Balance of Risks and Benefits in Preparation for Earthquakes

BRUCE A. BOLT

Widespread proposals to benefit from lessons of the 17 October 1989 (Loma Prieta) earthquake dramatize the difficulties associated with reducing seismic risk. There are three main problems. First, the understanding of earthquake generation is far from complete. For example, the unanticipated source style of this earthquake raises vital questions; claims of predicting its occurrence are weak, and, for practical reasons, the detailed pattern of damaging strong ground shaking was not predicted. Second, although their interactions are not well understood, competing social forces continue to prevent the optimum growth and application of knowledge for earthquake hazard mitigation. Third, the recent use of the probabilities of seismic risk has had mixed results. Because of indecision between minimizing loss of life and maximizing broader benefits, general agreement on acceptable earthquake risk remains confused.

CURRENTLY, THERE IS BOTH PROGRESS AND FRUSTRATION in significantly reducing earthquake hazards in the United States. This split verdict is evident from articles that have appeared in the popular press and scientific journals (*1–4*) since the damaging 17 October 1989 earthquake in the Santa Cruz Mountains of California.

Prescriptions for enhanced actions span a wide spectrum, from mandated expenditure of state and private funds to upgrade hazardous structures, to dramatic increases in federal and state research funds to seek further basic knowledge. In this article, I discuss, from the seismological point of view, some of the difficulties that are now faced in minimizing earthquake risk in a way that also maximizes social benefits. Most of the arguments and illustrations reflect the extensive scientific and social history surrounding the Loma Prieta earthquake, but the discussion applies more or less to all regions in the United States that are at appreciable risk from earthquakes. The national extent of this natural hazard has been well documented (*5*).

The Variability of Earthquakes

Almost every large earthquake has features worthy of close study in the faulted zones, in the damaged areas, and in the records of the strong ground shaking (*6*). Since 1985, three cases stand out.

The first case is the 1985 Mexico earthquake, of surface wave magnitude (M_s) 8.1, which did little damage relative to its great energy near its source along the west coast of central Mexico. The tragic twist was the major enhancement of seismic waves in limited parts of Mexico City at a distance of 420 km from the source. Although local building codes had already incorporated a factor to allow for soft soil layers, the amplification and duration of the ground shaking in parts of Mexico City were greater than had been expected; as a result, a number of 10- to 24-story reinforced concrete structures collapsed and 8000 persons died.

The Armenian earthquake in December 1988, M_s 6.9, resulted in 25,000 deaths and half a million people left homeless. It caused economic losses that may reach $16 billion. Although Armenia has its share of competent seismologists and engineers, clearly the presence of such experts was not sufficient for earthquake risk reduction to prevail against the contending societal, economic, and political pressures in that country. The result was an unconscionable number of fatalities and economic dislocation; a great many buildings were not seismically resistant, even though the area has been known from antiquity to be geologically unstable.

The Loma Prieta, California, earthquake of 17 October 1989, M_s 7.1, focused U.S. public attention on earthquake safety more than any other case in recent decades. The closer the threat, the more intense is our reaction. Indeed, "the World Series Earthquake" is a more incisive name than Loma Prieta earthquake in two significant ways (*7*). First, its conjunction with a great sporting event explains why many people were, uncharacteristically, safely in their timber-frame homes at 5:04 p.m. to watch TV coverage rather than in normal freeway commuter traffic or in congested areas of critical danger. Second, because the eyes of the nation were focused on San Francisco, the scenario of an actual damaging earthquake was played out visually before a wide audience.

Effective preparation for future earthquakes depends strongly on understanding their properties, as stated in the 1906 objectives of the Seismological Society of America: "It is possible to insure ourselves against (earthquake) damage by proper studies of their geographical distribution, activities and effects on buildings" (*8*). In this respect, certain fundamental seismological lessons were learned from studies of the Loma Prieta earthquake (*9*), and it is useful to consider these briefly.

