22 August 1975, Volume 189, Number 4203 SCIENCE

Earthquake Shaking and Damage to Buildings

Recent evidence for severe ground shaking raises questions about the earthquake resistance of structures.

Robert A. Page, John A. Blume, William B. Joyner

On 9 February 1971, a magnitude 6.6 earthquake occurred in San Fernando, California, on the northern edge of the greater Los Angeles metropolitan area. Although of moderate size in terms of energy radiated as seismic waves, the earthquake took 58 lives and caused more than $500-million damage to public and private property (*1*). Had the earthquake occurred during the working day, the death toll would have been much higher; had the duration of strong shaking been a few seconds longer, the toll would have been an order of magnitude or more higher.

The San Fernando earthquake alerted us to two facts. First, ground motion close to a fault that slips during an earthquake is more severe than it was once believed to be. Second, not all modern buildings and structures built according to earthquake codes possess the degree of safety intended, although the performance of buildings in past earthquakes indicates that many buildings are more resistant to shaking than design codes imply. Recognition of these facts has led to concern about the vulnerability of urbanized areas and critical structures to nearby earthquakes and has stimulated review of seismic design codes and estimates of ground shaking near faults. With the knowledge derived from the San Fernando and other recent earthquakes and from research advances in strong-motion seismology and seismic engineering, we have the opportunity to reduce substantially the seismic hazards associated with future earthquakes, some of which will be larger and will occur in more critical locations than the San Fernando earthquake.

This article is a general discussion of the nature of strong ground shaking from earthquakes and of methods for estimating the effects of shaking on buildings. Much of the discussion focuses on the San Francisco Bay region—one of the most seismically hazardous areas in the United States. We consider what the effects of a repetition of the 1906 San Francisco earthquake would be on present-day structures in the San Francisco Bay area. We conclude that, although most buildings are probably more resistant than is indicated by conventional analytical procedures, many may not be able to withstand the intense shaking that can occur close to the causative fault. A repetition of the 1906 San Francisco earthquake today could cause tens of thousands of deaths and billions of dollars of damage. Such potential losses could be reduced through improved engineering and construction practices and through more judicious land utilization.

Ground Shaking

The primary factors controlling ground shaking at a particular site are the seismic energy released by the earthquake (measured logarithmically in terms of magnitude), the distance of the site from the causative fault, and the response of surficial geologic materials to bedrock motion beneath the site. Other factors, such as the type of faulting (strike-slip or thrust) and variations in the characteristics of wave propagation from the source to the site, may contribute to the unexplained residual scatter in the available data on strong ground motion, but their role is less well understood at present.

Three characteristics of motion determine the damage potential of ground shaking: amplitude, frequency content, and duration. Damage tends to increase with amplitude of ground motion, but the relationship between damage and amplitude is generally complex. The complexity arises in large part from the nonlinear, inelastic response of soils and structures at damaging levels of ground motion. Frequency content is a key parameter because structures, and in some cases surficial geologic deposits, respond to shaking in a resonant manner, amplifying the motion at particular frequencies. If the shaking includes significant energy at frequencies close to the natural, or resonant, frequencies of either the structure or the soil column, larger deformations and stresses will occur in the structure. Duration of shaking is a critical parameter because failure mechanisms in structures and soils commonly depend on the cumulative number of cycles as well as the amplitude of the deformation.

Ground motion can be characterized in a number of ways. For many engineering purposes it is sufficient to characterize ground motion in terms of four parameters scaled or calculated from standard strong-motion recordings of earthquakes: peak acceleration, peak velocity, peak displacement, and duration of shaking above some threshold amplitude. Close to the fault, where damage is most severe, the dominant frequencies of ground acceleration, velocity, and displacement are respectively in the range 2 hertz and above, 0.5 to 2 hertz, and 0.5 hertz and below. Accordingly, peak values of acceleration, velocity, and displacement convey some information about the frequency content of the motion.

