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POSTEARTHQUAKE INVESTIGATIONS: A LABORATORY FOR LEARNING

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ABSTRACT

Holistic multidisciplinary investigations of the World's damaging earthquakes conducted by the United States and other countries have shown that they are the ultimate laboratory for validating theories, public policies, and professional practices for siting, design, and construction of earthquake-resilient buildings and lifeline systems. The results of these investigations have provided new ideas and realistic options for reducing earthquake risk.

KEYWORDS

Spitak, Armenia earthquake; Mexico earthquake; El Asnam, Algeria earthquake; Loma Prieta, California earthquake; Khilari, India earthquake; San Fernando, California earthquake; Northridge, California earthquake; Great Hanshin-Awaji, (Kobe) Japan earthquake; NEHRP; avoidance strategies; land use planning; emergency preparedness; reduction of vulnerability

LESSONS FROM DAMAGING EARTHQUAKES

Less than one hundred earthquakes of the more than twelve million that occur annually throughout the World cause a disaster as a result of either their size (i.e., magnitude) or their location close to an urban center. A disaster occurs when the physical and societal effects exceed the capacity of the urban center. Although a tragedy, the disaster provides a unique laboratory for multidisciplinary studies to document, understand, and explain what happened. Such studies are beneficial to the stricken community in the long run, because they enable it as well as other communities that are also at risk from earthquakes to use the experience to devise realistic countermeasures to minimize the potential impacts of future earthquakes.

Multidisciplinary postearthquake investigations of past earthquake disasters, such as those organized and led by the United States and by other countries, have provided a holistic portrait of what happened in the stricken community which can be transferred to other communities at risk from earthquakes. This portrait is derived from geologic, seismological, engineering, health care, and social science studies. Geologists use overflights, satellite observations, geodynamic measurements, paleoseismology, and field mapping to analyze faulting, liquefaction, and landslide phenomena. Seismologists use portable instrument arrays (e.g., GPS, seismicity, strong motion) along with permanent instrument arrays to characterize and understand the main shock and its aftershock sequence, to define the fault rupture zone, and document seismic wave propagation, ground response, and ground motion. Engineers use qualitative (e.g., photographs, slides, videos) and quantitative (e.g., accelerograph records, material testing, and block-by-block and building-by-building damage surveys) to document building and lifeline performance, to ascertain the nature, cause, degree, and spatial distribution of damage to foundations, structures, and facilities, and to predict the physical, human, and economic consequences of ground motion and ground failure on buildings and infrastructure. Health care specialists use site-specific determinations of casualties and building performance to correlate health care needs with building type, local geology, and land use in order to improve search and rescue efforts and to plan emergency health care. Social scientists use field work and qualitative and quantitative techniques to determine how the populace and government organizations in the stricken region used the available hazards and risk information, implemented public policies, and called for change in professional practices before, during, and after the disaster.

The results of these multidisciplinary investigations have provided critical data showing the thresholds at which the physical effects (i.e., earthquake hazards) of ground shaking, ground failure, surface fault rupture, regional tectonic deformation, tsunami wave run up, and aftershocks generated by the earthquake can damage and destroy buildings and lifeline systems in urban centers and cause socioeconomic impacts over broad geographic regions. They have shown that the vulnerability of the community to an earthquake disaster depends on physical (i.e., the magnitude of the earthquake, its focal depth and proximity to the urban center, the directivity of the energy release, the geometry and physical properties of the soil and rock underlying the structure) as well as societal factors (i.e., the degree of prevention, mitigation, and preparedness measures that are adopted as public policy and enforced by the community). Within a minute or less in the worst earthquake disasters, the direct economic losses have reached several tens of billions of dollars with the dead, injured, and homeless numbering in the hundreds of thousands.

