MITIGATING THE EFFECTS OF EARTHQUAKES: PROBLEMS, PROGRESS AND FUTURE TRENDS

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ABSTRACT

Over the past few decades, seismologists have made enormous progress in understanding the physical processes that govern the occurrence of earthquakes. For example, we now know that most earth tremors are generated by stresses that accumulate along the boundaries between the giant tectonic plates that constitute the Earth's outermost rigid layer. Seismologists have estimated the sense of ground displacement to be expected in many seismically active regions, and experience has shown that damage caused by direct shaking of the ground can be augmented markedly by such secondary effects as fires, landslides and tsunamis. Moreover, the number of fatalities and level of damage created by an earthquake are not only dependent on the size and location of the event, but they are also affected significantly by the quality of the buildings and the local ground conditions.

Nevertheless, one of the major goals of seismology, that of short-term (days to weeks) earthquake prediction, remains as elusive as ever. Although some seismologists claim that earthquakes may be predictable in the not-too-distant future, others suggest that their occurrence is essentially random and that research into earthquake prediction may be futile. By comparison, trustworthy earthquake hazard and risk assessments based on time scales of tens to hundreds of years are realizable. In many regions, these assessments are benefiting from the results of global projects aimed at:

(i) compiling dependable earthquake statistics,
(ii) ascertaining the present state of stress and strain rate,
(iii) mapping the distribution of active faults,
(iv) determining the rate of seismicity in the distant past, and
(v) estimating the expected level of ground-shaking by means of computer modelling. Furthermore, fast inexpensive computer technologies are allowing early warning and early-damage assessment strategies to be developed, such that disaster response personnel can be either forewarned of damaging waves approaching or informed where the most intense ground-shaking has occurred

As the International Decade of Natural Disaster Reduction (IDNDR) comes to an end, it is appropriate to consider how mitigation and preparedness measures for the natural disasters that will inevitably affect our planet may be better promoted and implemented. One approach is to concentrate our efforts on the large urban centres of the developing world, where the effects of natural disasters can be devastating to the people, their economy, their culture, and their environment. Several programs aimed at improving capacities for natural disaster mitigation and preparedness in the megacities of the developing world are currently underway.

1. INTRODUCTION

Earthquakes are amongst the most damaging natural phenomena to affect the Earth. Since the beginning of this century, more than two million people have lost their lives as a direct or indirect consequence of violent shaking of the ground. Two of the three most costly natural disasters to strike our planet since 1980 were the Northridge (California) and Kobe (Japan) earthquakes. Economic losses due to the Northridge event exceeded $30 billion and those due to the Kobe exceeded $100 billion. Although these were only moderate magnitude earthquakes (Northridge: 6.8; Kobe: 6.9), they generated ground accelerations over large areas that approached or exceeded that of the Earth's gravitational field. These events were not the so-called "Big Ones", which will eventually strike California and Japan. The Big Ones are likely to have magnitudes greater than 8, resulting in the release of thirty times more energy than either the Northridge or Kobe earthquakes. Based on recent experiences, losses due to the Big Ones in

California and Japan are expected to exceed $300 billion and an astounding $1 000-2 000 billion, respectively.

Most of the world's earthquakes (more than 95 per cent) are focused along the boundaries of tectonic plates (Figure 1). Although it is certain that earthquakes will continue to shake these same narrow zones, we cannot predict exactly when an earthquake will happen and how much energy it will release. A relatively small number of earthquakes (less than 5 per cent) occur within the plates themselves. Some intra-plate earthquakes are associated with active volcanoes overlying mantle plumes (e.g. Hawaii in the middle of the Pacific plate), whereas others are related to rifting within the continents (e.g. East African Rift). There is also a class of intra-plate earthquake that we really do not understand. Outstanding examples are the huge earthquakes that struck Missouri and Southern Carolina (southeastern United States) during the last century.

In addition to damage caused by direct shaking of the ground during an earthquake, secondary effects such as fires (through the rupture of gas lines), landslides and tsunamis can be equally or more devastating than the earthquake itself. A major problem that invariably occurs, even in the best prepared countries and cities, is the destruction of critical communication and other lifeline systems. Roads and railways often become impassable (Figure 2), telephone systems are either broken or choked by excessive use, electricity is interrupted so that television and radio stations cannot broadcast and water systems, which are required for extinguishing fires, are broken.