In recent years, the concept of "characteristic earthquake" on a particular fault has been formulated (*10*). If faulting processes repeat, there is a hope that the prediction of future earthquake behavior can be reduced to a known set of basic earthquake types. Yet the source of the earthquake in the Santa Cruz Mountains presents, at least for the time being, a number of problems that cast doubt on earthquake invariance along even such geologically well-exposed structures as the San Andreas fault. First, Loma Prieta is a peak 1157 m high on the east side of the San Andreas fault where the elevation of the Santa Cruz range is higher than that of peaks to the west of the San Andreas fault (see Fig. 1). Hence it was unexpected when the west side of the Santa Cruz Mountains was elevated on 17 October 1989, because continuation of such fault slip

The author is in the Departments of Geology and Geophysics and Civil Engineering, University of California, Berkeley, CA 94720, and with the California Seismic Safety Commission, 1900 K Street, Suite 100, Sacramento, CA 95814.

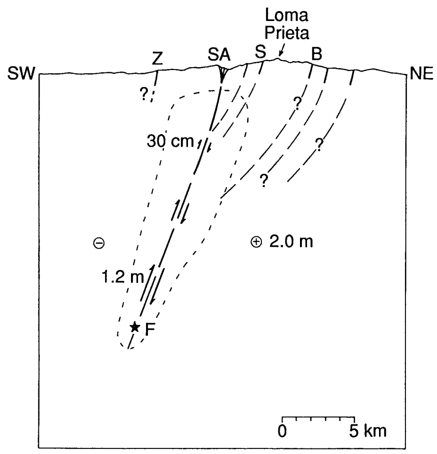

Fig. 1. Cross section of the source region of the 17 October 1989 (Loma Prieta) earthquake in the Santa Cruz Mountains, California (no vertical exaggeration); Z, Zayante fault; SA, San Andreas fault; S, Sargent fault; B, Berrocal fault; F, earthquake focus. Arrows along the San Andreas fault indicate the inferred vertical slip. The circles with + or − denote the direction of the right-lateral horizontal slip (*3*). The dashed line bounds the volume containing most immediate aftershocks.

entails reversal of the present topography. Second, although the San Andreas fault is a clear geomorphological rift through the Santa Cruz Mountains, the fault rupture or ruptures did not reach the surface. The geodetic measurements and observed slip on adjacent sections of the San Andreas fault that ruptured in 1906 entail that mainly right-lateral slip must occur at a high rate along the San Andreas plate margin in this region. Yet, on the evidence of the Loma Prieta earthquake source (*11*), surface ruptures of predominantly strike-slip type do not always occur, even in M_s 7.1 earthquakes. The problem is compounded in this case by the limited field data on fault rupture obtained for this segment of the San Andreas fault after the 1906 earthquake (*12*).

Confidence in modeling future earthquake sources is highly relevant to vulnerability reduction because response analyses of critical engineered structures require the definition of an earthquake source that is well established by geological and seismological analysis. This analysis was pioneered by the extremely low-risk requirements for operation of nuclear power reactors. At present in the San Francisco Bay area alone, predicted earthquake sources and ground motions are being developed for engineering studies of the Golden Gate Bridge, the Bay Bridge (a span of which fell on 17 October 1989), and the Bay Area Rapid Transit (BART) extensions.

A key question in strong ground motion specifications is what is the relevant maximum earthquake; that is, what is the realistic maximum limit to the fault length that will rupture? In attempting to estimate the probability of rupture lengths, geologists rely on the identification of fault segments that are separated by such mechanical barriers as changes in fault strike or lateral fault offsets. The importance of this segmentation method makes checks of its validity crucial to seismic risk estimates (*13*) as major earthquakes occur. There are bends in the San Andreas fault near the limits of rupture in the Loma Prieta earthquake, and their restraining role is now under study (*9*).

Although significant progress has been made in understanding each of the seismological questions discussed above, case histories such as Mexico City, Armenia, and Loma Prieta show that caution is still needed in drawing conclusions about ground motions to be used in the design of structures. In practice, the uncertainties involved are allowed for by the application of safety factors. Consequently, larger-than-necessary ground motions, given a realistic lifetime of the structures, are often adopted. Such conservative judgments would generally be applauded if there was not a need, on the grounds of other pressures and societal demands, for limits on construction costs (*13*).

Prediction of Ground Shaking Intensity

Industrialized countries with earthquake hazards are now in the third era of seismic risk. The first era was characterized by rapid, almost uncontrolled industrial and urban growth. The modern development of California, for example, from about the middle of the last century, was punctuated, but hardly affected, by major earthquakes in 1857 in southern California, and in 1865, 1868, and 1906 in northern California.