The most significant benefit of the scientific and technical investigations is that they have shown practitioners and decisionmakers what the most realistic countermeasures are, because the same or similar damage patterns and failure modes are repeated in earthquake after earthquake and the same mistakes in siting, design, and construction have been and continue to be made in every country. These fairly simple, but common mistakes, increase the vulnerability of buildings and lifeline systems to ground shaking and ground failure and contribute to the losses (e.g., damage, economic losses, mortality, morbidity, and loss of function). They include:

1. Underestimation of the strength, duration, and frequency composition of the lateral forces.
2. Lack of consideration of the frequency-dependent effects of soil amplification and topography on ground motion.
3. Inadequate consideration of the potential for soil/structure resonance.
4. Lack of consideration of the effects of shallow depths of focus, directivity, or fault rupture.
5. Ignoring the potential for and underestimating the damage potential of long-duration acceleration pulses.
6. Siting structures on liquefiable or unstable soils.

Mandate of the United States to Learn From Damaging Earthquakes

Starting in1977 when the National Earthquake Hazards Reduction Act was enacted into law in the United States and the National Earthquake Hazards Reduction Program (NEHRP) was created to protect people and property from the devastating physical and socioeconomic effects of earthquakes and continuing to the present, both the Office of the President and the Congress have provided mandates for the NEHRP agencies (i.e., the United States Geological Survey, National Science Foundation, National Institute of Standards and Technology, and the Federal Emergency Management Agency) to learn from damaging earthquakes throughout the world (United States Geological Survey, 1995). The goal is to accelerate the rate of learning and international sharing of data and experience by using, whenever possible, the unique laboratories provided by damaging earthquakes in culturally different but tectonically similar regions of the world.

Within the scope of international cooperation, the objectives are to:

1. increase fundamental understanding of earthquake processes (i.e., the hazard environment), performance of structures (i.e., the built environment), and behavior of people and organizations (i.e., the policy environment),
2. acquire perishable scientific, technical, and socioeconomic data which can be added to the knowledge base and disseminated widely to every country at risk from similar earthquakes, and 3. foster utilization of the new knowledge to improve public policies and professional practices for prevention, mitigation, and preparedness in every earthquake-prone region of the United States and abroad.

A number of notable damaging earthquake disasters throughout the world have now been investigated under the auspices of NEHRP by organized multidisciplinary teams of earth scientists, engineers, health care specialists, architects, planners, and emergency managers (Earthquake Engineering Research Institute, (1991), . These investigations of a wide variety of unique individual "laboratories" have produced a spectrum of lessons which provide a framework on what to expect in future earthquakes. Collectively, the investigations have deepened the understanding of earthquake processes and effects at the source, along the path, and at the site: provided technology for forecasting the temporal and spatial distribution of physical effects and societal consequences as a function of magnitude, distance, soil type, and structural inventory at risk, and introduced a wide variety of options to manage earthquake risk.

The "laboratories" include the notable earthquake disasters that struck Kobe, Japan in 1995, Northridge, California in 1994, Hokkaido-Nansei-Oki, Japan and Khilari, India in 1993), Landers, California and Erzincan, Turkey in 1992, Costa Rica in 1991, the Philippines in 1990, Loma Prieta, California and Newcastle, Australia in 1989, Spitak, Armenia in 1988, Mexico and Chile in 1985, El Asnam, Algeria and Irpinia, Italy in 1980; Tangshan, China in 1976, San Fernando, California in 1971, and Valdiva, Chile in 1960. Individually and collectively, these earthquakes have served as scientific laboratories for scientists, engineers, and others to acquire new perishable and non perishable data and to test theories and concepts for siting, designing, and constructing various types of buildings and lifeline systems founded on soil or rock located close to and far from the causative fault system in low- as well as high-seismicity regimes. The lessons from each earthquake, part of a continuum, comprise a compendium on what can happen, why certain damage patterns and damage modes keep occurring, and the best options for changes in public policies and professional practices to reduce the vulnerability of buildings and lifeline systems in future earthquakes. Some of the most important "earthquake laboratories" representing different cultural and tectonic settings are summarized below to illustrate the range and world wide applicability of the lessons.