2.
CONSTRUCTION PRACTICES AND GROUND CONDITIONS MAKE A DIFFERENCE

Experience has demonstrated that the number of fatalities and amount of damage caused by an earthquake are not only related to its magnitude, depth and geographic coordinates, but also to the quality of the affected buildings and the nature of the ground on which they are constructed. Two comparisons illustrate well the difference that construction practices and ground conditions can make. In 1960, a magnitude 5.9 earthquake caused around 12,500 deaths in the Moroccan city of Agadir. These fatalities resulted from the collapse of primitively built stone and brick houses situated on loosely consolidated sediments. In contrast, a slightly larger earthquake of magnitude 6 within the crystalline crust of the Canadian Shield shook a large region of northeastern North America in 1988. No deaths resulted from this event. Typical houses in this region are wood-framed with relatively light roofs.

In December 1988, a magnitude 6.9 earthquake devastated a large part of northwestern Armenia. Many poorly reinforced concrete buildings completely collapsed. As a consequence, more than 25 000 people lost their lives. Nearly one year later, an earthquake with magnitude 7.1 hit the Loma Prieta area of California. It caused much damage, but the extent and number of deaths were four hundred times lower than in Armenia. The key difference between the two earthquake zones was in the quality and type of buildings.

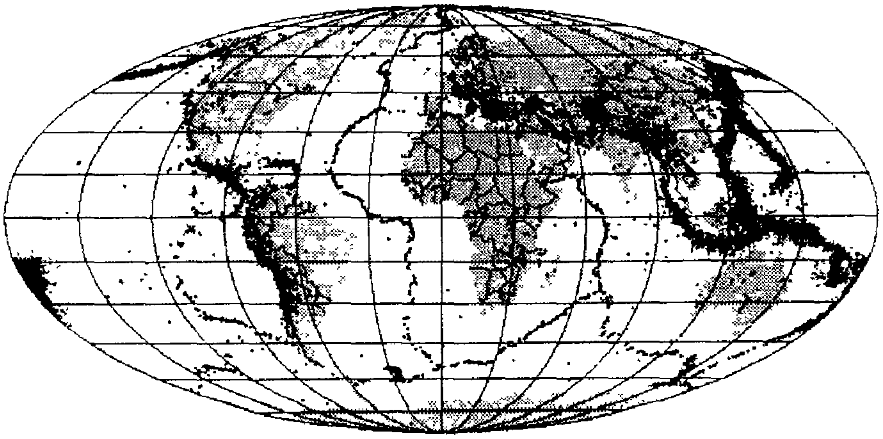

Figure 1. Earthquakes located during the period 1995-1998 by the Prototype International Data Center (Arlington, Virginia)

Figure 2. Spectacular collapse of the Hanshin Expressway as a result of the 1995 Kobe earthquake (Reproduced from the Kobe Geotechnical Collection, University of California, Berkeley).

3. EARTHQUAKE PREDICTION

Although earthquake prediction continues to be a hot topic of discussion, the optimism in the 1970s and 1980s that reliable means to predict earthquakes would soon be available has turned out to be ill-founded. Only a very few of the millions of earthquakes recorded since 1970 have been predicted ahead of their occurrence In the context of earthquake prediction, the following physical phenomena have been investigated (Wyss, 1997; Geller, 1997):

1. Changes in seismicity patterns;
   - foreshocks — increase of seismicity prior to a major earthquake;
   - seismic quiescence — decrease of seismicity prior to a major earthquake;
   - seismic gaps — inactive segments of seismically active faults;
   - increased moment release — increase release of seismic energy over a wide area prior to a more localized major event;
   - M8 algorithm — combination of statistical parameters based on observations of seismic quiescence and increased seismicity;
2. Variations in groundwater level, chemistry and temperature,
3. Crustal deformation;
4. Temporal anomalies in the earth's electrical, electromagnetic, magnetic, gravity and/or thermal fields;
5. Changes in seismic wave velocity;
6. Extraordinary behaviour of animals;
7. Unusual atmospheric conditions (e g strange noises, bright lights in the sky).