The Long Beach, California, earthquake in 1933 marks the initiation of a second era of seismic mitigation. Heavy damage to public schools led to political intervention and the passage by the state legislature of the Field Act, which set strict construction standards for public schools. During the subsequent 40 years, a band of dedicated pioneers studied earthquake problems and applied quantitative techniques to strengthen structures against earthquake forces. In the 1960s, large research expenditures resulted from the requirements by the Nuclear Regulatory Commission for earthquake-resistant design of nuclear power plants. This activity brought to bear advanced technical thinking on risk reduction by earth scientists and engineers, and a great amount of basic geological, seismological, and engineering knowledge was thereby put into practice.

The second era ended at about the beginning of the 1970s. The 1971 San Fernando earthquake, M_s 6.5, sharply illustrated the diversity of damage in a densely populated urban area. It stimulated the establishment in 1974 of the California Seismic Safety Commission, with the task to develop broad policy throughout the state. Nationally, in 1977, enhanced levels of federal funds were made available under the National Earthquake Hazard Reduction Program (NEHRP) (*5*).

The hallmark of the present or third era is the need for more quantitative and cost-effective efforts in risk reduction. Contemporary damaging California earthquakes such as Coalinga in 1983 and Whittier Narrows in 1987 stimulated this aspect of hazard reduction efforts. The balance between risk reduction and general benefits has become a central issue (*14–16*). Part of the debate hinges on the effectiveness of past research and its application and justification for future efforts. On the seismological side, one critical advance in the last two decades that can be thoroughly justified is the successful instrumental recording of strong ground shaking in many earthquakes in California and elsewhere. From these field records, the strengths, durations, and frequencies of the large seismic motions near the source of the waves can be directly measured. These ingredients are essential for prediction of the shaking of the ground at specified places in future earthquakes (*17*).

In brief, the availability of strong motion recordings now makes it possible, given a specified active fault source, for seismologists to compute realistically the radiated seismic waves. By computer calculations, these motions can then be transferred through the complex of rock structures between the fault and the specified site, and there through any soil column, to yield the expected ground shaking. This ability means that overlays or templates of the expected seismic intensities can be produced for any seismically vulnerable region such as San Francisco, Los Angeles, Salt Lake City, Seattle, Boston, and Memphis. Such maps are basic to development planning, to the assessment of the vulnerability of older structures, and to the design of earthquake-resistant new structures.

As we move toward this goal, the false security of hindsight must, however, be avoided. In practice, the full benefit of quantitative intensity mapping will require substantial one-time costs because of presently unmeasured subsurface properties. It is known that strong ground shaking varies dramatically from one earthquake or region to another. Oakland and the San Francisco peninsula were 70 km distant from the shaking source in the Loma Prieta earthquake, yet severe damage occurred in pockets (*2, 3*), leaving most of the bay area scared but unscathed (see Fig. 2). Buildings on the campus of the University of California at Berkeley, built on rock, were subjected to a maximum horizontal ground acceleration of one tenth of gravity (0.1*g*), and the strongest motion lasted for only a second or two. There was no significant structural damage. At the same distance from the fault rupture, part of the Cypress I-880 viaduct in Oakland, built on soft soils (Bay mud), failed (*4*). At that site, ground motions were about three times the acceleration and five times the duration of those at the nearby campus. The significant differences in the strength of shaking on soil and rock in the Loma Prieta earthquake, evident in Fig. 2, were not a surprise technically. They had been described, for example, in soil engineering amplification studies of the 1985 Mexico City damage patterns. Of considerable importance, a specific feature of the Loma Prieta earthquake source limited the shaking intensity. The rupture began at a central point at a depth of 18 km and then spread north and south along the San Andreas fault for about 8 s (*3*). If it had started at one end of the same fault zone and spread to the other end, the shaking duration would have been longer. More severe damage would most likely have occurred even though the earthquake magnitude would have been similar.

In consideration of the various sources of variability in earthquake shaking, the need to improve the reliability of risk maps and engineering codes for large future earthquakes becomes acute (*13*). It would be beneficial to study in much more detail than previously the effects of past great earthquakes. As in October 1989, it is known, for example, that the intensity in the great 1906 San Francisco earthquake also varied markedly (*18*). In some places in the Sacramento Valley high intensities were recorded, but in Sacramento the felt intensity of shaking was low. Mr. Marshall, a resident, reminisced that "I was awakened by my wife that she believed that we were having an earthquake. We arose and observed and verified the phenomena."