Instrumental recordings make up the most valuable source of knowledge concerning the nature of damaging ground motion. In 1932 the U.S. Coast and Geo-

R. A. Page and W. B. Joyner are geophysicists in the Office of Earthquake Studies, U.S. Geological Survey, Menlo Park, California 94025. J. A. Blume is president of URS/John A. Blume & Associates, Engineers, San Francisco, California. This article is adapted from papers presented at the 140th meeting of the American Association for the Advancement of Science, San Francisco, 27 February 1974.

detic Survey initiated a program to record strong ground motion for the purpose of providing engineers and architects with data that would be of use in designing earthquake-resistant structures. The response of the strong-motion seismograph was designed so that the trace amplitude of recorded ground motion was directly proportional to ground acceleration over the frequency range corresponding to the natural frequencies of common structures. Thus, a typical strong-motion seismograph functions as an accelerograph and records a history of ground acceleration, which can be integrated with respect to time to give records of ground velocity and displacement.

The Coast and Geodetic Survey's strong-motion program realized immediate success. In 1933 several records were obtained within 30 kilometers of damaging earthquakes of magnitudes 5 and 6 in Southern California. In connection with this program accelerographs were installed in seismically active areas throughout the western United States and Latin America. The number of accelerographs ranged between 30 and 40 from 1934 through 1950, after which there was a modest expansion of the recording program. In the mid-1960's there was a major increase in the rate of installation of accelerographs: the number of operational units jumped from 127 in 1965 to 455 in 1970. The increase was related to the occurrence of the great 1964 Alaska earthquake, amendment of the building code of the City of Los Angeles in 1966 to require tall buildings to be instrumented for strong motion, and implementation of the California State Water Project, which required instrumentation of critical structures. Today about 1200 strong-motion seismographs are operational in the United States (*2*), and there are extensive networks in other earthquake-prone countries including Japan and New Zealand.

Many valuable accelerograms have been obtained from the western United States, primarily California; however, there is still an alarming lack of instrumental data in the distance range where ground shaking causes significant damage. There are few data from within 10 km of the causative fault for magnitude 5 earthquakes and within 20 km for magnitude 6 earthquakes, and there are no data from within 40 km and more than 75 km, respectively, for magnitude 7 and 8 earthquakes. Experience in past earthquakes shows that these are approximately the maximum distances at which vibrational damage is serious in typical structures.

The existing set of strong-motion data provides a suitable basis for predicting ground motion at sites on rock and competent soil at distances greater than 10, 20, and 40 km for earthquakes of magnitude 5, 6, and 7, respectively. For example, the dependence of peak horizontal ground acceleration on distance from the causative fault and on earthquake magnitude is illustrated in Fig. 1 for sites on both rock and competent soil. Although there is considerable scatter, the data tend to separate according to magnitude and indicate an inverse power law dependence of acceleration on distance. Over the distances for which there are sufficient data, peak ground acceleration increases with magnitude and decreases with distance from the fault. A similar dependence of peak horizontal ground velocity on distance and magnitude is observed, but the rate of attenuation with distance is somewhat less than for peak acceleration.

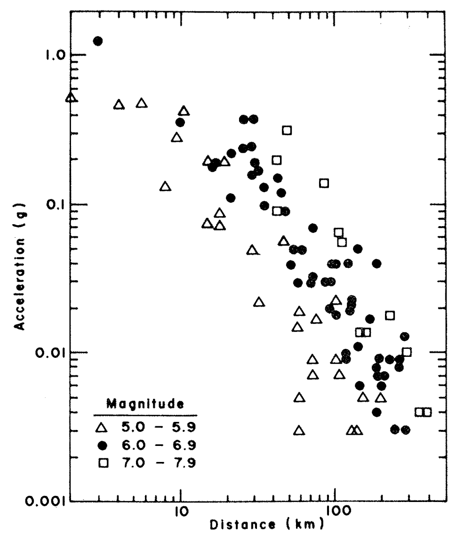


Fig. 1. Peak horizontal ground acceleration (in units of gravitational acceleration) versus closest distance from the slipped fault, for three ranges of earthquake magnitude. The acceleration values are the peaks recorded on a single horizontal component of motion, not the vectorial sums of the two horizontal components.