Although precursory phenomena have been observed prior to a small number of earthquakes, none of the proposed prediction techniques appears to be generally applicable. Some geoscientists have suggested that earthquakes belong to a class of physical processes governed by "self-organized criticality" and are, therefore, not predictable on a short-term basis There is an ongoing controversy regarding the wisdom of large expenditures directed towards earthquake prediction. Competing arguments can best be summarized by the following two sets of statements:

> "Theoretical work suggests that faulting is a non-linear process which is highly sensitive to unmeasurably fine details of the state of the Earth in a large volume, not just in the immediate vicinity of the hypocentre. Any small earthquake thus has some probability of cascading into a large event. Reliable issuing of alarms of imminent large earthquakes appears to be effectively impossible." (Geller, 1997),

which has been countered by:

> "However, based on measurements of elastic strain accumulation and release before and during large earthquakes, most seismologists believe that after a maximum credible earthquake, the crustal volume in which it occurred is not capable of another until sufficient elastic strain energy has been accumulated again This process typically takes in excess of 100 years. Thus, most seismologists believe that the random element in triggering large ruptures plays an important role, and that this impairs the capability of short-term [days to weeks] predictions, but that intermediate- and long-term predictions are not affected by this problem" (Wyss, 1997).

4. EARTHQUAKE FORECASTING: HAZARD AND RISK ASSESSMENT

Provided there are sufficient details on the history of seismicity and a thorough understanding of the prevailing tectonic regimes, the general level of seismicity to be expected across a broad area can be forecast for periods ranging from decades to centuries. This information is provided in the form of local and regional hazard maps. Hazard is defined as the probability of a certain area being affected by a potentially destructive process within a given time. For example, a typical seismic hazard map shows the maximum level of ground motion that has a certain probability (e.g. 10 per cent) of being exceeded within a defined period of time (e.g. 50 years). To improve the reliability of hazard maps, several high-profile global projects have been initiated over the past decade to:

- compile dependable earthquake statistics for most regions of the world;
- ascertain the current state of stress and strain rate:
- map the distribution of active faults throughout the continents;
- determine the timing and distribution of seismicity in the distant past by archeo- and paleoseismological investigations;
- estimate the expected level of ground shaking at various locations affected by large earthquakes via modelling studies based on detailed knowledge of the subsurface geology (Figures 3 and 4).

One highly successful international project (Global Seismic Hazard Assessment Program [GSHAP]) has involved the computation of hazard maps for most regions of the world based on relatively uniform databases, standard criteria and identical computational procedures (Giardini *et al.*, 1999). Through this project, nearly all countries now have regional seismic hazard maps, and estimates of seismic hazard are continuous across most international boundaries.

Once reliable seismic hazard maps are available, the next stage is to improve our understanding of the risk associated with earthquakes. Risk is a measure of the possibility of loss of lives, property, production capacity etc. within an area subjected to hazard. Risk is defined as the product of hazard, vulnerability and

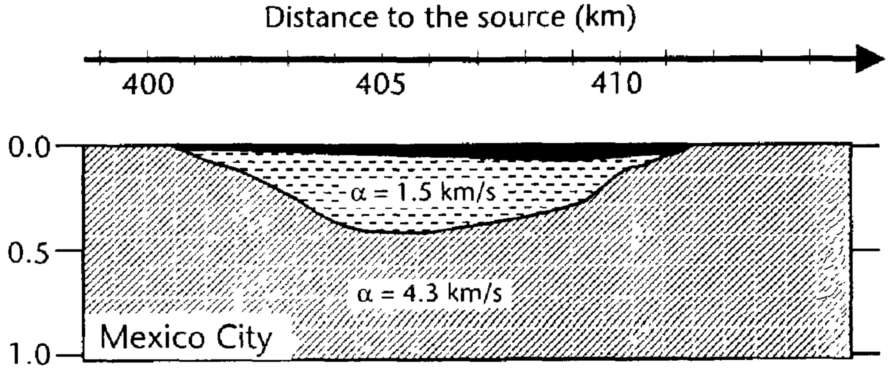

Figure 3. Simple model of the sedimentary basin underlying Mexico City Used for the computation of ground response due to an impinging earthquake wave (modified from Fah *et al.*, 1994)