The May 22, 1960 Valdiva, Chile Earthquake (National Research Council, 1987, and Wood, 1987)

This M 9.5 earthquake which occurred at 3:05 p. m., was a catastrophe, an end member of the type of earthquakes that can occur as a result of the ongoing subduction of the Nazca plate beneath the South American plate. Much larger than the M 7.8 earthquake that struck Chile twenty-five years later in March 1985, this catastrophic earthquake caused damage along 1,000 km (600 miles) of Chile's coastline, destroying an estimated 400,000 houses, and leaving over 5,000 dead. It produced strong ground shaking that lasted 3 1/2 minutes, caused subsidence of up to 2 meters (7 feet), triggered extensive liguefaction, and generated several tsunamis having flood wave run up of up to 10 m (33 feet) which damaged ships, flooded coastal areas, and destroyed buildings and factories. Tsunami wave run up affected every Pacific rim country.

October 10, 1980 El Asnam, Algeria Earthquake (Hays, W. W. and Rouhban, B. M., 1991)

This M 7.3 earthquake which occurred on a Friday (i.e., the "weekend") is typical of the type of earthquakes that can be expected as a consequence of the ongoing collision of the Eurasian and African tectonic plates. The El Asnam earthquake repeated the lessons learned in 1954 when a similar, but smaller earthquake destroyed Orleansville, the predecessor of El Asnam, exposing the lack of earthquake resilience of existing unreinforced masonry as well as new buildings that were not designed to withstand the strong horizontal and vertical ground shaking that occurred in the epicentral region. An estimated 9,612 people were killed or injured and the direct losses are believed to have reached $ 2 billion. Reconstruction was frozen for four years until a seismic microzonation study could be completed in 1984 and implemented during the following decade through new building regulations, urban land use plans, and government decrees.

November 15, 1980 Irpinia, Italy Earthquake (Wood, 1987)

This M 6.9 earthquake, which occurred at 7:34 p. m. is representative of the normal faulting earthquakes that can be expected in Central Italy. The earthquake exposed the vulnerabilities of isolated mountain villages crowning the mountain tops that are comprised of steep roads susceptible to blockage by landslides, narrow streets susceptible to closure by debris, and old unreinforced masonry buildings and nonductile concrete buildings that are susceptible to damage and collapse from ground shaking. The earthquake left economic losses of $ 3 billion, 5,000 dead, and 9,000 injured.

The July 28, 1976 Tangshan, China Earthquake (National Research Council, 1987, and Wood, 1987)

This M 7.8 earthquake which struck at 3:42 a. m. was totally unexpected and, therefore, resulted in a catastrophic disaster. It struck while most of the 1 million people who lived and worked in this industrial and coal mining center of northern China were sleeping with only a small number of them, such as the 30,000 coal miners working underground, awake and working. The combination of the location of the causative fault beneath the city and the severity of the earthquake ground shaking led to a disaster, leaving the city's building stock comprised mainly of unreinforced masonry buildings in ruins. It left at least 240,000 dead and an estimated 800,000 injured. Reconstruction took ten years.

September 19, 1985 Mexico Earthquake (Earthquake Engineering Research Institute, 1989a)

This M 8.1 earthquake, which occurred at 7:18 a. m., is representative of the type of earthquakes that can be expected as a consequence of the ongoing subduction of the Cocos plate beneath the North American plate. The earthquake exposed the well known zone of soil amplification in the old lake bed portion of Mexico City where soft soils having shear wave velocities in the order of 50 m/sec amplified ground motions by a factor of 5 or more relative to stiff soils for fundamental periods centered near 2 seconds, increasing the level of vibratory lateral force load for buildings well above the design norm of the building regulations in effect at that time. Even though the epicenter of the earthquake was 250 km to the west, soil amplification and soil/structure resonance contributed to the collapse of 400 buildings (including hospitals, schools, and government buildings) out of more than 1 million buildings located in Mexico City. An estimated 10,000 to 40,000 people were killed, 25,000 were injured, 200,000 were left homeless, and economic losses are believed to have reached $5 billion

December 7. 1988 Spitak, Armenia Earthquake (Earthquake Engineering Research Institute, 1989b)

This M 6.8 earthquake, which occurred at 11:41 a. m. local time, is representative of the type of earthquake that can be expected from the ongoing collision of the Eurasian and Arabian tectonic plates. The earthquake was a direct hit on Spitak. Overall, it exposed the well known lack of earthquake resiliency in old unreinforced masonry buildings, but it produced two "surprises" when many new precast reinforced concrete frame buildings collapsed and the deaths outnumbered injuries instead of the opposite which is typical. The ground motion levels in the epicentral region exceeded the design values prescribed by building regulations due to soil amplification and the proximity of the causative thrust fault to the urban centers. Schools and hospitals were shown to be especially vulnerable with collapses killing students, doctors, and nurses. The death toll is believed to have reached at least 25,000, injuries about 15.000, homeless about 500,000, and the cost of reconstruction about $16 billion.

