applied Technology Council
AWSS	Auxiliary Water Supply System
BCA	Benefit Cost Analysis
BOCA	Building Officials and Code Administrators International, Inc. One of three statutory members of the ICC. Producer of the National Building Code (NBC).
BSSC	Building Seismic Safety Council
BSSC	Building Seismic Safety Council. Producer, for FEMA, of the NEHRP Provisions and Commentary. For more information, see BSSC (2001b, p.431-444).
CBC	California Building Code. The 2001 CBC is based on the 1997 UBC model code.
CDMG	California Division of Mines and Geology, recently renamed as CGS (q.v.)
CGS	California Geological Survey
CUSEC	Central US Earthquake Consortium
DEM	digital elevation model
DOE	Department of Energy
DOI	Dept. of Insurance (California, aka CDI)
DPRI	Disaster Prevention Research Institute (Kyoto University, Japan)
EAL	Expected annualized losses
ECHO	Earth Change and Hazard Observatory
ELF	Equivalent Lateral Force
EPEDAT	Early Post-Earthquake Damage Assessment Tool
ERI	Earthquake Research Institute, founded 1923 from IEIC
FEMA	Federal Emergency Management Agency. Funding source for NEHRP Provisions and Commentary.
GPS	Global Positioning System
GSHAP	Global Seismic Hazard Assessment Program
GSN	Global Seismic Network
HEC	Hydrologic Engineering Center (USACE)
IBC	International Building Code. Published as a model code by ICC since 2000.
ICBO	International Conference of Building Officials. One of three statutory members of the ICC. Producer of the UBC.
ICC	International Code Council. Formed from three statutory members: BOCA, ICBO, and SBCCI. Producer of the IBC.

ICES	*Integrated Civil Engineering System*, a visionary project at MIT in the 60s to develop an integrated system of software – included COGO, STRUDL, BRIDGE, LEASE, PROJECT, ROADS and TRANSET. (only STRUDL is explained in this Glossary). Internal languages include ICETRAN and CDL. See "An Integrated Computer System for Engineering Problem Solving", D. Roos, Proc SJCC 27(2), AFIPS (Spring 1965).
IDNDR	International Decade for Natural Disaster Reduction
IEIC	Imperial Earthquake Investigation Committee (Japan), founded 1892 following Nobi Earthquake
InSAR	interferometric synthetic aperture radar
IRIS	Incorporated Research Institutions for Seismology
ISC	International Seismological Centre
IT	information technology
JMA	Japan Meteorological Agency
LESSLOSS	EU project for Risk Mitigation for Earthquakes and Landslides http://www.lessloss.org/main/index.php
LFRS	Lateral force resisting system
LIDAR	light detection and ranging
M	moment magnitude
MMI	Modified Mercalli Intensity
NASA	National Aeronautics and Space Administration
NCSEA	National Council of Structural Engineers Associations, of which SEAOC is one.
NEES	Network for Earthquake Engineering Simulation
NEHRP	National Earthquake Hazard Reduction Program
NEHRP	National Earthquake Hazards Reduction Program, a federally-funded program under which the NEHRP Provisions and Commentary by the BSSC (a part of NIBS)
NEIS	National Earthquake Information Service
NERIES	**Ne**twork of **R**esearch **I**nfrastructures for **E**uropean **S**eismology (http://www.orfeus-eu.org/neries/NERIES-proposal.htm)
NFPA	National Fire Protection Association. Producer of NFPA 5000, Building Construction and Safety Code, published as a model code since 2002.
NIBS	National Institutes for Building Standards
NISEE	National Information Service for Earthquake Engineering
NIST	National Institute of Standards and Technology
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NSMP	National Strong-Motion Program
PBO	Plate Boundary Observatory
PDE	Preliminary Determination of Epicenters

PEER	Pacific Earthquake Engineering Research
PGA	peak ground acceleration
PGV	peak ground velocity
PHIVOLCS	Philippine Institute of Volcanology and Seismology
PML	Probable Maximum Loss
PSHA	probabilistic seismic hazard analysis
RANN	Research Applied to National Needs, a program at NSF in the 1970s
Sa	spectral acceleration
SBCCI	Southern Building Code Congress International. One of three statutory members of the ICC. Producer of the Standard Building Code (SBC).
SCEC	Southern California Earthquake Center
SDDA	Seismic Design Decisions Analysis – a project at MIT 1973-78 (R.V. Whitman, PI)
SEAOC	Structural Engineers Association of California
SFFD	San Francisco Fire Department
SHA	seismic hazard analysis
STRUDL	*STRUctured Design Language*.- Dynamic and finite-element analysis, steel and concrete structures. Subsystem of ICES [see "ICES STRUDL-II Engineering User's Manual", R68-91, CE Dept MIT (Nov 1968) Sammet 1969, p.613].
UBC	Uniform Building Code. Published as a model code through 1997 by ICBO. Since 1961, its earthquake design provisions were adapted from the SEAOC Seismology Committee's Blue Book.
USACE	US Army Corps of Engineers
USCGS	U.S. Coast and Geodetic Survey
USGS	U.S. Geological Survey
WASH-1400	Reactor Safety Study (1975) aka Rasmussen Report
WWSSN	World Wide Standardized Seismographic Network

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Table 3 Terminology Example and Concordance

Term	Example	Victim(s)	Damage and Loss Terminology and Measures			
			FEMA 224 (1991)	**NAP (1999)**	**HAZUS-MH (2003)**	**MMC (2005)**
Owner	Accountant					
Asset	Laptop PC					
Hazard	MMI VIII (*Heavy furniture overturned*.)					
Damage	PC screen cracked	Owner	Damage	Damage	Direct Physical Damage and Induced Damage[9]	Damage
Property Loss (aka direct loss)	Cost of repairing screen (or replacing PC)	Owner	Direct Damage (aka cost of repair; % value, $)	Direct Loss (Primary, and Secondary – eg, Fire Following Earthquake)	Direct Economic Loss (costs of repair to buildings, contents and inventory)	Direct Loss (property damage)
Downtime (aka direct economic loss)	(a) repair screen: normally, 1 week, after EQ, ? weeks; (b) at greater cost, buy new PC, several days.	Owner	Loss of Function (% of functional capacity vs. time)	Loss of Function	Loss of Function	
Time Element Loss	Loss of income due loss of productivity given lack of PC (this is commonly termed Business Interruption, or BI)	Owner	Indirect Economic Loss[10] (change in GNP, %, $)	Indirect Loss	Direct Economic Loss (BI and loss of rents)	Direct Loss (BI)
Indirect Economic Loss	(a) upstream: delay in revenue for printer waiting for job; (b) downstream: delay in revenue due to client inability to close deal	(a) supplier (b) customer	Indirect Economic Loss (change in GNP, %, $)	Indirect Loss	Indirect Economic Loss	Indirect Loss
Indirect Economic Loss ('ripples')	(a) paper supplier loss of sales to printer, theater loss of sales since printer doesn't take family to movies; (b) restaurant loss of sales since client doesn't celebrate; extra cost of capital for seller side in the deal	(a) supplier's suppliers and customers (b) customer's suppliers and customers	Indirect Economic Loss[11]	Indirect Loss	Indirect Economic Loss	Indirect Loss

9 Induced Damage refers to things like Fire Following Earthquake.

10 Method of computation (I-O) combined TE and Indirect Economic Losses.

11 These were noted but not computed.

Table 4 Earthquake Spectra Special Issue on Loss Estimation, Nov. 1997
Paper Titles and First Authors

- *Methodologies for Evaluating the Socio-Economic Consequences of Large Earthquakes,* King et al
- *Loss Estimation Due to Seismic Risks to Highway Systems, Werner et al*
  An Earthquake Loss Estimation Methodology for Buildings Based on ATC-13 and ATC-21, McCormack and Rad
- *Earthquake Damage and Loss Estimation Methodology and Data for Salt Lake County, Utah (ATC-36),* Rojahn et al
- *Development of a National Earthquake Loss Estimation Methodology,* Whitman et al
- *Development of Building Damage Functions for Earthquake Loss Estimation,* Kircher et al
- *Direct and Indirect Economic Losses from Earthquake Damage,* Brookshire et al
- *The Role of Earthquake Hazard Maps in Loss Estimation: A Study of the Northridge Earthquake,* Olshansky
- *Advances in Earthquake Loss Estimation and Application to Memphis, Tennessee,* Shinozuka et al
- *Seismic Performance Evaluation of Fire Stations in Shelby County, Tennessee,* Hwang et al
- *Earthquake Loss Estimation for Europe's Historic Town Centres,* D'Ayala et al
- *Seismic Microzonation and Estimation of Earthquake Loss Scenarios: Integrated Risk Mitigation Project of Bogotá, Colombia, Cardona et al*
  Real-Time Loss Estimation as an Emergency Response Decision Support System: The Early Post-Earthquake Damage Assessment Tool (EPEDAT), Eguchi et al
- *The Treatment of Earthquake Portfolio Uncertainty: A Focus on Issues of Asset Distribution,* Woo