Such historical reports can be misleading because intensity is a strong function of the frequency of the waves and the duration of the shaking. The earthquake intensity maps produced just after the 1906 earthquake did not specify in sufficient quantitative detail where significant shaking might be expected in the future. Although some improvement in intensity mapping has occurred in recent years, the pattern of the Loma Prieta earthquake made it clear that, for maximum benefit in decision-making on rehabilitation and new construction, maps are needed that allow for earthquake source variability and the effect of soils.

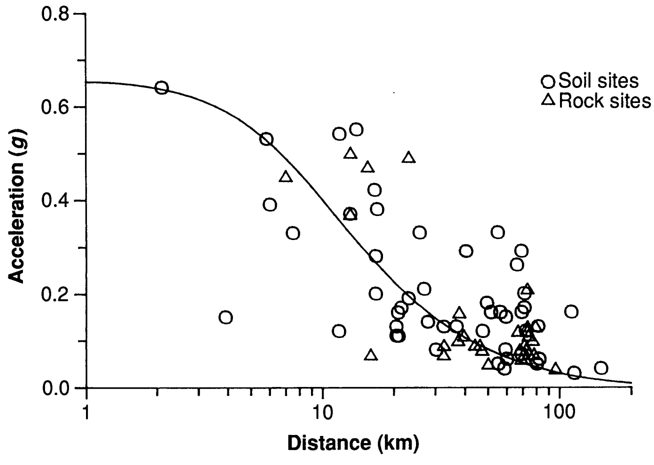

Fig. 2. Measured horizontal peak ground accelerations from a number of sites in the San Francisco Bay area, recorded by the California Strong Motion Instrumentation Program in the 17 October 1989 earthquake. The sites have been designated simply as soil and rock. The curve shows the average variation with distance from the earthquake source computed from recordings of earlier California earthquakes (*6*).

The Effectiveness of Probability Assessments

All statements of risk contain, either explicitly or implicitly, elements of probability (*15*). Yet, acceptance of statements of the chance of earthquakes or earthquake vulnerability, both for engineering design and for policy decisions, has been slow in coming. This public reluctance stems partly from a perception of differing expert opinions and partly from the observation that announced odds of natural hazards are often in error. On the positive side, the hesitancy is accompanied by an appreciation of the major simplifications needed to describe complex natural systems.

Numerical statements of odds are also sometimes difficult to interpret unless they are compared with odds for other hazards. Thus, the risk of death per year to an individual from a motor vehicle accident is about 1 in 4,000; from earthquakes in the most exposed metropolitan areas, the risk is perhaps 1 in 50,000. But much more is involved than these simple propositions. The individual risk clearly varies with individual situations. There is also a collective or societal risk. The first widely discussed estimate of the odds of a major earthquake in California was given in 1979 as 50-50 in 10 years (*19*). Criticism was twofold: first, that such statements were not specific enough, and second, that an even chance was not much of a risk! On balance, however, the reaction to this early probability description was favorable; the major benefit was a clearer awareness that the risk was immediate (10 years) and not indefinite (we can expect a big one sometime). Refinements since 1979 are largely improved geological databases, but limited attention has been given to the form of the probability statements or to their explanation.

A recent development has been the assessment of the odds of large earthquakes along segments of the San Andreas and other major active faults in California (*10, 12, 20*). Benefits from such assessments require careful application and consideration of the societal context. After the Loma Prieta earthquake, probability evaluations of this type were given much publicity. The combination of different bodies of observations indicated that there was a better than 1 in 2 chance of a major magnitude earthquake occurring in the San Francisco Bay Area in the next 20 years. One more specific study (*10*) gave the chance of a 6.5 to 7 magnitude earthquake along a 30-km-long segment of the San Andreas fault in the southern Santa Cruz Mountains as 30% in 30 years. This value was higher than for the adjacent San Francisco Peninsula segment of the San Andreas fault to the north and led to the impression that the earthquake was predicted (*21*). Any claim for a forecast in this case must, however, be regarded as weak. The estimated probability of a southern Santa Cruz Mountain earthquake was hedged by the adjective "equivocal" and assigned the lowest reliability rating. In addition, the Loma Prieta fault rupture overlapped but did not coincide with the predicted segment.