The April 18, 1906 San Francisco, California Earthquake (Added to provide background on the Loma Prieta earthquake discussed below) (Wood, 1987)

This M 8.25 earthquake, which struck at 5:12 a. m., is representative of the great magnitude earthquakes that are believed to occur about once every 130 plus or minus 20 years in Northern California on the right-lateral-strike-slip San Andreas fault zone marking the boundary of the North American and Pacific plates. This earthquake produced surface fault rupture and surface displacement that could be mapped in the field for more than 300 km (186 miles) from San Juan Bautista to Point Arena. The concept of "elastic rebound" as an explanation for the earthquake cycle was devised from the field observations. The earthquake exposed the locations and structures in San Francisco that were vulnerable to ground shaking, ground failure, and fire (see discussion of Northridge, California earthquake below). It showed that: 1) unreinforced masonry buildings and structures founded on soft Bay mud are susceptible to damage from enhanced ground shaking caused by soil amplification, 2) structures founded on water saturated man-made fill are susceptible to foundation failure from liquefaction and lateral spreading, amd 3) the threat of conflagation increases when underground water pipelines are ruptured by liquefaction and lateral spreads. Twelve major fires burned 28,000 buildings in 75 hours because fire fighters were without water. An estimated 750 people were killed.

October 17, 1989 Loma Prieta, California Earthquake (State of California, 1990)

This M 7.1 earthquake is representative of the type of earthquakes that occur along the right-lateral-strike-slip San Andreas fault zone in Northern California marking the active boundary of the North American and Pacific tectonic plates. With an epicenter in a rural area 60 miles from San Francisco and Oakland, this earthquake occurred at 5:07 p. m., long after many people had left work to attend the World Series or to watch it on television. It destroyed unreinforced masonry buildings, damaged bridge systems, and left 63 dead, 11,000 injured, and 25,000 homeless. Losses reached $8 billion. Many of the strong ground motion records acquired in the earthquake demonstrated the increased vulnerability of buildings and lifeline systems to ground shaking and ground failure when founded on Bay mud and land fill in parts of San Francisco, Oakland, and other locations. It also demonstrated the fragility of unreinforced masonry buildings, elevated highway overpasses, airport runways, and underground pipelines to ground shaking, liquefaction, and lateral spreading, and served as a reminder of the continuing susceptibility of the Marina District to fire and lateral spreading.

September 29, 1993 Khalari, India Earthquake (The Society for Earthquake and Civil Engineering Dynamics, 1993)

This M 6.3 earthquake is representative of the type of infrequent, but devastating moderate magnitude earthquakes that can occur at great distance from the well known active Himalayan seismic belt in India's northern border region. This intraplate earthquake was a "surprise," not only because it occurred in a low seismicity region on a shallow unknown fault system, but also because it happened at 3:46 a. m. on a Wednesday while people were sleeping in the supposed "security" of their unreinforced masonry homes. These homes, which typically have heavy stone roofs, are well known for their vulnerability to earthquake ground shaking, but, because of the low seismicity, were not designed to withstand the strong ground shaking that occurred. Not a single house remained standing in Khilari. The death toll reached at least 23.000.