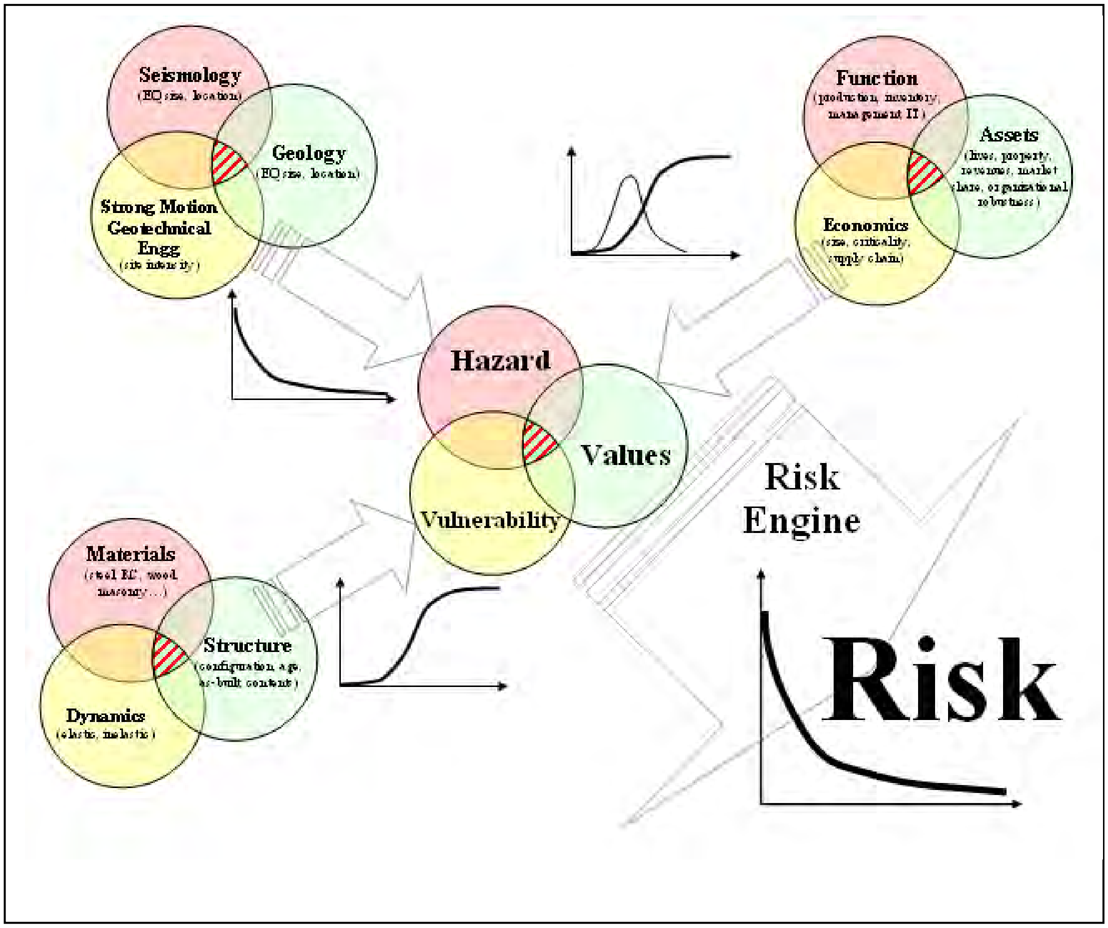


Figure 1 Elements of Seismic Risk

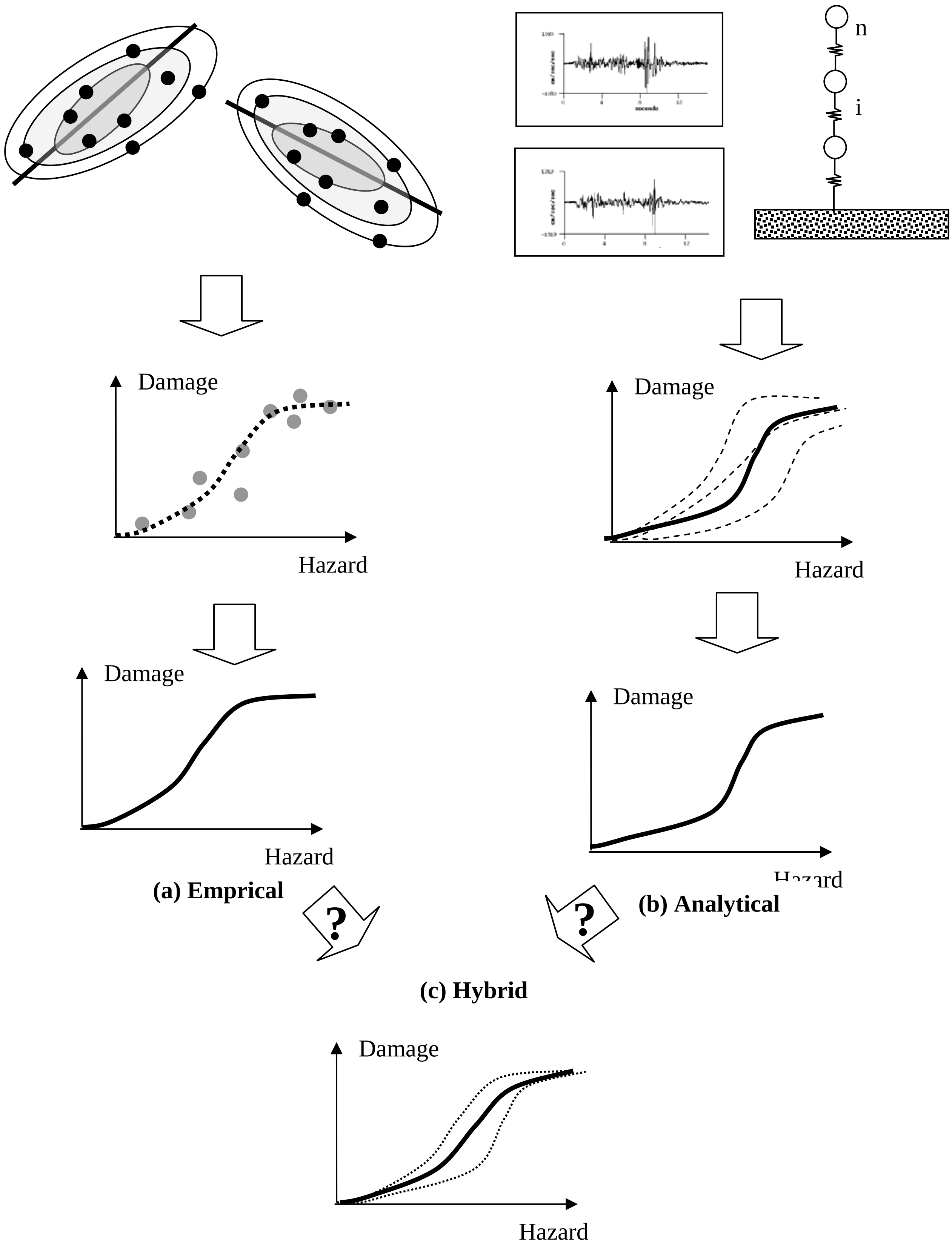


Figure 2 Vulnerability Development Methods

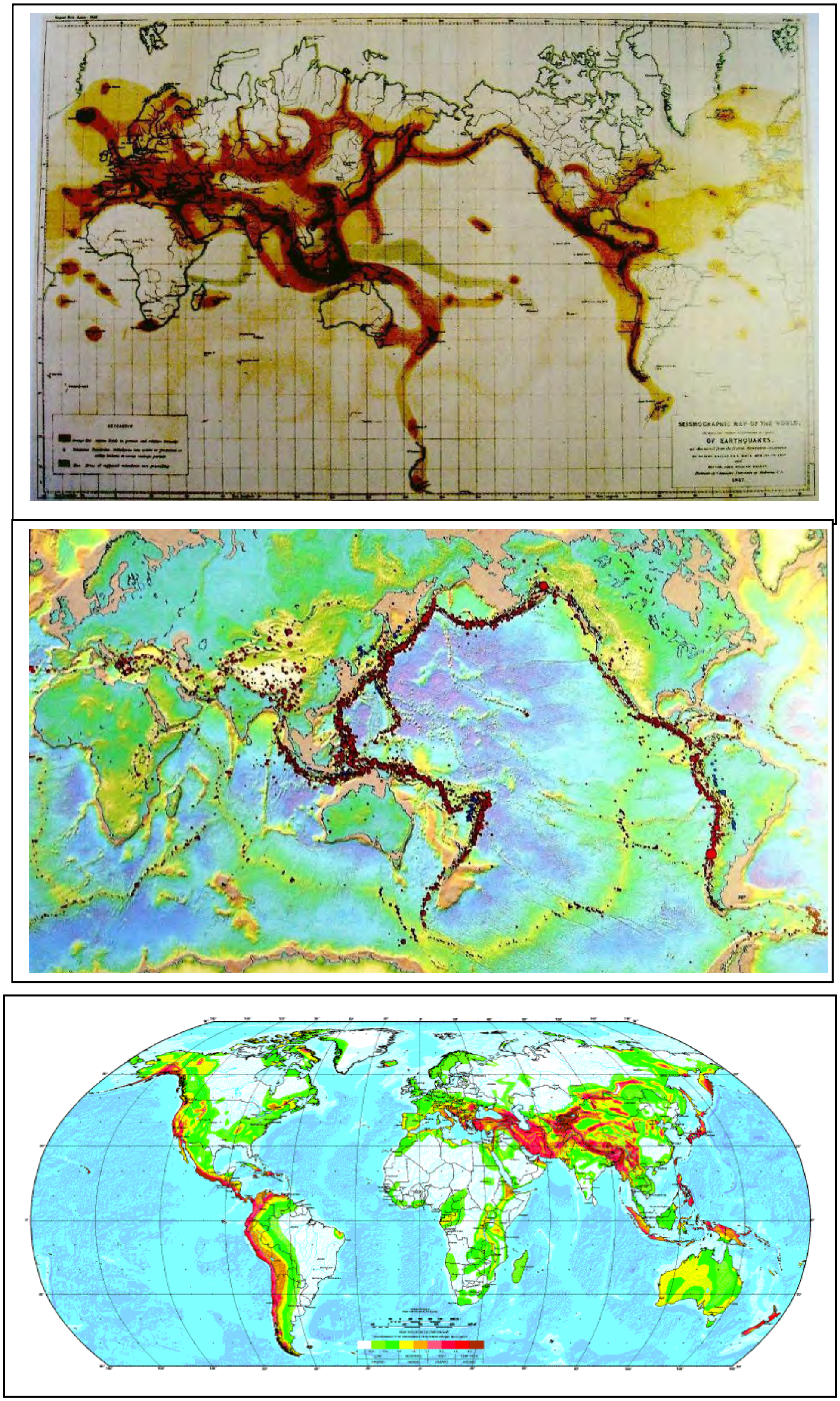


Figure 3 (t) Mallet's 1850 Map; (m) Global Earthquakes 1900-1999 (Agnew, 2002); (b) Global Seismic Hazard Analysis Project Map (GSHAP, 1998)

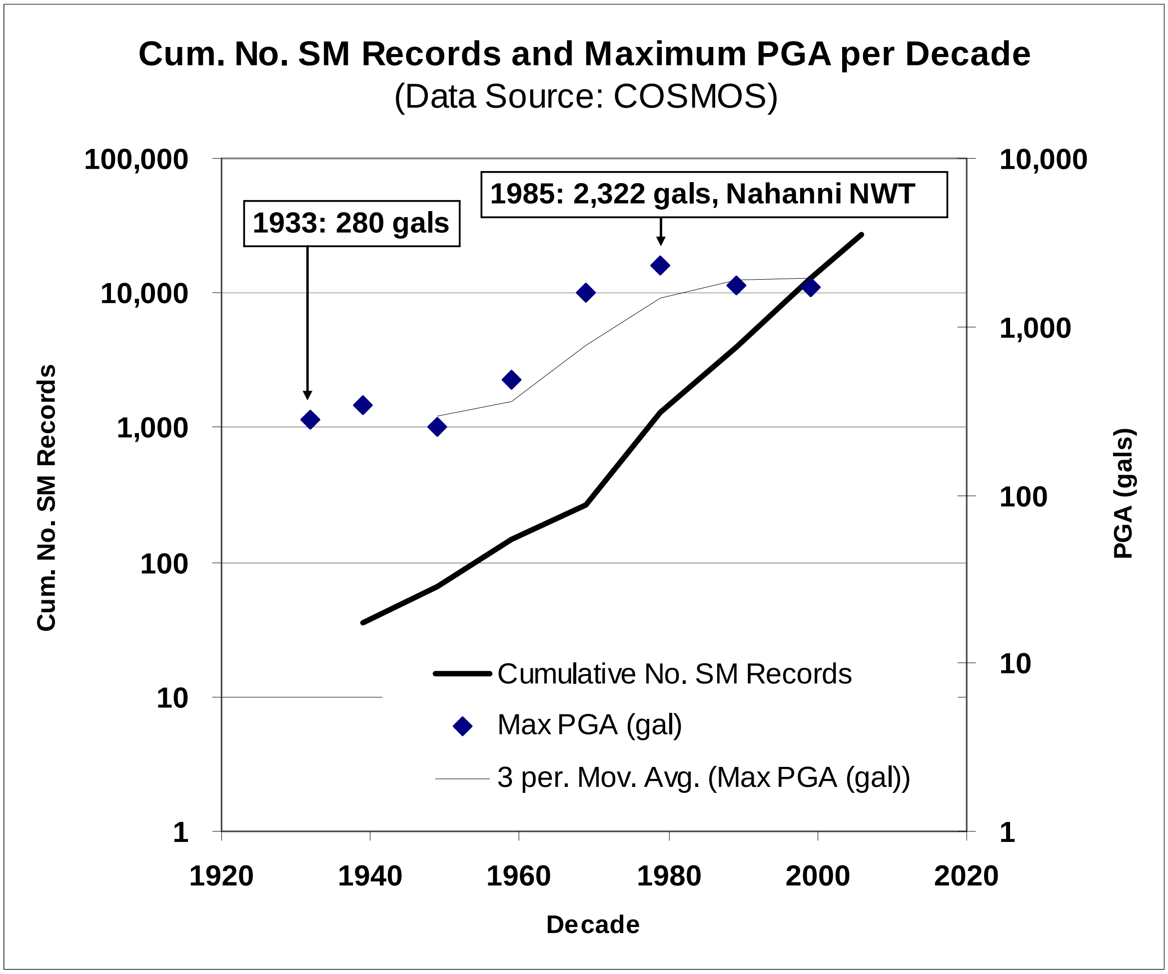


Figure 4 Cumulative number of strong motion records in the COSMOS database, from 27 in 1933 to 27,000 today. COSMOS is probably the most complete and representative