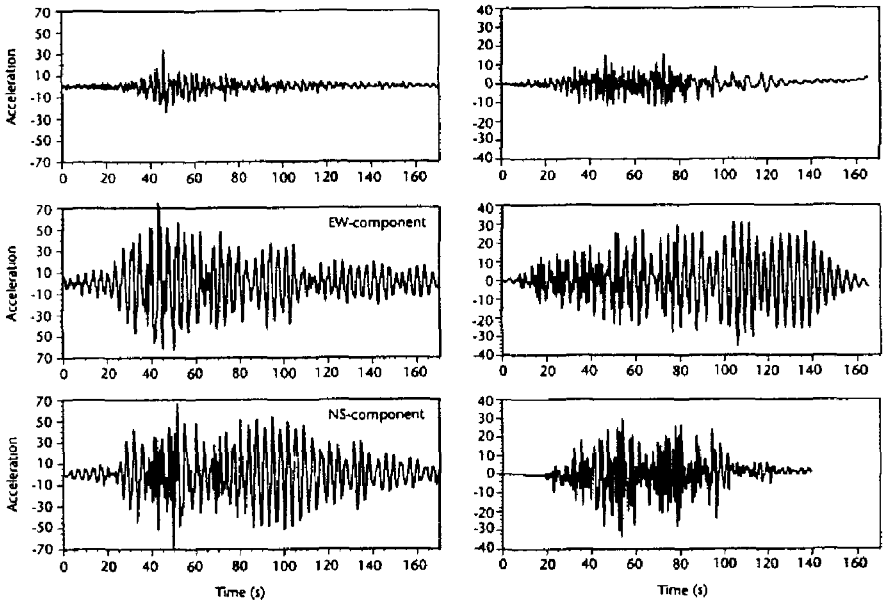

Figure 4. For the 1985 magnitude 8 earthquake landward of the Central American Trench (see Figure 5), comparison of (A) recorded ground motion within Mexico City with (B) that predicted from the simple sedimentary basin model of Figure 3 (modified from Fäh *et al.*, 1994).

value. To estimate risk, in addition to having sufficient hazard information at hand, we need to perform for each region a vulnerability study and a standardized inventory of populations, buildings, lifelines, transportation systems and critical facilities.

5. EARLY WARNING SYSTEMS

Although there is no general method for predicting earthquakes, there are a limited number of regions in the world where it is possible to warn urban managers and citizens of approaching seismic waves from relatively distant, but potentially damaging earthquakes. Early warning systems are comprised of:

- one or more seismographs immediately above the active earthquake zone;
- computers that can estimate very quickly (in a few seconds) the magnitudes; occurrence times and locations of earthquakes from the seismographic records;
- very fast communication links between the seismographs, computer systems and urban centres; and,
- effective means to transmit information to critical facilities and the general public.

After the onset of a large earthquake, it may take several seconds to more than a minute for dangerous shear and surface waves to hit an exposed urban center. During this time, the earthquake parameters have to be reliably determined, the information distributed, and the necessary precautionary actions implemented. In addition to enabling the public to take appropriate safety measures to protect themselves, early warning systems may be used to trigger the cessation of oil and gas flow through pipelines, the re-routing of electricity, the safe shutdown of oil refineries and nuclear power plants, the slowdown of high-speed trains, and the saving of crucial information on computer discs.

Presently, early warning systems of different sophistication and purpose are operational in three countries: Japan, Mexico and Taiwan (Lee and Espinosa-Aranda, 1999). A fourth system is currently under development in Romania (Wenzel *et al.*, 1999). Only the Mexican early warning system is capable of issuing earthquake alerts to the general public. It was developed after a magnitude 8.1 earthquake devastated a broad area of Mexico City in 1985. This earthquake actually occurred 350 km from the city, within the Central American Subduction Zone (Figure 5). Nevertheless, it resulted in 10 000 deaths within the city limits, 50 000 injuries, 250 000 homeless, and US $5 billion worth of damage. The 1985 earthquake was not an isolated event. Since the beginning of this century, 28 earthquakes with magnitudes greater than 7.7 have shaken this region (Figure 5). Earthquakes along the Central American Subduction Zone generate high-amplitude shear and surface waves that may take more than one minute to reach