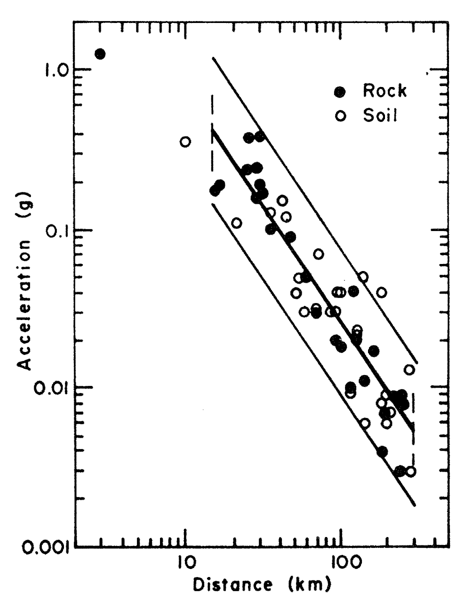


Fig. 2. Peak horizontal ground acceleration versus closest distance from the slipped fault as a function of geologic site condition for earthquakes in the magnitude range 6.4 to 6.6.

Figure 2 displays peak acceleration data for earthquakes in the magnitude range 6.4 to 6.6. All but one of the data points in the distance range 15 to 100 km are from the 1971 San Fernando earthquake. Over the range 15 to 300 km, the data are distributed log-normally about an inverse power law relation with an exponent of −1.5, as indicated by the heavy line in Fig. 2. The light lines define the region lying within 2 standard deviations of the least-squares line through the data. If the fitted line were the true population mean, we would expect that in future earthquakes, for example, peak acceleration on rock or competent soils at a distance of 30 km would range between 0.05 and 0.43*g* at 95 percent of the sites. Some of the scatter in the data may be explained in terms of such factors as radiation pattern of seismic waves from the source and variations in earth structure along different propagation paths, but further study and additional strong-motion records are needed to establish this.

Close to the fault, where there are few or no instrumental data, there is a physical upper limit to the amplitude of motion. On solid rock, the limiting value will depend on the driving stress that causes the fault to slip. On soil, the maximum value may be further limited by plastic deformation in the soil section during large motions. Hence, the attenuation curve must flatten at short distances. Such behavior may be reflected in Fig. 2 by the solid point at a distance of 3 km that lies below a linear extension of the attenuation curve.

Knowledge about the severity and nature of shaking close to the causative fault is necessary for proper planning, design, and construction of nuclear power plants, cities, dams, and the other increasingly complex facilities of a technological society. Strong-motion records obtained in the past decade and particularly since 1970 have led to increased estimates of the severity of ground motion close to the fault. In 1940, a peak value for ground acceleration of 0.35*g* was recorded at a site on thick alluvium at a distance of 10 km from a magnitude 6.4 earthquake. For 26 years, no larger peak acceleration was recorded during any earthquake, and many believed that 0.35*g*, or a value somewhat larger, was about the maximum to be expected during any earthquake. In 1966, as more accelerographs were installed, a value of 0.5*g* was recorded adjacent to the fault in a magnitude 5.5 shock; that number was then accepted by many as the maximum possible acceleration. More recently, in the 1971 San Fernando earthquake (magnitude 6.6), a peak acceleration of 1.25*g* was recorded on a rock ridge 3 km from the fault plane (*3*). Thus, we now recognize that rock accelerations close to the slipped fault in earthquakes as small as magnitude 6.6 can exceed 1*g* (at least in some circumstances), that no near-fault recordings exist for earthquakes larger than magnitude 6.6, and that many existing structures were designed when the maximum possible severity of ground motion was seriously underestimated.

In view of the paucity of strong-motion records near the fault for earthquakes of magnitude 6 and smaller and the complete lack of such records for earthquakes of magnitude 7 and 8, there is no empirical reason to assume that the current maximum recorded acceleration value of 1.25*g* (*3*) will not be exceeded during any future earthquake, especially where local topography may amplify the motion.