database of strong motion records, although an estimated 150,000 strong motion records are estimated to have been recorded (author's estimate). Also shown in the graph is the maximum peak ground acceleration (PGA) by decade – the more observations, the greater the maxima. The highest recorded PGA was 2,322 gals in the 1985 Nahanni (Canada) earthquake.

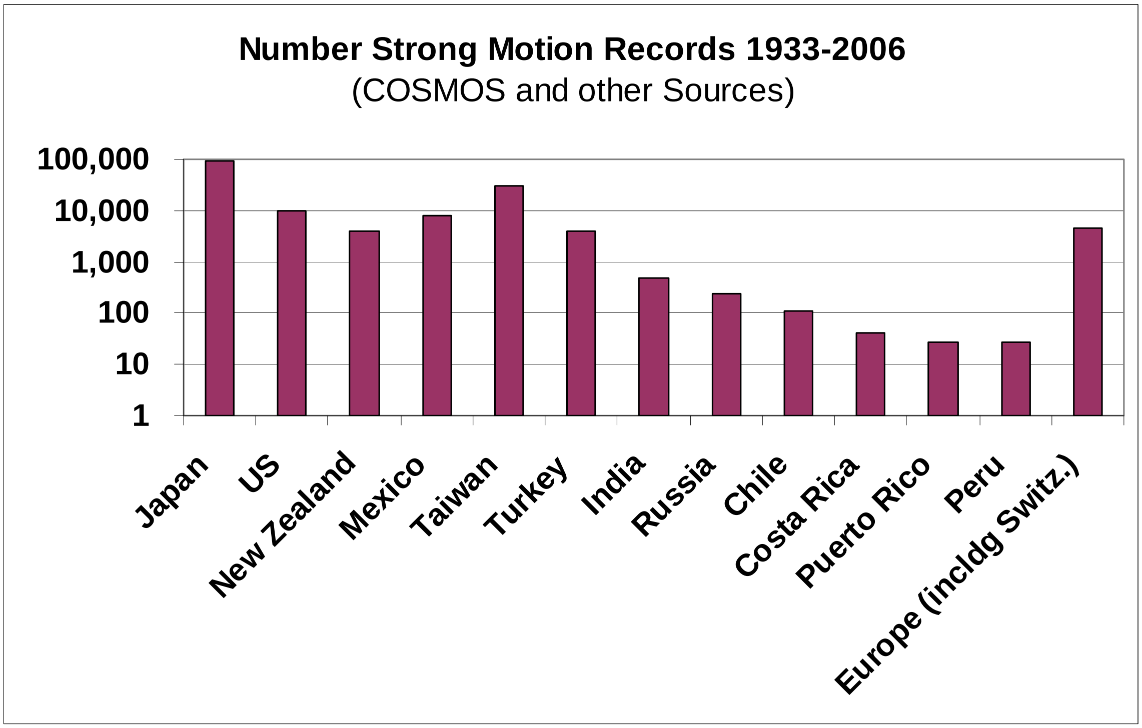


Figure 5 Number of Strong Motion records by country (compilation by the author). Japan has almost 100,000 records, or about 60% of the world total.