If probability assessments are to be adopted widely as a basis for risk reduction, considerable caution and care are needed in formulating such statistical statements. Among the explanations required are: What is the range of earthquake size involved rather than the specification of a particular magnitude? What are the overall uncertainties in the calculations? And are such statements predictions at all or only summary accounts of past events? Wider public acceptance depends on replacing ill-defined probability statements, which lead to community worries, by stricter conditional statements in which the extent of reliability is clearly expressed (*22*). An attempt to provide such an explanation has been made in the recent reassessment of probabilities of damaging earthquake occurrence in the San Francisco Bay area (*23*), but the full uncertainties are probably underrated.

Probability models have also been used to prepare ground shaking hazard maps for the whole United States and for specific regions (see Fig. 3). These maps (*24*) give the expectation of exceedance in a given time (such as 100 years) of seismic intensity parameters (such as acceleration). In computing the expectation of these parameters, the older concept of discrete hazard zones, drawn mainly on the basis of the historical seismicity, was abandoned and replaced by the rate of occurrence of earthquakes of various magnitudes weighted by geological evidence of active fault systems. These maps have now been incorporated in many building code provisions, with the explicit understanding that a balance of risk is implied between the odds of larger shaking and the high cost of overdesign.

Acceptable Risk

Even when probability models are worked out in appropriate ways and are clearly explained, there still remains the difficulty of lack of agreement on the major goals of hazard abatement. Unquestionably, the trend in recent years in the United States has been to maximize life safety rather than economic loss. For example, the Uniform Building Code in its 1988 and earlier editions specifically states that "The purpose of this code is to provide minimum standards to safeguard life or limb, health, property and public welfare while regulating and controlling design and construction" (*25*). The practical problem, of course, is how to manage joint treatment of life safety and property damage. Not only may there be incompatibilities, but, when minimal standards apply, damage to structures can be significant even though casualty loss is low.

The tested effectiveness of modern building codes has indicated that older structures present the greatest risk (*26*). The trade-off between life safety and reconstruction costs is well illustrated by recent studies of the seismic resistance of state-owned buildings in California. It is estimated that over $20 billion of state properties are involved, and much of this property is vulnerable to damage. One of the first quantitative studies of this problem began at the University of California at Berkeley in 1974 through the work of "the Chancellor's Seismic Review Board." After extensive discussions, this board, on which I served, chose life safety as its highest priority. There was agreement that, when strengthening or reconstructing buildings, compliance should be with the equivalent code requirements on items affecting life safety.

Subsequently, the California Seismic Safety Commission, after testing the proposed hazard evaluation methodology on 40 state-owned buildings, recommended that priorities for upgrades of state-owned structures should be based on a benefit-cost ratio (BCR), defined as the number of lives saved per reconstruction dollar. As a consequence, structural engineers were retained to provide a prioritized list of state-owned structures based on the BCR method. Such a list was essential to obtain cost estimates so that the state government could fund a realistic schedule of upgrading.

The estimation of the BCR measure of benefit depends on the evidence that certain classes of construction perform poorly in earthquakes whereas other classes resist the shaking. This capacity can be quantified through a life safety ratio (LSR), which predicts the expected number of fatalities per 10,000 occupants before reconstruction, given the class of the structure and the appropriate shaking intensity for the specified seismic zone. Thus, from experience, unreinforced masonry buildings have been allocated a particular LSR value and reinforced concrete structures another.

The computational equation is

$$\mathrm{BCR} = \frac{(\mathrm{LSR})\,(\mathrm{ECO})\,(\mathrm{SCF}) - (\mathrm{LSRG})\,(\mathrm{ECO}^*)}{10{,}000\,(\mathrm{RC})}$$

where ECO (equivalent continuous occupancy) is the average number of persons occupying the building each 24-hour day of the year, SCF (seismicity correction factor) depends on the earthquake occurrence rate in the zone, and RC (reconstruction cost) is the cost to rehabilitate this class of structure in order to reduce the hazard to the prespecified life safety goal (LSRG). The single asterisk denotes the value after reconstruction.

