Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Toward worldwide seismic zonation in the 21st century

W.W. Hays
US Geological Survey, Reston, Va., USA

B. Rouhban
United Nations Educational, Scientific and Cultural Organization, Paris, France

ABSTRACT: This paper reviews accomplishments in seismic zonation made during the 20th century and forecasts future trends in this emerging professional practice. The outlook for the future is bright because of the efforts of a worldwide network of cooperating organizations to promote the practice of seismic zonation as part of the International Decade for Natural Disaster Reduction (IDNDR). During the 21st century, communities throughout the world are expected to use expert systems to perform seismic zonation in both the pre- and post-earthquake environments and to apply the results as a part of their national earthquake risk management practices (i.e., prevention, mitigation, and preparedness measures to reduce the risk from earthquake hazards of ground shaking, ground failure, and other physical effects).

1 SEISMIC ZONATION IN THE 20TH CENTURY

This paper describes some of the accomplishments in seismic zonation made during the 20th century and forecasts the trends expected to occur worldwide in the 21st century.

Seismic zonation--the division of a geographic region into smaller areas or zones expected to experience the same relative severity of ground shaking or ground failure--was recognized as a viable technical goal in the early 1900's (Hays, 1980). Since the early 1900's, many scientists and engineers throughout the world have recommended seismic zonation as a solution when community decisionmakers in either their own country or in other countries asked their advice on the selection of the safest and most suitable part of the urban area for new development or on guidelines for reconstruction after portions of the community had been damaged or destroyed after a major earthquake. Many of them observed that the damage distribution usually correlated closely with the spatial distribution and physical properties of the underlying rock and soil (Earthquake Engineering Research Institute, 1991). They responded to the long-term need of the international community for seismic zonations maps by developing scientific and technical methodologies to construct deterministic maps that were based primarily on empirical ground motion and damage data acquired from postearthquake investigations (Hays 1980). These initial methodologies focused on the identification and delineation of soils that were expected either to amplify the ground motion in narrow period bands or to fail through liquefaction or landsliding processes (i.e., falls, topples, slides, spreads and flows of soil and rock). The early maps mainly depicted the ground shaking hazard on national and regional scales, portraying the spatial variation of local site effects (e.g., soil amplification) on the basis of what had happened in the most recent earthquakes. The maps were limited in their treatment in space and time of earthquake recurrence, source parameters, regional seismic wave attenuation, and uncertainty. The state-of-practice was slow to develop because of: 1) the limitations of the seismicity and strong motion data bases, 2) the gaps in knowledge about the physical processes, especially of the earthquake source, and 3) the inability to model these processes analytically (Hays, 1991). In spite of these limitations, some practitioners in some countries (e.g., Japan) were able to use the maps for important risk-reduction applications in their countries. These applications usually happened after a damaging earthquake had exposed flaws in siting, design, and construction practices and provided a window of opportunity to change and improve them. However, most countries, if they had not experienced a damaging earthquake in the preceding 10 to 20 years, usually did not choose to adopt or apply the seismic zonation maps, justifying their inaction with the following assertions (Earthquake Engineering Research Institute, 1991):

1. Seismic zonation is a local research problem, not an accepted international professional practice.
2. Some of the proposed methodologies are based on extrapolations of limited data and, therefore, are uncertain and unreliable.(e.g., especially for applications in urban areas involving construction sites close to an active fault or for designs involving large- to great-magnitude earthquakes)
3. Some methodologies are controversial and avoided by community decisionmakers, not only because of the limitations of the databases but also because of the lack of consensus between scientists and engineers on "standard" procedures or acceptable practice.

After the 1970's, probabilistic seismic zonation maps began to be constructed on national, regional, and urban (i.e., microzonation) scales (Hays, 1980; Earthquake Engineering Research Institute, 1991). In the 1990's, they began to supersede deterministic maps. These advances were the result of: 1) significant increases in the seismicity and strong ground motion data bases, 2) deeper understanding of the earthquake source through paleoseismicity and paleoliquefaction studies, 3) improved regional models of seismic wave attenuation which took into account heat flow and crustal structure, 4) improved models of soil amplification and soil failure under various levels of seismic excitation, and 5) better estimates of uncertainty.