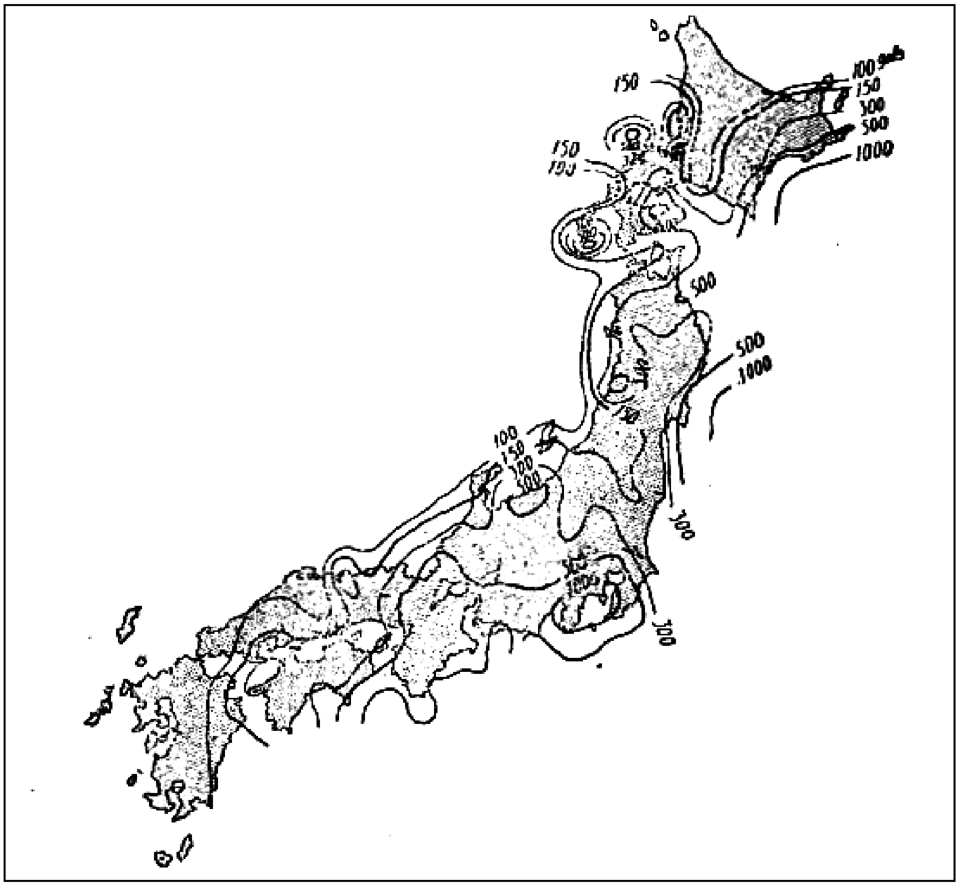


Figure 6 Expected maximum acceleration in 200 years (Kawasumi, 1951)

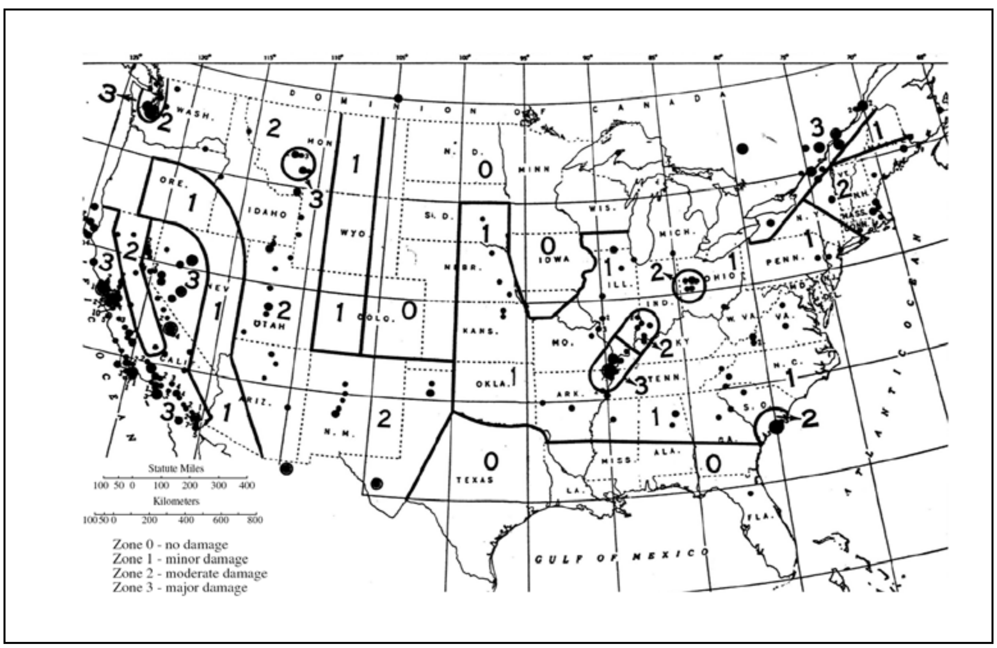


Figure 7 Seismic 'probability' map, 1949 Uniform Building Code (Roberts and Ulrich, 1951) – this map, which is not probabilistically based, was retracted by the US Coast and Geodetic Survey in 1952, but remained in the UBC until 1970.