BCR ratings deserve wider national and international use. In

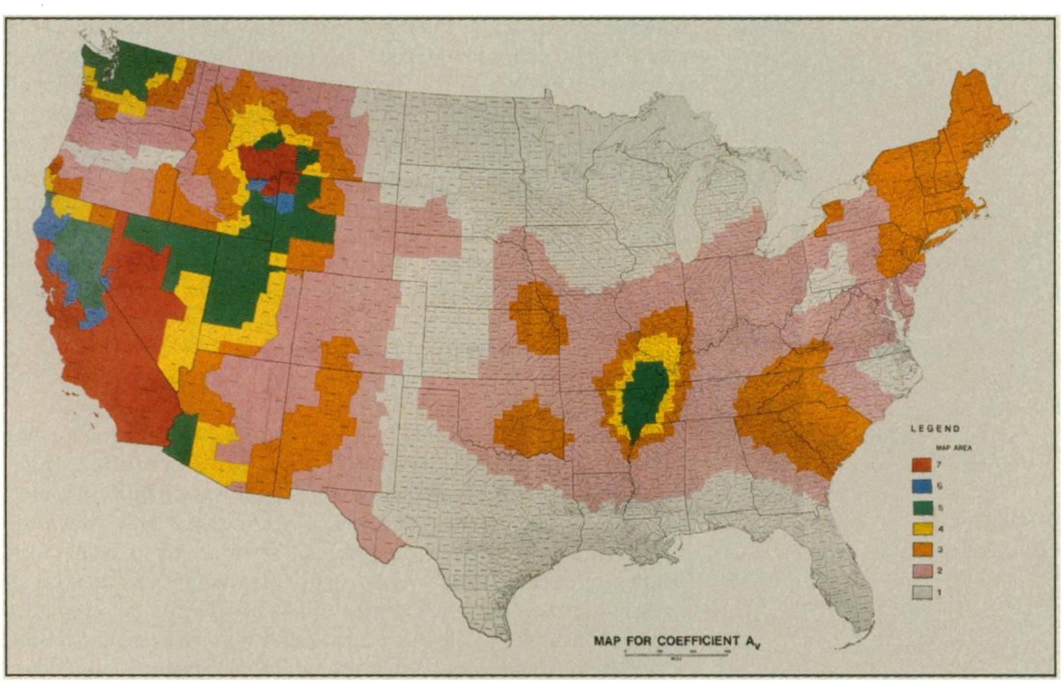

Fig. 3. Zoning map based on the odds of exceeding seven specified levels of seismic ground accelerations in the United States in any 50-year period. The original smooth contours have been replaced for political reasons by county boundaries (*24*).

California, they have been used to allocate funds for more detailed engineering studies and, when combined with additional engineering evaluation, to set priorities for reconstruction. After the Loma Prieta earthquake reemphasized the grave danger of collapse in earthquakes of certain classes of structures in certain locations, it was realized that the rating list for the state-owned buildings required reexamination. Because the BCR values are highly sensitive to the LSR ratings, several modifications have been suggested that give weight not only to structural material but also to details of the structural system.

In conjunction with the BCR method with its emphasis on life safety, a separate system of structural seismic performance ratings based only on engineering judgment has also been developed at the University of California. Each building has been judged as "good," "fair," "poor," or "very poor." For example, a "poor" structure would be expected to suffer significant structural and nonstructural damage leading to appreciable life hazard. These ratings are dependent on structural engineering considerations and not on the occupancy of particular buildings.

Although these rating systems have been in place for 15 years, progress toward rehabilitation has been slow. Strong criticisms of the state and the University of California for lack of progress in upgrading structural performance were made by the Seismic Safety Commission after the Loma Prieta earthquake.

Past difficulties in achieving more widespread earthquake safety suggest that emphasis on a life safety criterion to drive rehabilitation also deserves critical reexamination. One of the lessons after the 1989 Loma Prieta shaking was the seismic fragility of many crucial facilities in modern urban and industrial society. Failure of "lifelines"—electrical power, water, sewage, communication, and transportation—can prostrate the economy. The severance of the San Francisco Bay Bridge on 17 October 1989 and a widespread power failure in San Francisco, 70 km from the seismic source, prove this point. The same problem has long concerned authorities in Japan. The soaring real estate values in Tokyo continue to encourage the filling of coastal land tracts, and these have become heavily populated industrial and commercial zones. It is estimated that a magnitude 7.9 earthquake, similar to the Great Kanto earthquake that devastated Tokyo in 1923, could produce liquefaction and hence disrupt lifelines over 26.5 square miles of reclaimed land along the city's major waterways. Such economic loss has evidently been regarded as acceptable, perhaps because of lack of informed debate.