Simplified models of the fault mechanism suggest that peak ground acceleration and velocity at the fault surface are proportional to the effective, or driving, stress causing the fault to slip. Estimates of effective stress operating during earthquakes are currently subject to considerable uncertainty. For an effective stress of 100 bars, peak ground motions on rock of 2*g* and 100 centimeters per second are to be expected at the fault surface (*4*). For comparison, values of 1.25*g* and 115 cm/sec were recorded on rock at a distance of about 3 km from the slipped fault during the San Fernando earthquake, for which an effective stress of 100 bars has been estimated (*5*). Figure 1 shows that over the distance range for which data are available, peak acceleration increases with magnitude; this behavior may reflect an increase of effective stress with magnitude. These considerations lead us to expect that near-fault peak accelerations and velocities on rock are likely to exceed 1 to 1.25*g* and 100 to 125 cm/sec for shocks of magnitude 7 and 8.

Figure 2 includes acceleration data from sites on both rock and firm soil. At these levels of motion and for the surficial geologic conditions at these particular sites, there is no pronounced difference between the two sets of data. Closer to the fault, however, where the motion is more intense, the influence of surficial deposits on the nature of ground shaking would be more important.

The influence of surficial geologic deposits on bedrock acceleration and velocity as calculated for specific geologic sections from the San Francisco Bay region is illustrated in Fig. 3, A and B. In both parts of Fig. 3 the bottom trace is an arbitrary time history for a bedrock site; the peak values of motion are 0.7*g* and 68 cm/sec. The middle trace is the computed motion for a site with about 220 meters of older bay sediments overlying bedrock. The computational procedure allows for the nonlinear behavior of the sediments in response to the bedrock motion in the bottom trace. The top trace is for a site with about 10 m of mud overlying 175 m of older bay sediments, which in turn rest on bedrock. The sediments and mud cannot efficiently transmit to the surface the intense, high-frequency motion that governs acceleration, but they can readily transmit the lower frequencies that determine velocity. Accordingly, the effect of the surficial, geological deposits in this case is to attenuate peak acceleration to about one-third the bedrock value but to amplify peak velocity by about 30 percent and to extend the duration of shaking.

To properly assess the influence of surficial deposits on damage from ground shaking, one must consider the amplification or attenuation of the spectral components of motion. A widely used tool in engineering seismology is the response spectrum, which describes the maximum response of a suite of damped harmonic oscillators with different natural periods to a particular input motion (*6*). The response spectrum is useful in representing the frequency content of ground motion because it portrays the elastic response of simple idealized structures. Assessment of damage potential requires, in addition, an evaluation of the performance of real structures compared