The February 9, 1971 San Fernando, California Earthquake (Added to provide background on the Northridge earthquake discussed below)

This M 6.4 earthquake, a rural earthquake occurring in San Fernando Valley on the edge of metropolitan Los Angeles at 8:00 a. m., is representative of the threat posed by earthquakes generated on a "blind" thrust fault, and, except for surface fault rupture, was a good model of what to expect in the Northridge earthquake (see discussion below) that would occur in San Fernando Valley 23 years later on January 17, 1994. The San

Fernando earthquake caused collapse, severe damage, and loss of function for hospitals, dams, and elevated highway structures (e.g.,the San Diego Freeway interchange), and left 64 dead and 11,000 injured. Losses in 1971 dollars reached $0.5 billion; $1billion in 1987 dollars. It produced a major "surprise" when one of the 240 strong motion accelerographs that were recorded exhibited horizontal ground acceleration of 124 % of gravity. This unique record for that time was recorded within a few kilometers of the epicenter on rock associated with a topographic feature at Pacoima dam. The Pacoima dam record also exhibited breakout phases associated with the nearby surface fault rupture, and "the killer pulse," a long duration aceleration pulse associated with the fling of the fault. The 240 strong motion acelerograph records acquired in this one earthquake were a catalyst for researchers and practioners, leading to new alalyses and improved siting and design criteria for buildings, hospitals, earth dams, highway structures, and critical structures. The professional practice of lifeline earthquake engineering was born as a result of this earthquake.

January 17, 1994 Northridge, California Earthquake (California Seismic Safety Commission, 1995)

This M 6.7 earthquake, which occurred at 4:31 a. m., illustrates what can happen in the epicentral area of an urban earthquake and is representative of the "blind" thrust fault, the least frequent but most destructive as a single event of the three types of scenario earthquakes that are now used to increase preparedness in the Los Angeles area. In this case, instead of "the big one" caused by rupture of the San Andreas fault or a moderate one caused by rupture of the Newport-Englewood fault, a blind thrust fault ruptured in response to the ongoing north-south compression caused by the big bend in the San Andreas fault system marking the active boundary of the North American and Pacific plates and produced the moderate-magnitude Northridge earthquake. The earthquake produced several "surprises": 1) verification of the web of blind thrust faults beneath Los Angeles, one of which produced the 1971 San Fernando earthquake (described above), 2) the exceptionally strong horizontal and vertical ground accelerations in a 20 x 20 square kilometer epicentral area which approached 2 g, a factor of more than 2 greater than the expected level of ground shaking in a 50-year exposure time and well above the actual design value prescribed in the edition of the building code in effect at that time, 3) ground motion characterized by a long duration acceleration pulse (i.e., the "killer" pulse), 4) damage to elevated highway systems, and 5) damage to welded moment steel frame buildings. Economic losses reached $ 40 billion with over $ 12 billion in insured losses; mortality 61, injured 15,000, and homeless over 50,000.

January 17, 1995 Great Hanshin-Awaji, Japan (Kobe) Earthquake (Earthquake Engineering Research Institute, 1995)

This M 6.9 earthquake, which occurred at 5:46 a. m., was located 20 km (12 miles) from Kobe on a right-lateral-strike-slip fault instead of the expected scenario of a larger magnitude subduction zone earthquake located in the trench about 100 km (60 miles) from Kobe. It is representative of the type of extreme urban earthquake disaster that can be expected when a combination of negative geotechnical factors happen. The negative factors in this case included: 1) a damaging level magnitude, 2) an epicenter 20 km from Kobe, 3) a relatively shallow depth of focus, 4) fault rupture directivity effects focused toward Kobe, 5) enhanced ground shaking due to amplification of soft soils underlying much of Kobe, and 6) liquefaction and lateral spreading of man made soils in the port area. The surprises included: 1) the extent of the damage of the elevated Hanshin expressway, 2) the nature and extent of the damage to the port facilities, 3) the collapse of so many single family dwellings, 4) damage to welded steel frame buildings, and 5) the long duration acceleration pulse in the ground motion. The economic losses are believed to have exceeded $140 billion; deaths reached 5,600, injuries exceeded 6,800; and the homeless reached at least 250,000. The disaster led to a renewed and urgent effort by the Japanese Government to implement improved earthquake loss prevention and mitigation measures and to strengthen earthquake preparedness and emergency response. At the time of this paper, a mix of scientific, technical, operational, and policy options were being considered along with enhanced international cooperation under the auspices of various existing cooperative programs and the International Decade for Natural Disaster Reduction (United Nations, 1989) to achieve this natiional objective.