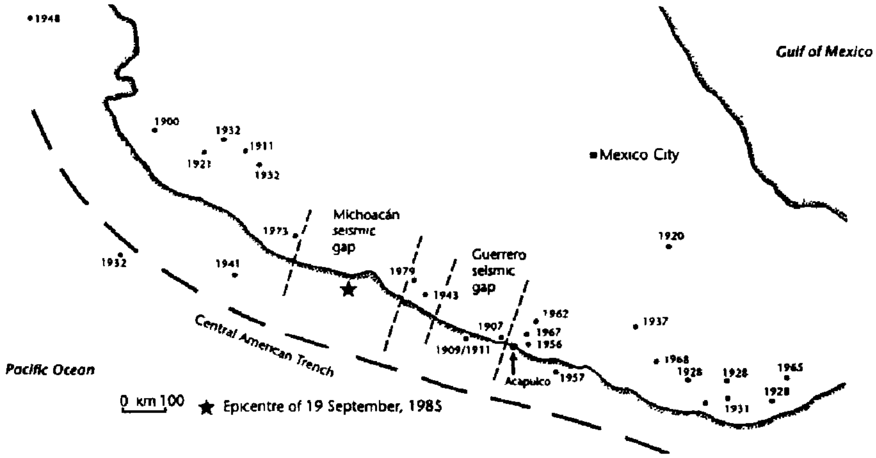

Figure 5. Map showing Mexico City relative to seismicity of the Central American Subduction Zone. Locations of earthquakes with magnitudes greater than 7.7 are displayed (Degg, 1992)

Mexico City, thus allowing adequate time for warnings to be broadcast. According to Lee and Espinosa-Aranda (1999), this system has already been responsible for one successful earthquake alert. In September 1995, it broadcast information that gave a 72-second warning to the general public of high-amplitude seismic waves arriving from a magnitude 7.3 earthquake.

Even for those cities built directly above dangerous earthquake zones, rapidly available information on the level of ground shaking affecting each region during a major earthquake may be used to implement many of the safety measures and actions mentioned above. Furthermore, such information enables disaster relief officials to direct their efforts to locations where injured citizens are likely to require emergency aid and where critical facilities are likely to have been damaged. A key element in early warning and early damage assessment strategies is the availability of real-time systems that very quickly provide earthquake parameters and supply estimates of ground-motion throughout an affected area. The introduction of inexpensive, yet very fast electronic and computer-based technologies is allowing low-cost and ever more effective systems to be developed.

6.

PROMOTING EARTHQUAKE MITIGATION AND PREPAREDNESS

Effective disaster management requires that strategies for mitigation and preparedness be in place before an earthquake occurs and that swift measures for the response, recovery and reconstruction be implemented subsequent to the event (Figure 6) Immediately after a major earthquake, details of the catastrophe are likely to be newsworthy on a global scale. Typically, national and international relief agencies provide the necessary resources for rapid response and partial recovery, with emphasis on reducing the death toll, minimizing human suffering, restoring crucial lifelines and re-activating commercial activities. Funds for the reconstruction phase are generally much more difficult to obtain, and in only a few countries are appropriate mitigation and preparedness strategies in

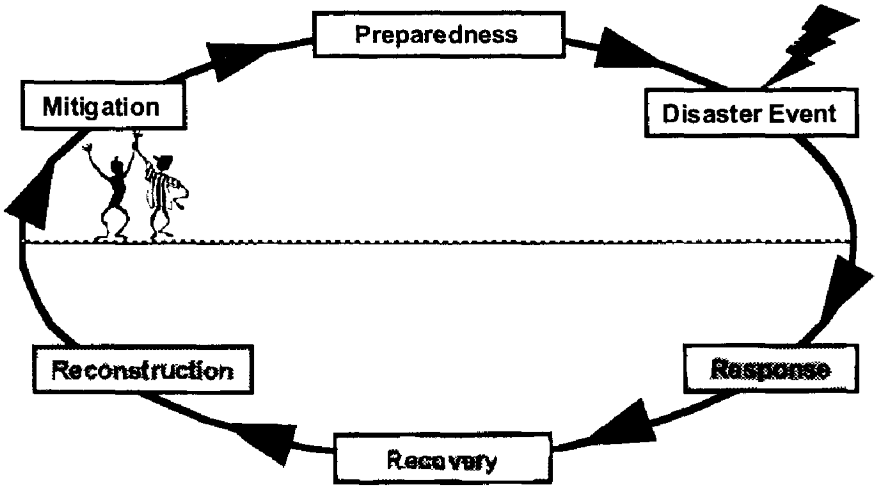

Figure 6 Cycle of disaster management (The Institution of Civil Engineers, 1995)

place. Yet, it has been estimated that for every dollar spent on the protection side of the disaster mitigation cycle (Figure 6), ten dollars are saved on the recovery side; efficient earthquake mitigation and preparedness strategies make economic sense.