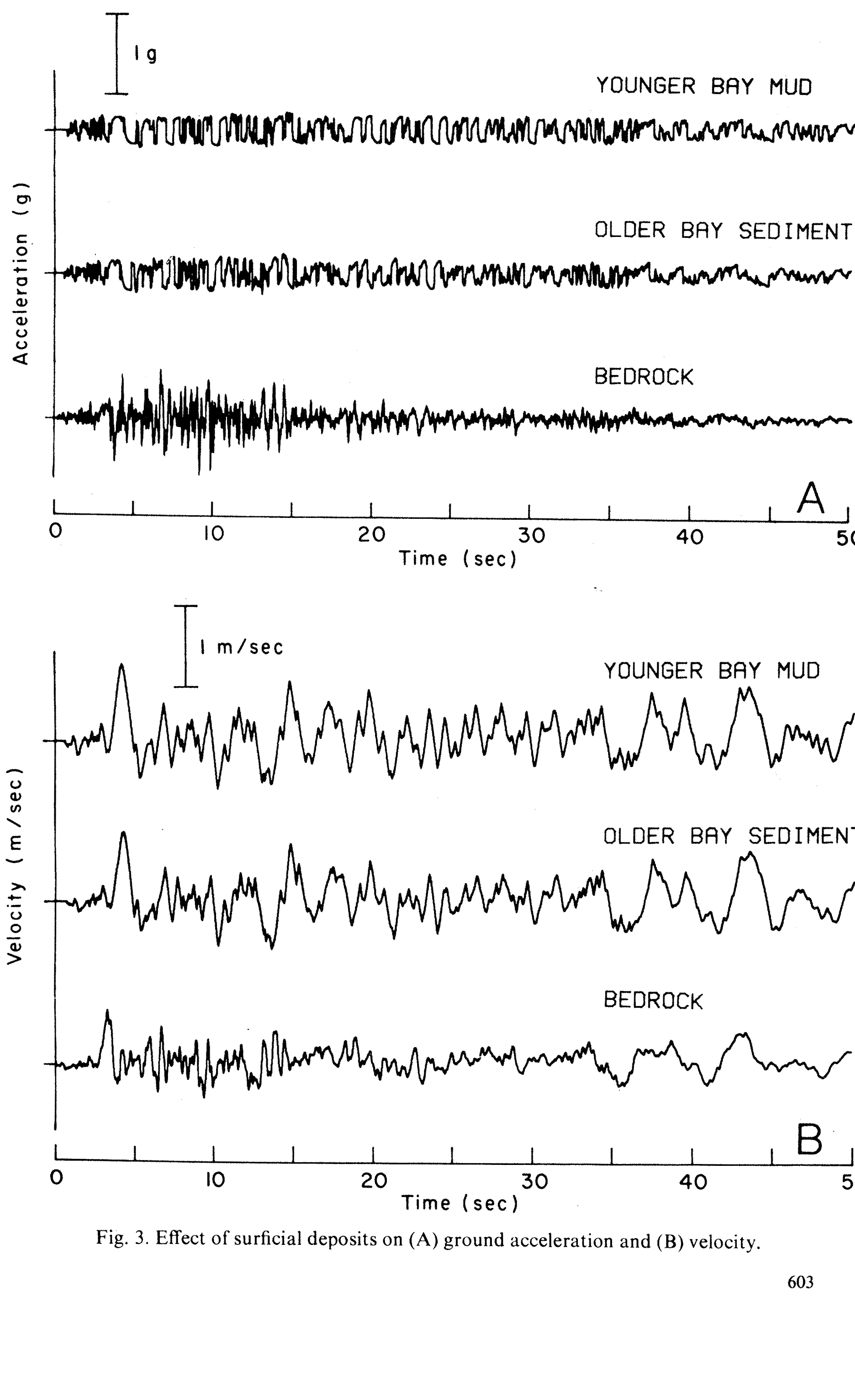


Fig. 3. Effect of surficial deposits on (A) ground acceleration and (B) velocity.

to idealized systems and a consideration of the behavior of the real structures beyond the elastic limit. Figure 4 shows the velocity response spectra at 5 percent damping for the three sites considered in Fig. 3. The soft surficial deposits decrease the amplitude of shaking at periods less than 0.8 second and increase the amplitude at periods greater than 1.5 seconds. The greatest amplification occurs at the natural period of the soil column, which is between 2.6 and 2.8 seconds for this example. The natural period depends on the thickness and rigidity of the soil and would therefore differ for different sites, as might also the period ranges over which amplification or attenuation occur.

Although soft surficial materials may limit the high-frequency content of transmitted energy, these materials may also be susceptible to failure, particularly failure involving soil liquefaction. This might result in even greater damage to structures than would be caused by shaking at a site on rock.

Effects of Shaking on Buildings

In earthquake-prone regions buildings must be designed to resist substantial lateral forces in addition to the normal vertical force of gravity. Practically without exception, buildings are adequately designed, or even overdesigned, for gravitational forces; one rarely reads of a building that collapses under its own weight or even under imposed gravitational loads, except perhaps for snow accumulation. Similarly, essentially all buildings are adequately designed for lateral forces exerted by winds (although not tornado and hurricane winds). Unfortunately, the same cannot be said with regard to earthquake shaking.

In an effort to assure public safety most buildings are designed to satisfy legal code requirements. For example, Section 2314 of the *Uniform Building Code* (*7*) specifies lateral force requirements to be used as minimum design criteria for earthquake-resistant construction. The intent of the lateral force requirements, as stated by the Structural Engineers Association of California (*8*), is to achieve buildings that are able to (i) resist minor earthquakes without damage; (ii) resist moderate earthquakes without structural damage, but with some nonstructural damage; and (iii) resist major earthquakes, of the intensity or severity of the strongest experienced in California, without collapse, but with some structural as well as nonstructural damage. Structural damage is that affecting the main support system of a structure, for example, supporting columns and beams or bearing walls. Nonstructural damage refers to that affecting elements of a building that are not relied upon for support of the structure, such as stairways, filler walls, windows, and lighting fixtures, but that may be essential to proper and safe operation of the building. Thus, the seismic provisions of building codes are not intended to prevent all damage, as many believe.