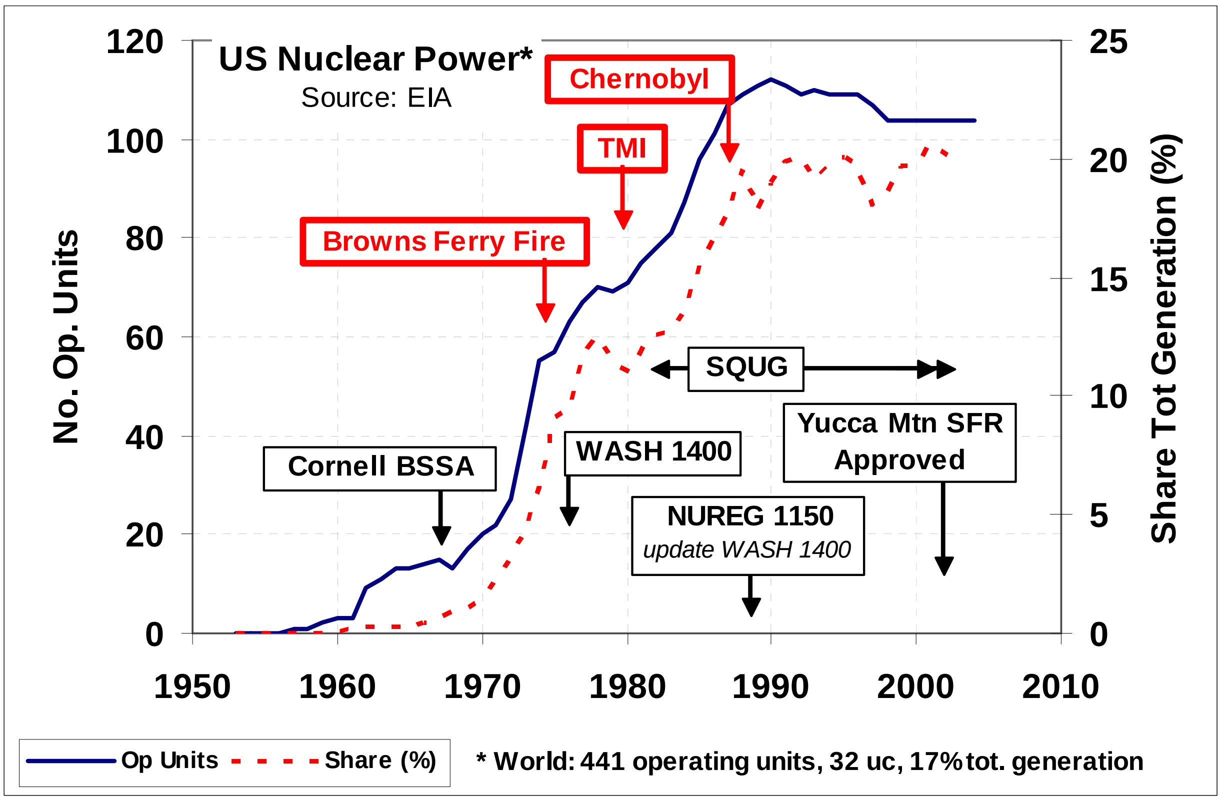
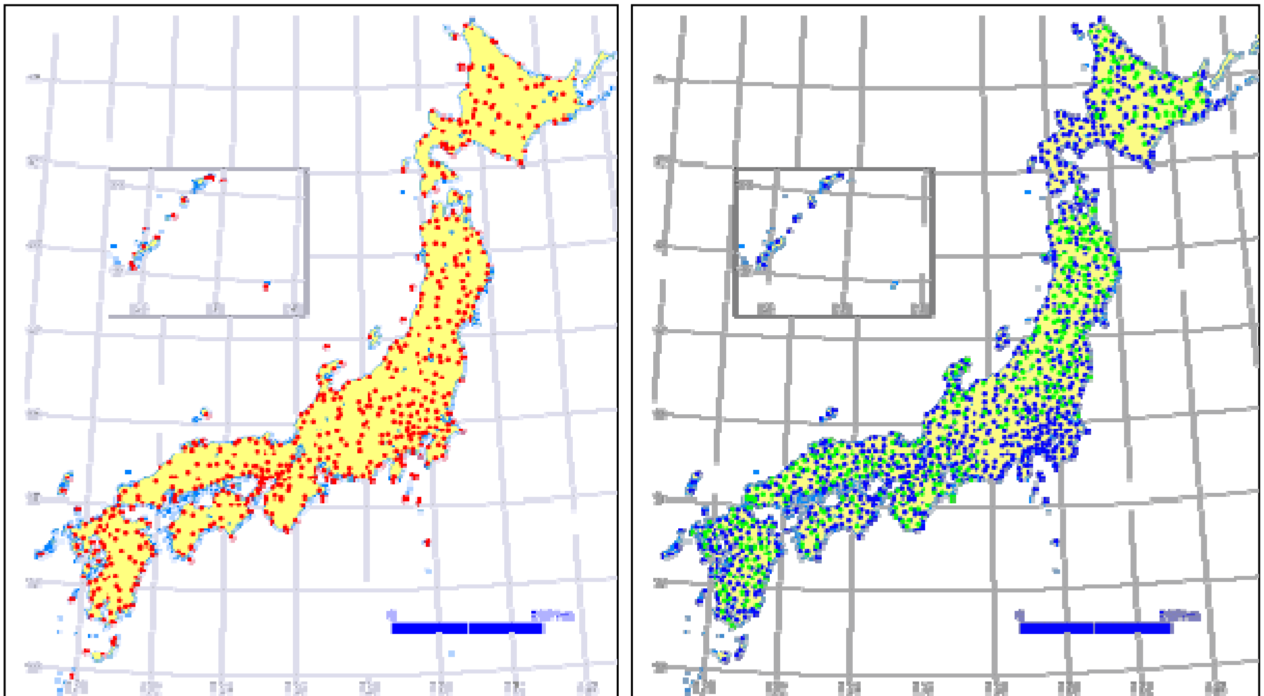


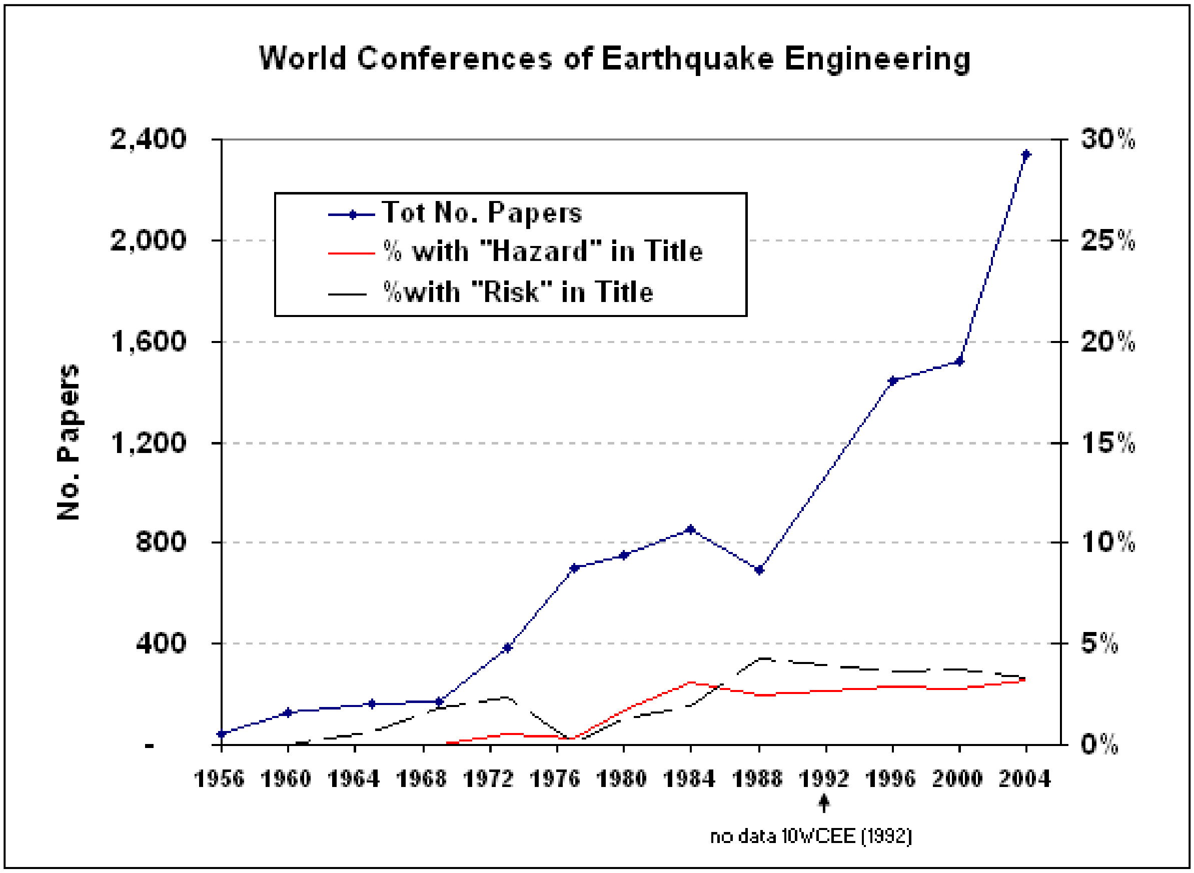
Figure 8 US Nucleaer Power Growth and some related events



JMA seismic intensity meter stations

K-Net (blue) and KiK-Net (green) sites

Figure 9 Two of the larger Japanese Strong Motion Networks (Kashima, 2000)