An illustrative case comes from the serious damage that occurred to unreinforced structures on the campus of Stanford University in the Loma Prieta earthquake. The costs of damage rehabilitation are estimated to exceed \$160 million. There is little doubt that the damage would have been significantly more severe at the Stanford campus, given the types of structures at risk, if the seismic source had been closer or of longer duration. In such a case the institution and its complex research facilities would have been seriously diminished as a center of higher education for months or even years. The lesson is that, in decision-making on risk reduction, the failure to allow for the functioning of key institutions, as well as life safety, can have the gravest consequences. Yet, apart from hospitals, few assessments have been made of the relative importance of physical plant in institutional survival.

Earthquake Insurance

Earthquake insurance is regarded as an important component in reducing both hazards before and losses after earthquakes. The basis of the insurance system is its ability to predict losses and to spread the risk. Because large earthquakes are infrequent, the usual actuarial procedures, as used in casualty and fire loss, are not reliable (*27*). Also, in the United States, in contrast to other countries such as New Zealand, the public generally is not insured against earthquake damage, and so the risk is not spread over a broad pool of policy holders.

Recent earthquakes have stimulated a reassessment of the role that insurance should play in mitigating earthquake loss. The Whittier earthquake of 1 October 1987 had special significance to insurance evaluation because it occurred in an urban area. Types of losses were revealed that are likely to occur in even larger earthquakes. Insured losses from this earthquake, M_s 5.7, were widely spread among 137 insurance groups. By 1987 the deductible had been increased to 10%, as compared with the 5% deductible for homeowner's earthquake coverage at the time of the 1971 San Fernando earthquake. The total number of claims for the Whittier earthquake was 8417, and for the San Fernando event, 9099. In 1987 dollars, the net loss for insurance in 1987, including workmen's compensation, was almost \$73 million, whereas in 1971 it was about \$130 million. By comparison, disaster relief programs paid out after the Whittier earthquake \$175 million in grants and loans, in addition to tax relief, which was not available to purchasers of insurance.

In a great earthquake, property damage alone in a metropolitan area could amount to \$70 billion, of which insured losses are now about \$50 billion. In covering such an immense loss, the insurance industry would have to liquidate much of its surplus invested funds. This liquidation of bonds and stocks would disrupt the money market and depress investment prices. For this reason, a cooperative effort to respond to the earthquake threat at the federal level has been proposed recently by a group of insurance representatives (*28*) and by a number of congressional representatives. One scheme consists of establishing a prefunding mechanism through the enactment of a Federal Earthquake Insurance and Reinsurance Corporation Act. The suggested advantages are that the insurance industry could offer wider and more affordable residential earthquake coverage underwritten by the federal government. Economic consequences would be mitigated by the accumulation of funds for recovery, and thus the amount of federal disaster relief could be reduced.

In California, competing plans for a similar catastrophic program or a limited mandatory insurance for homeowners have recently been proposed (*29*). As one comprehensive alternative, the Seismic Safety Commission has recommended that the state should work with the federal government, other states, and the national insurance industry to produce a program that incorporates insurance as a significant component of earthquake hazard mitigation. Insurance for dwellings would be the most important benefit (*30*). The state would create a tax-exempt fund to provide earthquake insurance for homes and to expand the program eventually to aid small businesses. This state earthquake policy would supplement homeowners' policies and would also be administered by the same agent. Premiums would be paid into, and claims paid from, the state-sponsored fund. Home mortgage lenders would require earthquake insurance as a condition of granting a loan.

The greatest overall benefit from earthquake insurance accrues when there is a link between the availability of low-cost insurance and a requirement to upgrade the seismic resistance of the structure. In the case of homes, inspections at the time of purchase would establish premium levels according to the degree of risk inherent in the dwelling and its location. Both state and federal governments need to examine the trade-offs between disaster insurance and disaster relief programs in order to optimize the advantages of insurance mechanisms. An important side benefit could be the widespread reduction of risk, not by government regulation, but by market incentives contained in graduated insurance premiums.