Practitioners accepted the transition from deterministic to probabilistic maps as a part of earthquake risk management, a professional practice that evolved rapidly during the 1980's and 1990's. Recent damaging earthquakes (e.g., 1980 Algeria, 1985 Chile, 1985 Mexico, 1988 Armenia, 1989 Loma Prieta, 1990 Philippines, and 1991 Costa Rica) contributed to the scientific and technical advances and social acceptance of seismic zonation (Hays, 1986). Each earthquake provided a scientific "laboratory" for acquiring important empirical and instrumental data to fill gaps in the knowledge base about: a) earthquake recurrence, b) source characteristics, c) regional seismic wave attenuation, and d) local site effects (Earthquake Engineering Research Institute, 1991). Each postearthquake investigation contributed to: 1) the expansion of data bases, 2) confirmation or rejection of theories, hypotheses, and professional judgments, 3) identification of ways to improve past and present siting, design, and construction practices, and 4) changes in community earthquake risk management policies and practices. In addition, 155 signatory nations adopted a resolution in the 44th General Assembly of the United Nations calling for an IDNDR. The IDNDR provided an unprecedented opportunity for nations of the world to cooperate during the 1990's to reduce loss of life, economic loss, and human suffering from natural disasters (United Nations, 1989).

2 THE IDNDR, POSTEARTHQUAKE INVESTIGATIONS, AND SEISMIC ZONATION

During the 1990's, the IDNDR led to the formation of worldwide networks of cooperating organizations to promote important ongoing technical activities such as postearthquake investigations and professional practices such as seismic zonation. Postearthquake investigations, which take advantage of the scientific "laboratory" to learn, proved to be an important source of basic knowledge and a catalyst for increasing the professional capacity to perform seismic zonation as a part of earthquake risk management. After a damaging earthquake (e.g., 1906 San Francisco; 1923 Tokyo-Kyoto; 1964 Prince William Sound, Alaska; 1964 Niigata; 1965 Caracas; 1980 El Asnam, Algeria; 1980 Campania-Basilicata, Italy; 1985 Mexico; 1988 Armenia; 1989 Loma Prieta; 1990 Philippines; and 1991 Costa Rica). Public officials seek an immediate investment of capital in their stricken community and the best scientific information to rebuild it in such a way that the chances of a repetition of the disaster are reduced. To accomplish this goal, the following scientific investigations are conducted to acquire basic data for improving seismic zonation maps:

1. Geological studies - geologic field work and geodetic measurements to determine the cause, nature, type, degree, and spatial distribution of faulting, regional tectonic deformation, liquefaction, landsliding, and wave inundation (if any) from tsunamis, seiches, and dam failures.
2. Seismological studies - measurement programs using arrays of permanent and mobile seismographs to locate the main shock and individual earthquakes of the aftershock sequence, to define the spatial extent and temporal changes of the rupture zone of the causative fault, and to determine the focal mechanism of the main shock.
3. Engineering seismology studies - measurement programs using arrays of permanent and portable strong motion accelerographs to measure the amplitude, spectral composition and duration of strong ground motion of the main shock and aftershocks for a wide range of magnitudes, epicentral distances, and rocks and soil types.
4. Engineering studies - investigations of individual buildings and lifeline systems comprising the inventory of the urban center to determine the failure mechanisms; nature, degree, and spatial distribution of damage, casualties, loss of function, and economic impacts to each component of the inventory of structures (e.g., single family buildings, low-to-high-rise buildings, schools, hospitals, industrial facilities, bridges, utilities, power plants).
5. Social science studies - interviews and on-site observations to determine how the populace reacted before, during, and after the earthquake, focusing especially on community behavior and decisionmaking during the emergency response and recovery periods.

Postearthquake investigations have gradually provided the comprehensive technology base (i.e., scientific and technical databases, and technical capacity) needed to advance seismic zonation as a professional practice. They have provided many important lessons, such as: the destructiveness of an earthquake is related to the parameters of three complex systems (Figure 1): 1) the solid earth system, which consists of the a) earthquake source, b) seismic wave propagation paths, and c) geometry and physical effects of the local site geology, 2) the quality of construction of the built environment system, which consists of buildings and lifeline systems, and 3) the socioeconomic-political system, which regulates land-use and the siting, design, and construction of buildings and lifelines in the urban area, before an earthquake disaster strikes.

A second lesson is that it is now technically possible to identify and avoid those locations in an urban area where damage to the built environment caused by physical parameters of the earthquake's source, path, or local geology is expected to be most severe. Engineering solutions, which cost more, are always possible if avoidance is not possible as an option.

A third lesson is that damage to the built environment is caused by a relatively small number of physical factors. They include: 1) soil-structure resonance; 2) liquefaction; 3) lateral and/or torsional displacements; 4) irregularity or asymmetry of buildings with regard to elevation, plan, and discontinuities in mass, strength, and stiffness; 5) hammering or pounding of adjacent buildings; 6) design, arrangement, and fastening of non-structural elements; and 7) quality of workmanship.