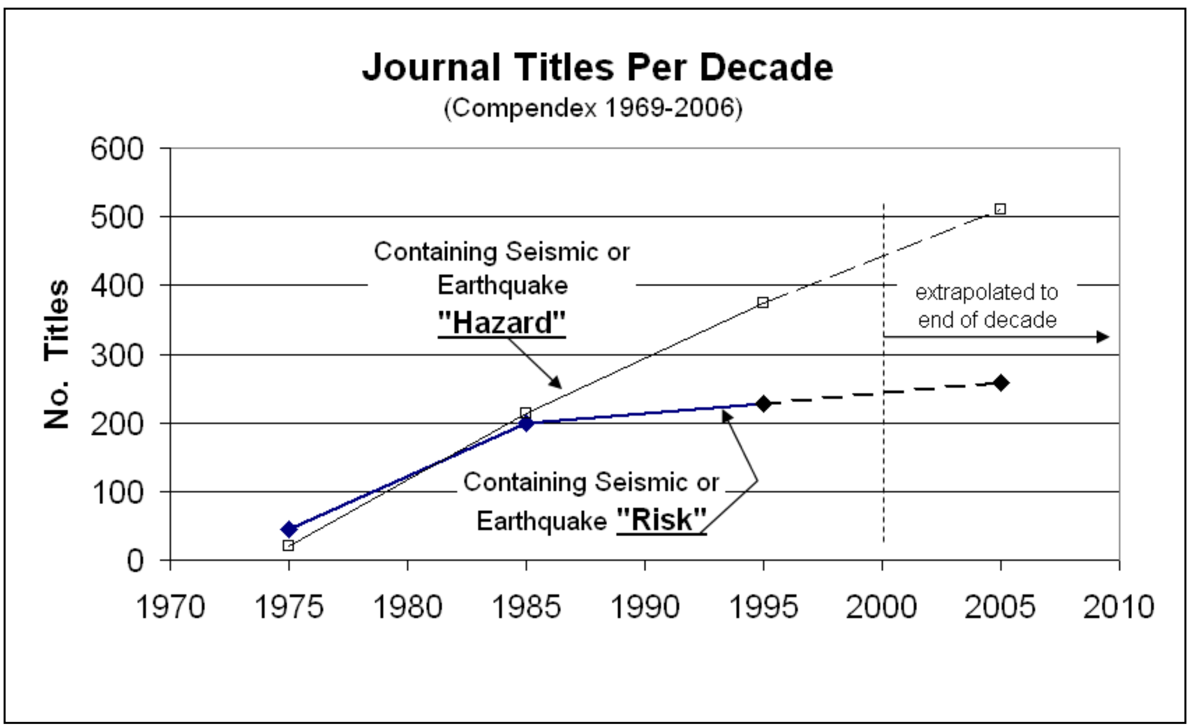
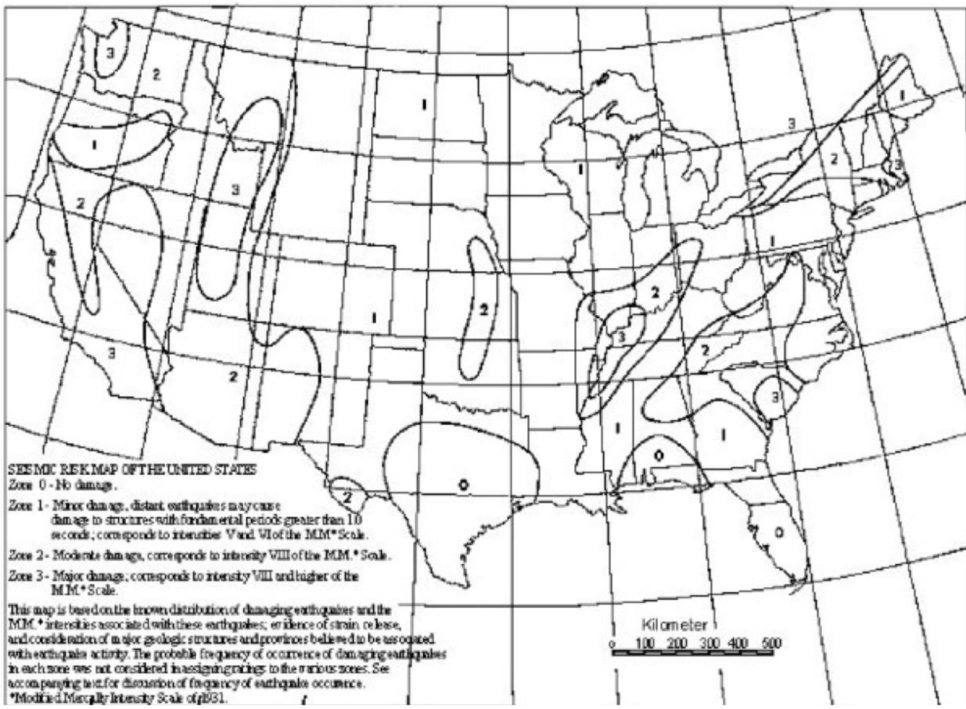
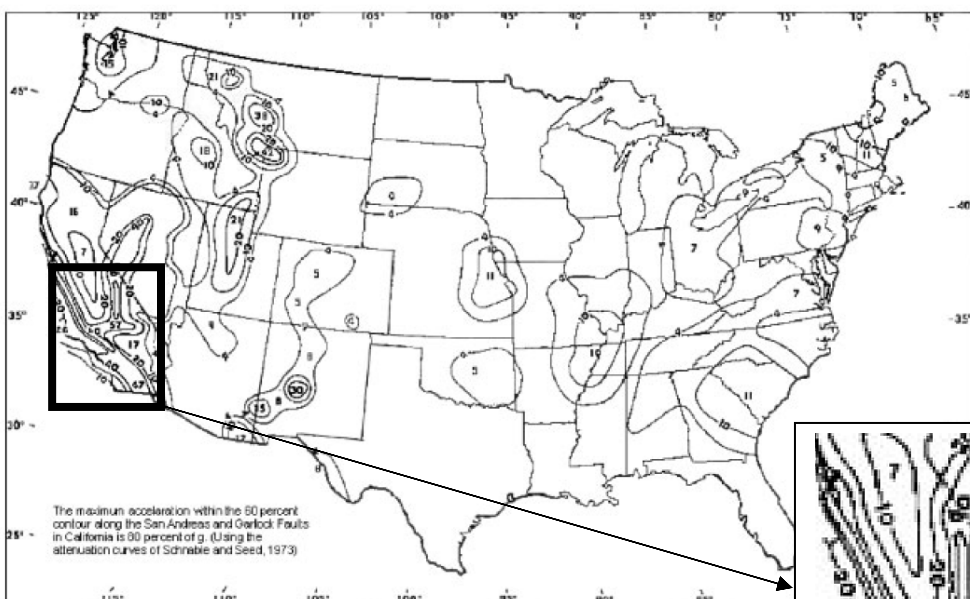


Figure 10 (t) World Conferences, growth of papers (b) Journals with titles containing words 'risk' or 'hazard'





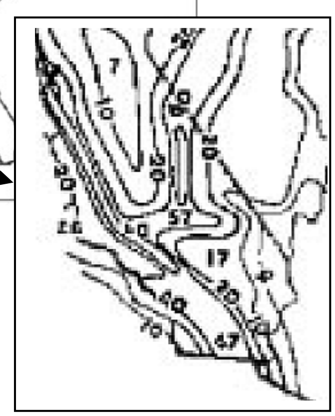


Figure 11 (t) 1969 Algermissen map; (b) 1976 Algermissen map

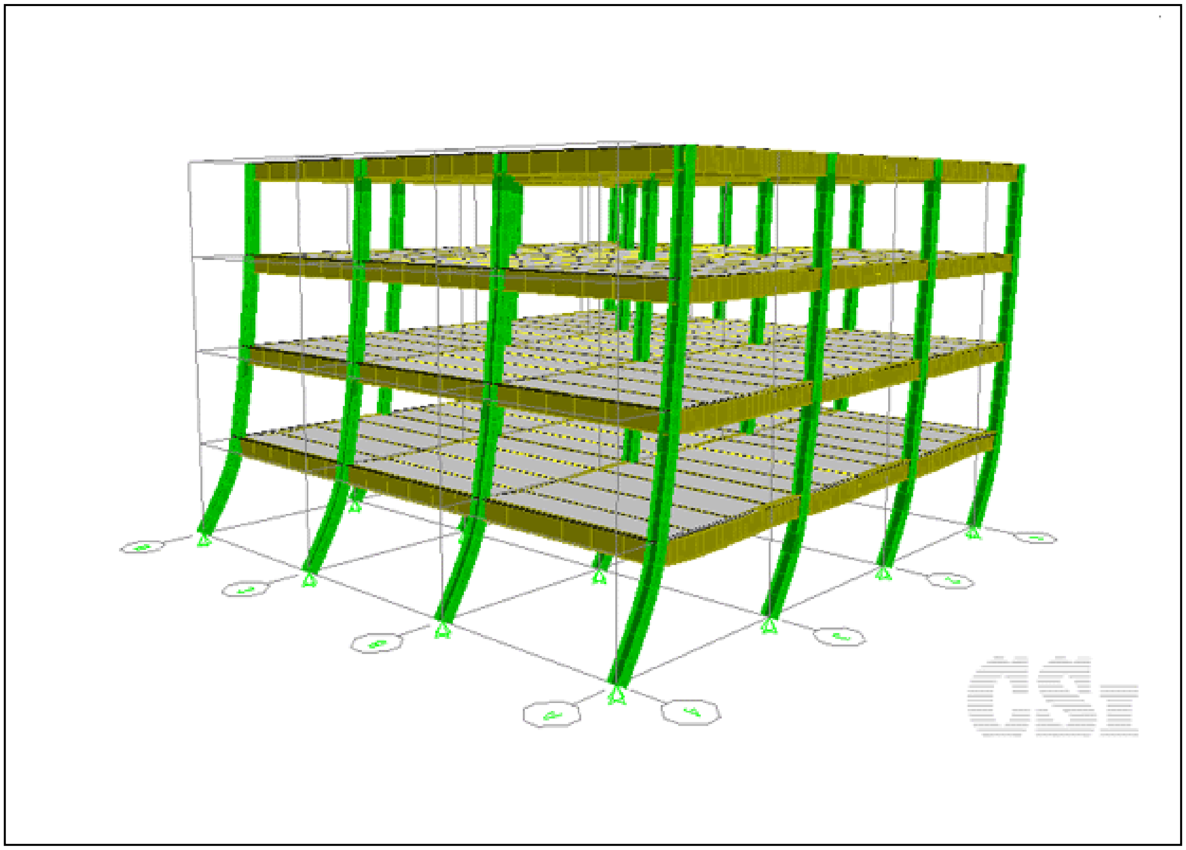


Figure 12 Example of visualization of deformed structure (from ETABS, courtesy of CSI, Inc.)