Not all structural properties that are critical to survival of a building are accounted for in traditional design analysis. Perhaps the most significant structural property generally overlooked is the capacity of the building to yield and absorb energy in the inelastic range between initial distress and ultimate failure. In many buildings this is the major line of defense, and it accounts for their apparent anomalously high resistance to earthquake shaking. There are methods of accounting for this capacity (*9*, *10*), but they are not as yet generally employed. Furthermore, in some buildings, especially of the older and more traditional type, there is a random but often important reserve capacity in nonstructural elements such as filler walls, partitions, or stairways. Although few of these buildings would pass modern code requirements, their nonstructural elements may mean the difference between survival and collapse in a major earthquake.

It is fortunate that these and other defenses are available, because the earthquake demands may far exceed the design forces of even the most modern seismic building code. We can hope that future codes will recognize these energy absorption factors in an orderly way as a supplement to lateral force design (*10*). In the meantime, conventional methods of analysis of structural response generally indicate that a building is on the point of collapse when, in fact, it may have great reserve resistance.

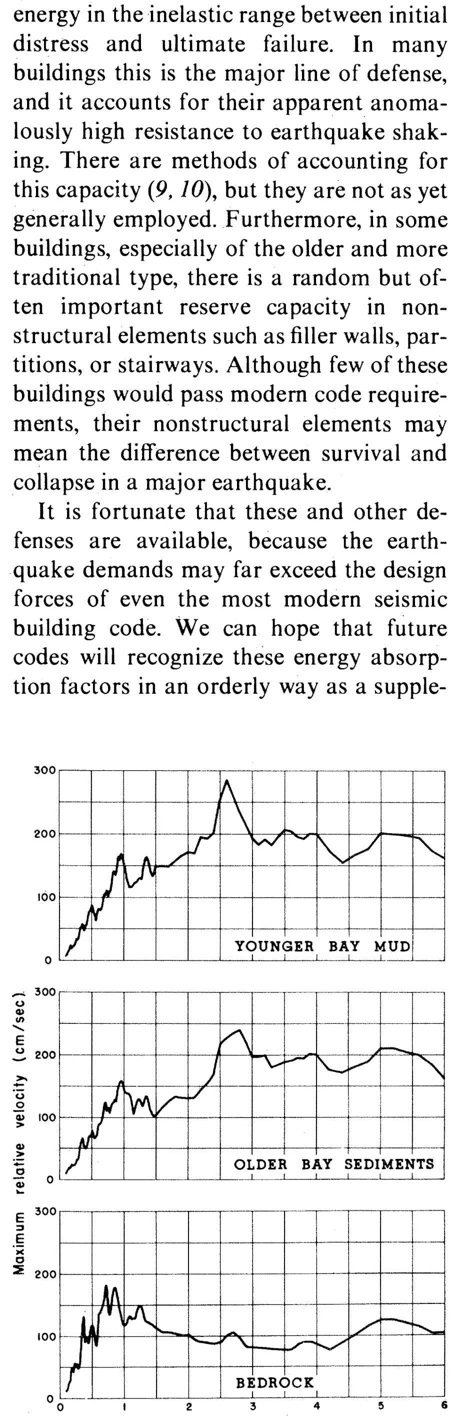


Fig. 4. Velocity response spectra for the ground motions in Fig. 3. The spectra represent 5 percent of critical damping.

The effects of shaking on a specific building may be estimated by engineering analysis in which one calculates the response of the structure to some postulated earthquake or ground motion. In the most sophisticated approach the dynamic behavior of the soil and structure is numerically modeled as an idealized inelastic system, which is driven by an assumed time history of ground motion. The limitations of this approach are the paucity of data on the dynamic behavior of real buildings and on the high-strain properties of real soils, the difficulty of realistically representing most buildings as idealized inelastic models, and the lack of detailed knowledge about failure mechanisms in real structures. The inelastic dynamic approach is also the most costly and is generally justified only in special cases. Simpler and less costly is the elastic dynamic approach, where the results for an elastic system are adjusted to allow for inelastic response of the structure (*9*).