Barriers and Advances

In earthquake engineering, there has been an undoubted improvement in construction codes in recent decades (*26*), as a result of the understanding gained about the relative effectiveness of structures of various types in strong shaking. New techniques of shaking limitation have been introduced, such as the partial isolation from the ground of buildings at their foundations. The broad research base in earthquake hazard mitigation is, however, not satisfactory. Earthquake engineers and earth scientists have generally complained of a significant reduction in federal research funds since 1985. Present financial support cannot maintain robust programs of teaching, observations, and research in this field in the universities.

An effort has been made over the last decade to increase support by state legislatures for earthquake engineering studies, particularly in those areas of the country that have a high earthquake risk. For example, there has been some progress in obtaining increased funding from the states of New York and California. In California, strong motion observation activities were recently strengthened by the allocation of approximately $200,000 a year from the state's Strong Motion Instrumentation Program (under the Division of Mines and Geology) for directed research on problems of earthquake engineering and strong ground motion.

The nongovernmental component of research support has also received much attention in recent years, and there have been some notable successes by individual schools, groups, and centers in obtaining significant new funds from industrial and other private sources, including Japanese construction companies. In spite of these sources, it is agreed that federal programs must provide the focus and impetus for a cohesive and effective national effort (*5*).

In the mustering of broad political support, it is paradoxical that the practical aspects of earthquake risk reduction both contribute to and inhibit achievement of the ultimate safety goals. Although the benefits of research and application would appear to be obvious, in fact both are subject to deadlines, feasibility questions, and conflicts of interest that damp down enthusiasm and public support. Physicists, on the other hand, have been successful in proposals for a $6 billion particle accelerator, and space scientists for a $1 billion space vehicle. In terms of national welfare, it might be expected that the risk involved in earthquakes would give special force to the claims for funds and resources for earth scientists, engineers, planners, and others involved in enhancing seismic safety. Seismological history tells otherwise. Risk reduction is characterized by bursts of activity and political support after damaging earthquakes, and decay curves that have a half-life of a year or so before public effort recedes.

The present era of earthquake safety programs coincides with the International Decade of Natural Disaster Reduction. This initiative has been agreed to by the United Nations as a major effort to reduce, in the next 10 years, the risk from earthquakes, volcanoes, floods, and other natural hazards. The United States will be expected to help developing countries with knowledge, equipment, and education. Such aid need not be a one-way street. Appropriate interactions with foreign countries, such as field teams investigating local earthquakes and programs of research, technology applications, and emergency preparation, should be mutually helpful.

Can the promise of an era of minimal risk be delivered in a decade? Grave doubts have arisen because of declining financial support against inflating costs. The most difficult problem is finding the capital, against competing economic demands, for reconstruction of vulnerable buildings and lifelines. In the research field, the key federal funding for NEHRP has remained at about $68 million during the last 4 years, augmented by a special sum of $20 million after the Loma Prieta earthquake. For 1991, Congress increased NEHRP funding to about $100,000,000. In California, the overall progress of the state Hazard Reduction Program slipped in 1989. Before the Loma Prieta earthquake, only 40% of the initiatives contained in California's earthquake hazard reduction program were on schedule. An ever-present difficulty for stable funding is the criticism that, at both the state and the federal levels, some earthquake initiatives constitute pork barrel projects. Stronger justification for all projects is needed so that vested interests do not result in undeserved barriers to worthwhile activities.

The earthquakes of 17 October 1989 south of the San Francisco Bay area and that of 1971 in the San Fernando Valley made clear that major earthquakes near metropolitan areas will have serious economic effects, not only regionally, but nationally. Industries and institutions will not be able to operate effectively for a considerable time after such an earthquake, reducing the living standards of the whole country. Seismological evidence indicates that strong ground shaking in one or more major metropolitan areas of the country is likely in the next 10 or 20 years. Despite the remaining prediction difficulties in seismology and technical gaps in engineering, there are really no insurmountable reasons why earthquake risks to both the individual and society cannot be reduced during the International Decade to levels comparable with those of more familiar threats.

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31. My thanks for assistance with references and debatable points to A. Becker, D. Brillinger, W. Savage, S. Scott, T. Tobin, and E. P. Wheaton.