A fourth lesson is that the community decisionmakers can manage this risk. The application of seismic zonation is most effective when urban planners, architects, engineers, geologists, seismologists, and

ELEMENT	KEY PARAMETERS
SOURCE	MAGNITUDE, DEPTH OF BRITTLE-DUCTILE TRANSITION ZONE, DIRECTIVITY
PATH	DISTANCE, Q
SITE	THICKNESS, MATERIAL PROPERTIES, AND GEOMETRY OF SOIL DEPOSITS

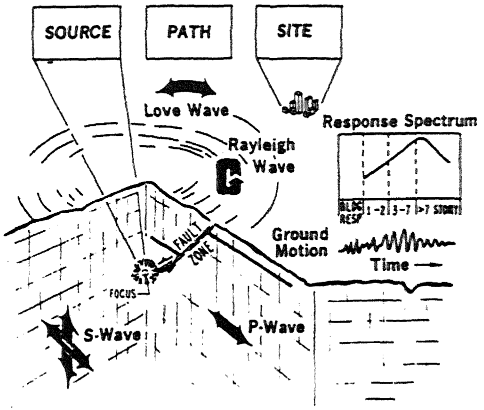

Figure 1.--In the 21st century, the worldwide practice of seismic zonation will be based on integrated scientific databases (i.e., an expert system on seismic zonation). With an expert system, communities will be able to identify the most suitable and safest locations for construction projects on the basis of integrated data on: a) the solid earth system, b) the built environment system, and c) the social economic-political system.

disaster managers work cooperatively to integrate the databases, lessons, and experiences in the development of an urban master plan and to devise realistic criteria and guidelines for the siting, design, and construction of buildings and lifelines. Realistic seismic zonation maps, which integrate the solid earth system with the built environment system and socioeconomic-political factors,the outcome of such cooperations pay off with reduced loss of life, damage, and societal disruption.

SEISMIC ZONATION IN THE 21ST CENTURY

Forecasting the future of a complex professional practice such as seismic zonation is challenging for two reasons: 1) scientific, technical, and societal breakthroughs are often subtle and may or may not exceed expectations, and 2) nature, the basis for many rapid breakthroughs, is inexhaustible, providing new laboratories for learning at unexpected times and often at unexpected locations.

Although some aspects of the practice of seismic zonation are controversial, even after international conferences and several hundred technical papers on seismic zonation, the outlook for the part of earthquake risk management seismic zonation is bright during the 21st century. The following reasons stand out. First, the concerted worldwide effort being made during the 1990's to improve community risk management policies and practices as a part of the IDNDR, is expected to produce significant results in the 21st century. Second, interdisciplinary cooperation among scientists, engineers, health care workers, urban planners, emergency mangers, and others to develop and apply knowledge-based and experience-based expert systems to facilitate consensus and worldwide production of a "standard" set of seismic zonation maps for ground shaking, surface fault rupture, liquefaction, landsliding, and, where applicable, tsunami and seiche flood wave runup. Third, more nations will begin to undertake and accomplish seismic zonation in the pre-earthquake environment during the 21st century rather than primarily, as now, in the postearthquake environment after a damaging earthquake. Fourth, the IDNDR will serve as a catalyst to accelerate the transfer of technology (Hays and Rouhban, 1991) on seismic zonation and to facilitate the formation and strengthening of networks of cooperating organizations. For example, International Fora on Seismic Zonation, sponsored by the U.S. Geological Survey and the United Nations Educational, Scientific, and Cultural Organizations (UNESCO), and others are expected to improve mechanisms for sharing information and experiences worldwide. Regional programs such as: the Hazard Mapping Program in California (State of California, 1990), the Cooperative program for Seismic Risk Reduction in the Mediterranean (SEISMED) (Hays, van Essche, and Maranzana, 1991), and the Worldwide Earthquake Risk Management Program (WWERM) (Williams and Hays, 1989) are expected to increase the technical capacity of many nations, through the expanded cooperation and sharing between scientists, architects, engineers, health care specialists, urban planners, and emergency managers.

CONCLUSIONS

Seismic zonation in the 21st century is expected to provide nations worldwide with a wider range of options for consistent, earthquake risk management than presently available. For example, communities will regulate the siting, design, and construction of short, stiff buildings and stiff bridges on the basis of seismic zonation maps, placing them whenever possible at locations that are not expected to experience high levels of ground acceleration during their useful life (e.g., on deep, soft soils at least 40 km from any potential causative faults capable of generating magnitude 6 or greater earthquakes). Also they will regulate the siting, design, and construction of tall, flexible buildings and long, linear lifeline systems on the basis of seismic zonation maps, placing them at locations that are not expected to experience high levels of long-duration ground velocity and ground displacement during their useful life (e.g., on firm soil or rock within about 40 km of causative faults capable of generating magnitude 6 or greater earthquakes). Many innovative urban planning, design, and construction options will be available to the communities having state-of-the-art seismic zonation maps during the 21st century.

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