There is an alternative approach in which seismically induced stresses in structures are determined from response spectra derived statistically from a large set of strong-motion records or calculated for a few assumed time histories of ground motion. If the spectra are for elastic response, which is usually the case, adjustments are necessary to allow for the effects of inelastic behavior.

It is also possible to estimate the effects of shaking on a group of buildings or a city by statistical evaluation of what has happened in prior earthquakes. In extrapolating from one earthquake to another, one must consider differences not only in earthquake magnitude, distance to the slipped fault, and local surficial geology, but also in buildings, including their dimensions, type of construction, materials, age, and condition, and the earthquake code (if any) followed in their design.

If the effects of shaking on buildings can be estimated, one may wonder why some buildings are not earthquake resistant. There are many reasons for this.

1) Most existing buildings were constructed before building codes contained earthquake provisions. In San Francisco, for example, there are 153,400 buildings, of which 58 percent were constructed before there was a nominal state earthquake requirement (1933) and 76 percent before there was a local earthquake design code (1948). This does not necessarily mean that all the older buildings are poor risks; on

the contrary, some are expected to perform well because of careful workmanship, abundance of materials, good design, and fortunate geometry.

2) The seismic building code provisions are not intended to prevent all damage, but to prevent extensive damage in moderate earthquakes and collapse in major earthquakes. To make total damage prevention a legal requirement would not be economically desirable or even feasible.

3) The evolution of building codes lags behind the acquisition of new knowledge, and codes are often developed as compromise measures from several different viewpoints. Even if knowledge were complete, the codes would not necessarily be perfect.

4) Only in the last decade or so has there been reasonable funding of earthquake engineering research, and only a small portion of this has gone into studies of the seismic response of buildings. Before this, most of the research effort was voluntary and sporadic.

5) Buildings are complex and difficult to model, especially when such nonstructural elements as filler walls, partitions, or stairways interact with the structural system. The characteristics of contemporary buildings are different from those of the traditional buildings on which existing codes were at least implicitly based.

6) Calculating the response of buildings to an earthquake is a complex, nonlinear problem not readily amenable to deterministic analysis. Not only does ground motion differ from one earthquake to another, but also soil conditions vary from site to site, and structural and dynamic characteristics vary from building to building.

If we can estimate the effects of shaking on buildings, we can estimate the damage to be expected in future earthquakes. In discussing damage, seismic engineers frequently distinguish between structural and nonstructural damage. The cost of the structural system in a building is ordinarily only a fraction of the total construction cost, ranging from 20 to 40 percent for typical buildings. Thus, it is possible for a building to perform acceptably by code standards during a major earthquake—that is, to resist collapse—but be a severe economic loss.

Several quantitative measures of ground shaking are used for comparing or predicting damage. Peak ground motion, in terms of either acceleration or velocity, is of limited usefulness because of resonant response phenomena that depend on the frequency content of the motion. Response spectra are more useful and reliable, as shown in experiences with underground nuclear detonations. Of particular promise is a recently proposed engineering intensity scale (*11*), which describes ground motion in terms of spectral response values in specified frequency intervals. On the basis of several earthquakes and an underground nuclear event, a response velocity of 1 cm/sec at 5 percent damping is tentatively identified with the threshold for damage. Response velocities of more than 200 cm/sec have not caused complete destruction. Unfortunately, the usefulness of all of these quantitative measures for predicting damage has been restricted by the scarcity of instrumental records at damaging levels of motion.

Table 1. Approximate average damage cost factors for buildings in the United States today. Modified Mercalli intensities are based on earthquake effects, as described in the following partial list (*12*): (VI) Felt by all. Persons walk unsteadily. Windows, dishes, glassware broken. Wall plaster and masonry cracked. (VII) Difficult to stand. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices. (VIII) Steering of cars affected. Partial collapse of ordinary masonry not reinforced against lateral forces. Frame houses moved on foundations if not bolted down. (IX) General panic. Weak masonry destroyed; reinforced masonry seriously damaged. Frame structures, if not bolted, shifted off foundations. Frames racked. (X) Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures destroyed.