Class of Construction	Expected Average Loss Ratio	Soft Ground Factor	Bed Rock or Stable Ground Factor
1. Steel-frame buildings **on reinforced concrete mat foundation,** having rigid cross-bracing, with strong gusset plates uniting columns to strong horizontal girders between windows, with curtain walls of **reinforced concrete** poured around the steel frame, and with ordinary interior finish. Not more than 100 feet tall. (Expected damage, chiefly cracked plaster.)	Per cent. of Sound Value 3%	Add nothing (See pages 44 and 620)	Deduct nothing Perhaps Add? (See page 810)
2. Tall steel-frame buildings with less-rigid cross-bracing than Class 1, with ordinary brick curtain walls and rock-concrete floors and uncertain foundations. Not more than 100 feet tall...............	5%	"	"
3. Tall reinforced concrete buildings without rivetted or welded structural steel-frame, and with ample strength at column connections and having ample horizontal cross-bracing by walls around windows, particularly in first story. Not over 100 feet tall..	8%	"	"
4. Wood-frame dwellings, **set on good foundation walls** (not on posts or slender piers), not above 2½ stories high, excluding stucco exteriors. (Expected damage chiefly cracked plastering and chimneys.) If on tall posts or slender piers the loss ratio will probably be 5 to 10 times as great....................	3%	2 to 4 times average loss Ratio.	¼ to ½ average loss Ratio.
5. Factory buildings **of good design** having bearing walls of **brick in cement mortar,** or of reinforced concrete. Strong wood floors, with little expensive interior finish. No plastered walls or ceilings. Comparable with illustrations on pages 313 and 334. **Not more than 4 stories tall**	5%	To be modified by structural conditions	To be modified by structural conditions
6. Ordinary brick residence, mercantile and office buildings, **of excellent design** with brick bearing walls and wood floors. General average of unrated risks **not exceeding 2½ stories**..................	6%	"	"
7. Same as Class 6, but for **general average of unrated risks,** not exceeding 4 stories............	10%	"	"
8. Brick veneered, wood-frame or concrete-frame residence, mercantile and office buildings, or stucco exterior on wood lath, or with hollow-tile partitions.	25%	"	"
9. General average of commercial buildings with reinforced concrete frames and columns, (no steel frame) with curtain walls and **partitions of hollow-tile,** and **large window openings** in lower story.	10% to 20%	"	"
10. Buildings of doubtful quality of design and construction, uncertain wall ties, unanchored parapets, uncertain quality of mortar.................	20% to 40%	"	"
11. Concrete-block and hollow-tile buildings....	50%+	"	"

Figure 13 Building Earthquake Loss Ratios (Freeman, 1932)

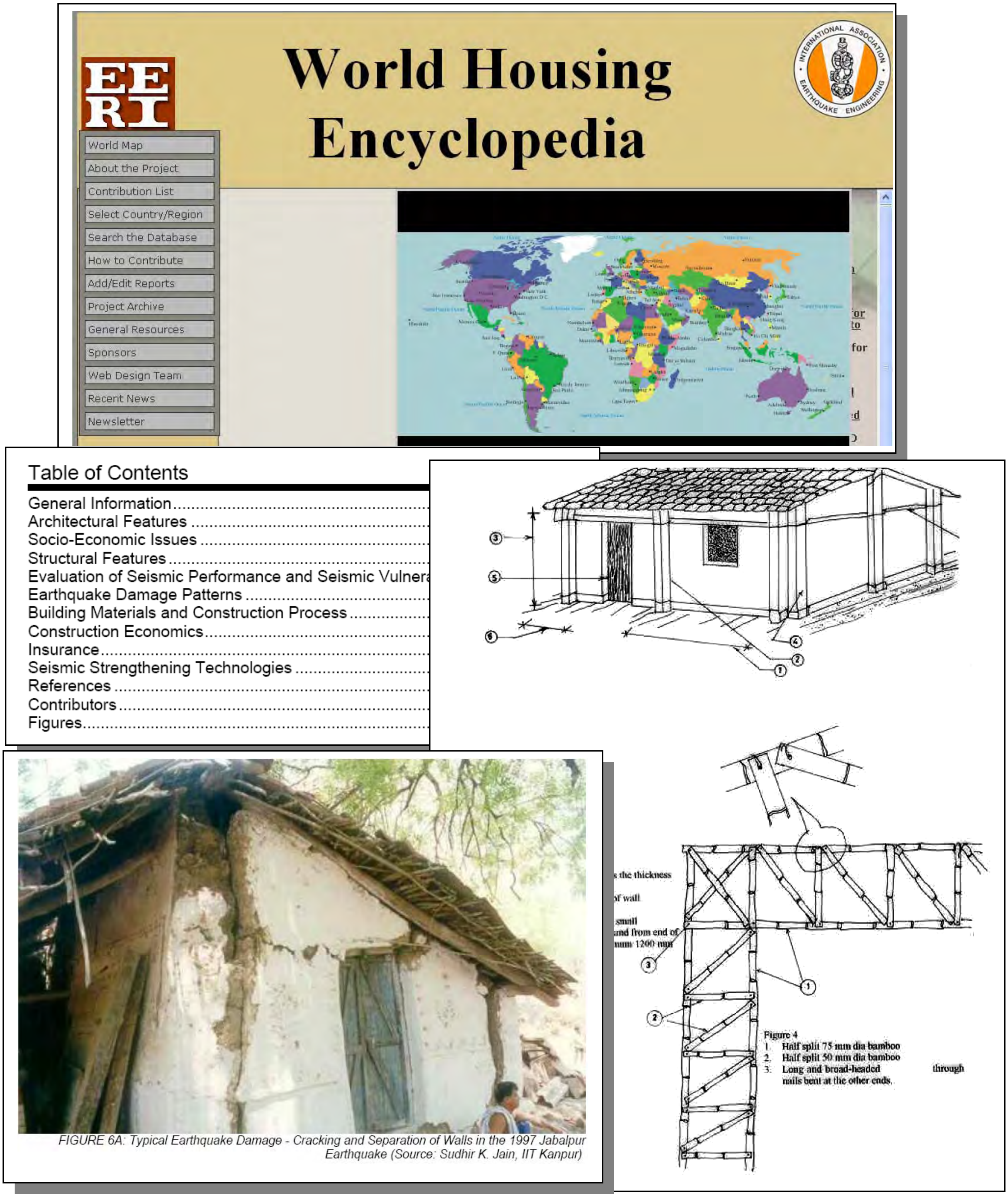


Figure 14 World Housing Encyclopedia (EERI)

