HISTORY OF SEISMIC RISK ANALYSIS

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ABSTRACT :
Seismic risk is the average loss, or potential or probability of a loss, due to the occurrence of an earthquake, and is the combination of earthquake hazard, assets at risk and vulnerability of the assets to the effects of the earthquake. The history of seismic risk assessment is reviewed and found to be a confluence of seismology, earthquake engineering, probability and other fields over the last 150 years, surrounded by broader social and technological influences. Today seismic risk assessment is well established, although fundamental improvements are still needed.

KEYWORDS:
Risk, hazard, vulnerability, analysis, history, Cornell

1. INTRODUCTION

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. 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. This paper briefly reviews the history of these elements.

2. HAZARD

The history of seismology, and seismic risk analysis, 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. Mallet 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. 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.

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. The Seismological Society of America was established, but it had been *the fire* that did the damage, 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).

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.

In 1920 there was no seismological observatory in Southern California. Harry Wood and John Anderson built a practical seismograph which began to generate good quality data which Charles Richter, when he arrived in 1925, began to analyze. 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. 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. 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[1].

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 when located at a standard distance from the epicenter. 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

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

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[2]. 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[3]. 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. 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 was 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 , so that Charleston SC moved from Zone 3 to Zone 2, and then the following year the map was withdrawn . The 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. 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.*

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.

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

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

[3] 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.

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, 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 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 (not unlike the detail of Kawasumi's 1951 map), when compared with the 1970 map, shows the analytical capability the Cornell method provided.

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. 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). 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. VULNERABILITY

It is ironic 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. This is due to the long tradition of national observatories for the earth sciences, including seismology, but no comparable national centers for engineering until very recently. There are two fundamental approaches to determining 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. 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. 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 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 1971 San Fernando (California) earthquake 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 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 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. 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.

3.1 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. 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 .

4. RISK ANALYSIS METHODS

Due to space limitations, assets are not discussed and we proceed to 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). 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.

5. ASSESSMENT

As of this writing, 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.

6. 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)

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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