A common mission of several projects contributing to the International Decade of Natural Disaster Reduction (IDNDR) is to markedly increase the resources directed towards earthquake mitigation and preparedness. Here, three international projects shall be mentioned briefly (WSSI, GHI, RADIUS) and a fourth (EMI) reviewed in a little more detail.

One of the first projects to become truly operational as a result of IDNDR was the World Seismic Safety Initiative (WSSI), which was initiated in 1992 by the International Association for Earthquake Engineering. The goals of WSSI are to:

- disseminate state-of-the-art earthquake engineering information;
- incorporate experience and research findings into recommended practices and codes;
- advance engineering knowledge through problem-focused research;
- encourage governments and financial institutions to establish policies directed towards understanding and preparing for future earthquakes.

Countries in which WSSI has been particularly active include Bangladesh, Burma, Malaysia, Nepal, Singapore, Sri Lanka, Uganda and Vietnam.

GeoHazards International (GHI) was established in 1993 as a non-profit organization dedicated to reducing earthquake-related death and injury in developing countries. Until quite recently, GHI concentrated on two high-profile development and training projects, one in Quito (Ecuador) and one in Katmandu (Nepal) Over the past two years, GHI has also been a major contributor to the IDNDR project "Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disaster (RADIUS)". The principal objectives of the RADIUS project are to raise the awareness of earthquake risk among decision makers and the general public, and to provide them with appropriate earthquake mitigation technologies. Specific components of RADIUS include the development of.

- seismic damage scenarios for several cities;
- a practical manual for seismic damage assessment in urban areas;
- guidelines for simple assessment of seismic safety of buildings and for practical retrofitting.

Cities chosen for full-case study by RADIUS are Addis Ababa (Ethiopia), Guayaquil (Ecuador), Tashkent (Uzbekistan), Tijuana (Mexico) and Zigong (China). Also under investigation are the cities of Antofagasta (Chile), Bandung (Indonesia), Izmir (Turkey) and Skopje (TFYR Macedonia).

6.1
EARTHQUAKE AND MEGACITIES INITIATIVE (EMI)

The Earthquakes and Megacities Initiative (EMI) is an international scientific non-governmental organization dedicated to the acceleration of earthquake mitigation, preparedness and recovery of large urban centres, with emphasis on developing countries. EMI has many goals in common with other IDNDR-oriented projects. One difference is its concentration on problems associated with very large cities. Growth in world population and urbanization is truly alarming. By the year 2000 it is expected that 450 cities with populations greater 1 million inhabitants will crowd our planet. Of these, 50 cities with populations more than 3.5 million and 25 with populations greater than 8 million will compete for limited space and resources (Figure 7). More than half of these cities will be located in the developing world, of which 50 per cent will be situated in major earthquake zones (compare Figures 1 and 7). EMI's multidisciplinary scientific agenda includes four major themes:

Assess earthquake hazard by:

- modelling ground motion for realistic earthquake scenarios;
- encouraging the installation of local seismographic and strong-motion networks.

Determine vulnerability and risk by:

- reviewing the effectiveness of building codes and their implementation;
- developing methodologies for collecting standardized inventories of buildings, lifelines, transportation systems and critical facilities;

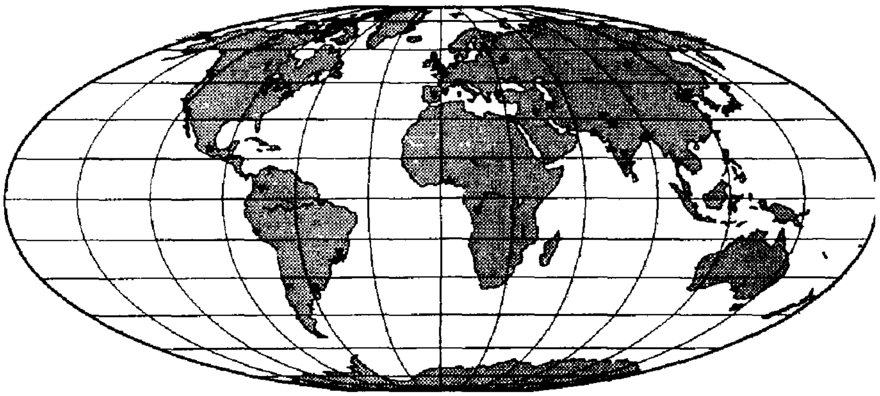

Figure 7. Map showing the locations of large urban centers. ★ — megacities with populations greater than 8 million, ▼ — large cities with populations greater than 3.5 million.