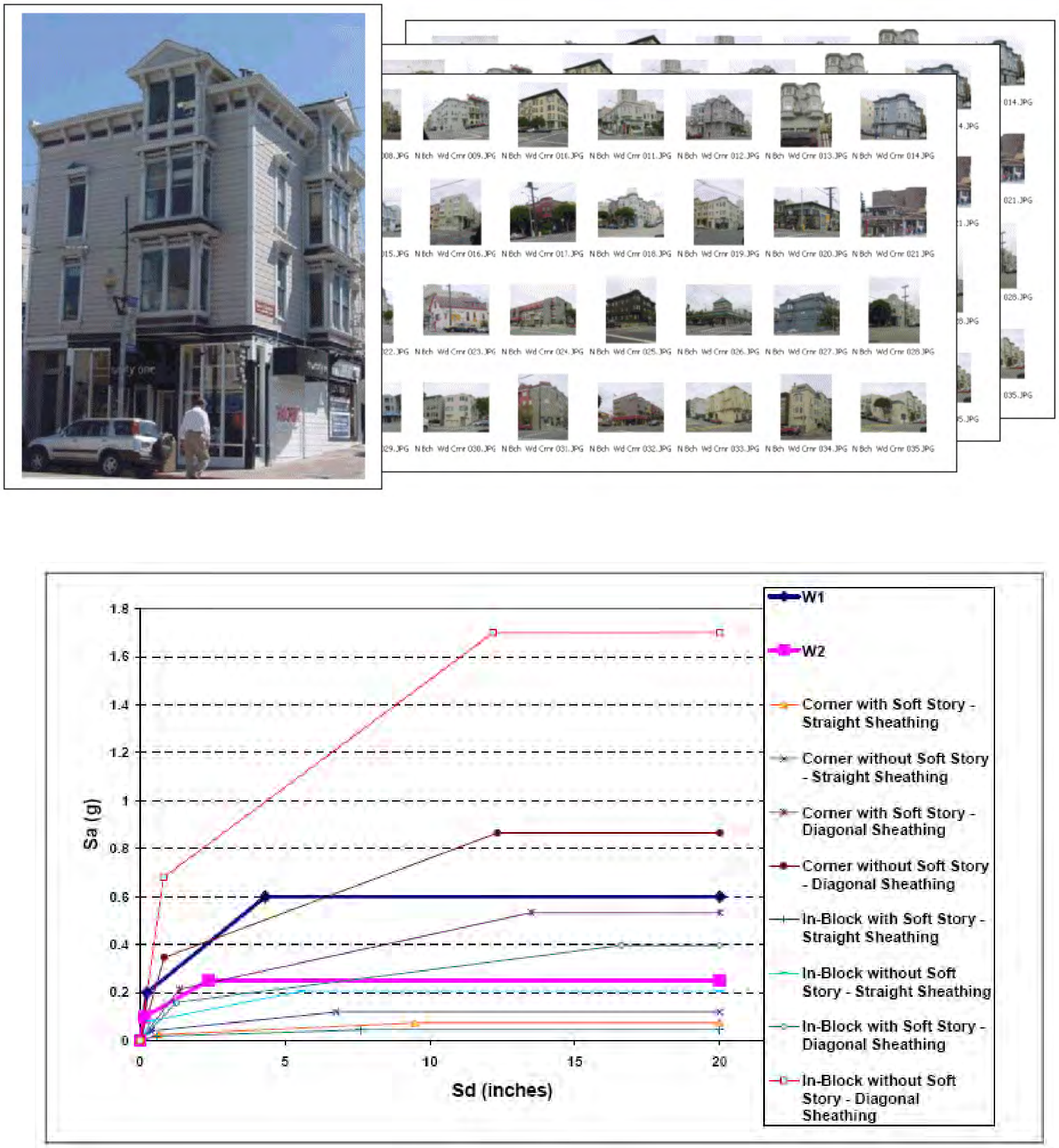


Figure 15 CAPSS Photo Survey and Capacity Spectra for Corner Apartment Building, with factors for diagonal / straight sheathing, corner / in-block, pounding and interior partitions (Kornfield, 2006b)

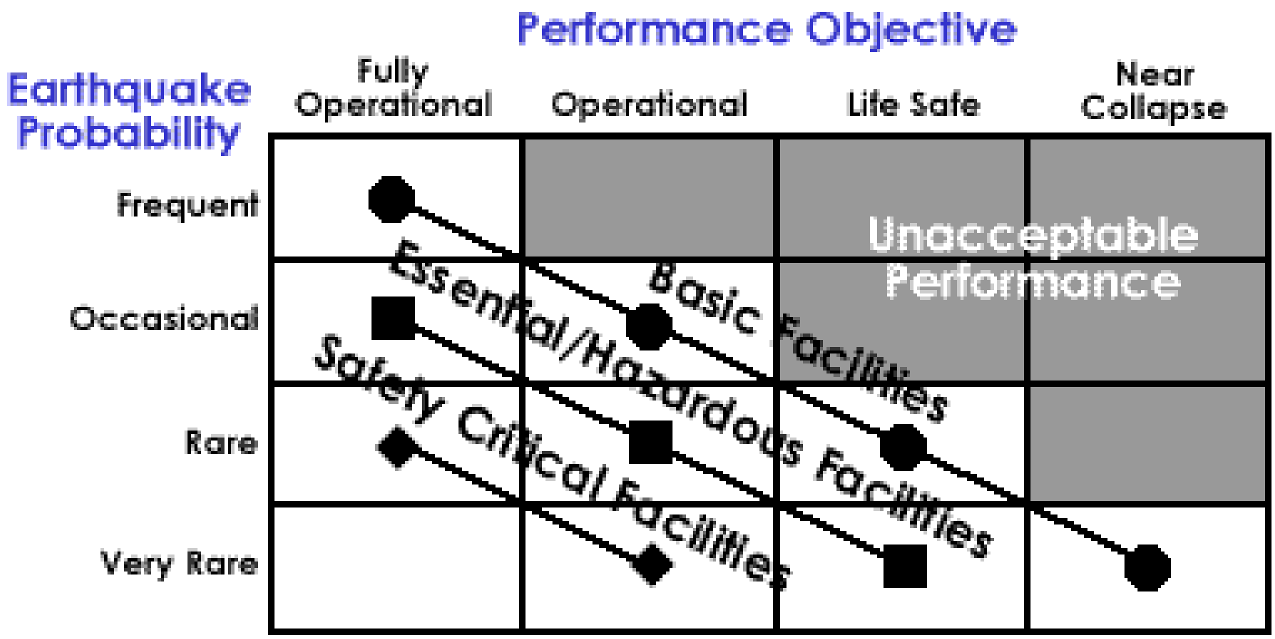


Figure 16 Vision 2000 Performance Levels

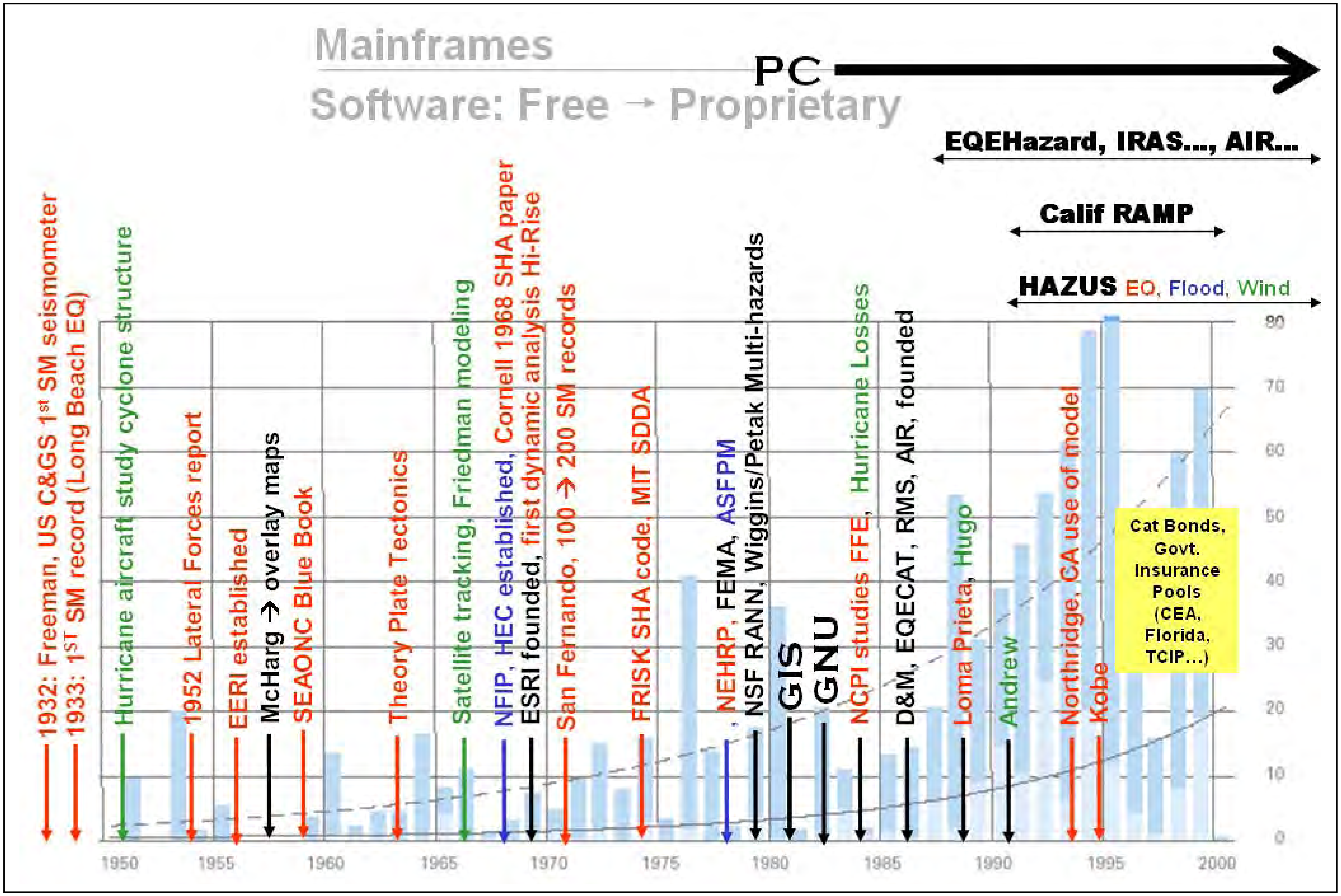


Figure 17 General developmental trend of seismic risk assessment 1950-2000, overlaid on natural hazards losses and also showing selected related trends (background: Munich Re)