BENEFICIAL RESULTS OF POSTEARTHQUAKE INVESTIGATIONS

The perishable data, new knowledge, and increased understanding gained from multidisciplinary postearthquake investigations have been beneficial to practitioners and decisionmakers in every earthquake prone country throughout the World, aiding them in their efforts to reduce earthquake risk. The typical applications in a comprehensive risk management program are summarized below and include: 1) avoidance strategies, 2) land use, 3) emergency preparedness, and 4) reduction of vulnerability through coordinated interdisciplinary planning.

Lesson on Avoidance: Avoidance is the least expensive and most logical strategy to reduce risk.
Planning Option: Whenever possible, community decisionmakers should take actions that avoid the hazard and reduce the risk to new development at every site that:

1. has the potential for enhanced ground shaking caused by soil amplification and increased damage caused by the frequency-dependent resonance of soils and structures having similar fundamental periods of vibration (e.g., Mexico, Spitak, Loma Prieta, and Erzincan earthquakes).
2. has soils that either can liquefy or that are unstable and susceptible to large permanent displacements (e.g., Costa Rica, the Philippines, Loma Prieta, and Kobe earthquakes).
3. has the potential for surface fault rupture (e.g., Landers)
4. is located on coasts susceptible to tsunami wave run up (e g., Hokkaido-Nansei-Oki).
5. faces enhanced severity, frequency composition, and duration of ground shaking because of the proximity to the causative fault, topography, directivity, or the shallowness of the earthquake source (e.g., Khilari, Kobe, Loma Prieta, Spitak, Erzincan, El Asnam, and Newcastle).

Lesson on Land Use: Expect earthquakes to recur where they occurred in the past in response to the regional and local seismic cycle of stress build up and release.
Planning Option: Correlate the type and density of land use with the expected ground shaking, ground failure, and tsunami wave run up hazards.

Lesson on Emergency Preparedness: Expect "surprises!" Earthquakes will strike without warning at the "worst" time of day and season of the year without consideration of political boundaries and the state of readiness.
Planning Option: Develop scenario earthquakes and exercises that facilitate planning for both the expected and unexpected, keeping in mind that there is always an event that is worse than the one we planned for.

Lessons on Reduction of Vulnerability and Coordinated Planning: A community's vulnerabilities are caused by past mistakes in planning, siting, design, and construction which will ultimately be exposed by a damaging earthquake. "Acceptable risk" before the disaster (i.e., damage, loss of function, and socioeconomic impacts) will be transformed into "unacceptable risk" afterward.
Planning Options: Anticipation is more effective than reaction, and integrated knowledge than fragmentary knowledge in reducing the risk. Community decisionmakers and practitioners should work together to devise comprehensive coordinated earthquake risk management programs, having a mix of emergency preparedness to deal with the inevitable and mitigation measures to reduce losses to new and existing development, strengthening important buildings, lifelines, and essential facilities. Physical plans for new community development should avoid locating new buildings and lifeline systems in locations subject to surface fault rupture, on soils that have the same fundamental resonant periods of vibration as the structure, in configurations where they will hammer or pound, on unstable soils susceptible to liquefaction, lateral spreads, and landslides which, among other effects, can increase the susceptibility to fire, and in locations likely to be flooded from tsunami wave run up, seiches, or dam break.

CONCLUSIONS

Geologists, seismologists, engineers, health care specialists, social scientists, architects, planners, and emergency managers are involved in postearthquake investigations. Each damaging earthquake provides unique experiences and data which increase fundamental understanding of the physical and social dimensions of an earthquake disaster. The results of holistic, multidisciplinary investigations are being used to: 1) facilitate the recovery process in the stricken community and country, 2) add to the cumulative and growing compendium of fundamental lessons provided by past earthquakes for practitioners and decisionmakers, 3) communicate the new knowledge, data bases, and lessons to other countries at risk from earthquakes, and 4) foster the application of the knowledge, data, and new lessons to reduce earthquake risk.

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