- applying damage-loss estimation models that include economic and social impact;
- modelling disaster scenarios for emergency preparedness and response.
- Evaluate options for sustainability by
- examining the effects of cultural differences in perceptions and response to risk;
- studying earthquake constraints on the long-term sustainability of megacities;
- investigating the technical, social, political, historical and economic factors that would allow earthquake mitigation measures to be integrated in urban planning policy at different government levels.

Promote earthquake mitigation and preparedness by:

- designing regional-dependent educational programs aimed at earthquake preparedness and earthquake awareness;
- promoting special procedures to protect cultural heritage items and monuments;
- advocating new construction methodologies for non-engineered buildings and new training programs for local builders;
- promoting seismic code provisions to encourage cost-effective retrofitting;
- encouraging improvements in emergency response coordination and communication.

EMI's scientific and technical agenda involves the promotion of multi-disciplinary research to evaluate the effects of earthquakes on large urban areas and to develop technologies and methods for the mitigation of such effects. In addition, EMI participants focus their efforts on specific projects expected to have a high impact in accelerating earthquake preparedness, mitigation and recovery. These activities are aimed at building and sustaining local and regional capacity of selected organizations and institutions in megacities of developing countries. EMI's capacity-building action plan for the next five years includes the Twin Cities, Regional Center and Training and Education projects.

The Twin Cities project pairs up two or more large cities in a formal exchange and development of knowledge that involves researchers, practitioners and end-users (Figure 8). Usually, one of the cities has more advanced knowledge on mitigation and preparedness procedures than the other, or has experienced a recent earthquake disaster. Exchanges between the cities are intended to result in the implementation of low-cost mitigation measures and improved emergency response. The following city grouping are currently involved in the EMI Twin Cities project: Los Angeles - Mexico City, Bogota - Managua, Naples - Cairo, Izmir – Tashkent, Tehran-Yeravan, Beijing - Manila - Kobe.

Under the auspices of the Regional centres project, megacities with active mitigation programs contribute expertise to large areas and provide the motivation to build partnerships with managers of large metropolitan centres, international development agencies and risk mitigation advocates. In contrast, the Training and Education project involves knowledge and information sharing to build local and regional capacities The focus is on four project areas: training, establishing databases and directories of resources and activities, coordinating researcher or student exchanges to increase access to information, and running special workshops and seminars.

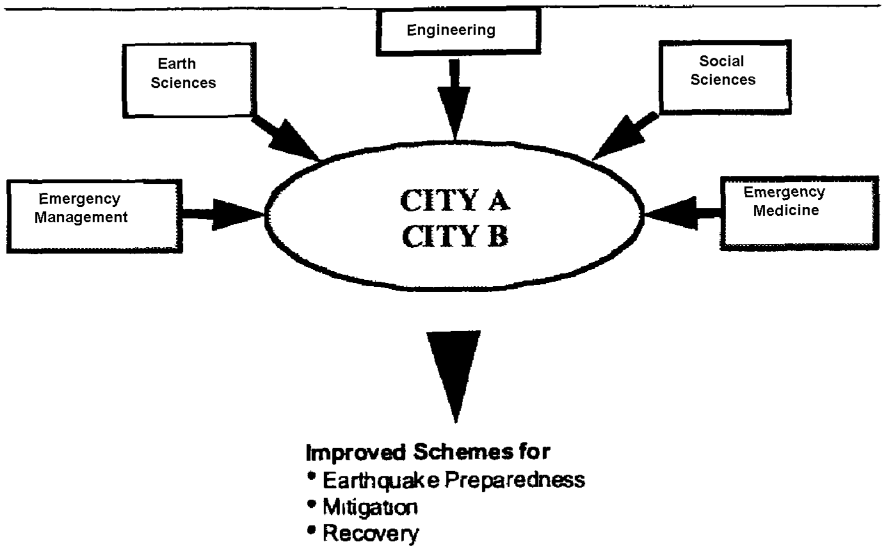

Figure 8. Concept of the Twin City project operating under the auspices of the Earthquake and Megacities Initiative.

ACKNOWLEDGEMENTS

I would like to thank Donat Fäh, Urs Kradolfer, Frank Lehmann, and Frank Nitsche for assistance in preparing the figures for this article.

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