Modified Mercalli intensity	Damage cost factor (%) for	
	Wood frame dwellings	Other buildings
VI	<0.2	<1
VII	2	5
VIII	5	15
IX	8	35
X	12	>50

Another tool for comparing or predicting damage is the modified Mercalli intensity scale, which is an index of combined earthquake effects on structures, people, animals, and natural objects and includes the indirect as well as the direct effects of shaking (*12*). Although originally intended as a noninstrumental measure of the severity of ground shaking, the scale is subjective and is most useful today as a measure of overall earthquake effects rather than of ground shaking. An intensity scale that depends in part on the observed performance of buildings is subject to wide variations in use depending on the nature of the buildings. The modified Mercalli scale as used today involves various degrees and types of damage. For earthquakes of comparable size, ratings based on damage results for a village of dried mud masonry or rubble would be different from those based on damage results for San Francisco or Los Angeles.

To advance the art of damage estimation, it is essential to have recordings of ground motion, damage data, and knowledge about the buildings exposed to the ground motion (whether or not they are damaged) and to analyze this material extensively. This has been done to a limited extent for the San Fernando earthquake (*13*) and for underground nuclear explosions (*14*). The results show that low, residential wood frame buildings are generally quite resistant to ground motion and sustain less damage than other buildings. Most but not all buildings can withstand considerable acceleration or velocity without damage or with nominal damage.

The damage (structural and nonstructural) cost factor for an area, defined as the total repair cost divided by the total building replacement cost, has been found to be as low as 1 percent for 0.6*g* spectral acceleration (at 5 percent damping) in the fundamental period range of low residential buildings and only about 2 or 3 percent for 1.0*g*. Another study indicates that for taller buildings the damage cost factor is more than an order of magnitude greater for comparable levels of spectral accelration at the fundamental periods of the taller buildings. The damage cost factor varies widely depending on the design criteria, the type of building, and other considerations. Table 1 shows the average damage cost factors, in terms of modified Mercalli intensity, for wood frame dwellings and other buildings for contemporary U.S. conditions, with many buildings that predate earthquake codes.

San Francisco Earthquake of 1906

The great (magnitude 8.25) San Francisco earthquake of 18 April 1906 ruptured the San Andreas fault offshore a short distance from the city, releasing energy up and down the coast for hundreds of kilometers. Fortunately, the earthquake occurred early in the morning. The damage was catastrophic but not total. Although the fire that followed destroyed much valuable evidence of earthquake damage, what was seen before the fire and what remained after the fire have been carefully studied. The fire was limited to blocks in the eastern part of the city, including the entire business area. The population of the city proper was about 400,000, of whom an estimated 600 died from the earthquake and fire.

The tallest building was 19 stories high and had steel frame and brick walls. This building sustained earthquake damage and was burned out, but it is still in use today under modified architectural treatment. There were 52 major buildings in the downtown area. These buildings generally had massive exterior walls of unreinforced masonry; some had complete steel frames, and some had metal frames only in the interior. A few of the large buildings, such as the original Palace Hotel, had wood floors and masonry walls and partitions. The Palace suffered only nominal earthquake damage but was completely burned out and subsequently razed. Although none of the buildings had been designed specifically for earthquake shaking, many of them had been designed for strong wind forces and most had great strength and rigidity because of their massive nonstructural walls.

Of the 52 major buildings in San Francisco proper, 7 were under construction at the time and were subsequently completed; 6 were destroyed by the earthquake or the fire or were subsequently razed; and the remaining 39 were repaired. Most of the 46 surviving buildings are still in use today, although a few have been replaced by modern structures.

Today there are 23,157 buildings in San Francisco that survived the 1906 earthquake and fire. Almost 99 percent of these have 1 to 3 stories; 235 have 4 to 8 stories; 13 have 9 to 13 stories; and 4 have 14 to 19 stories. Most of the 1- to 3-story buildings are wood frame residences, which generally have a good record of earthquake resistance.

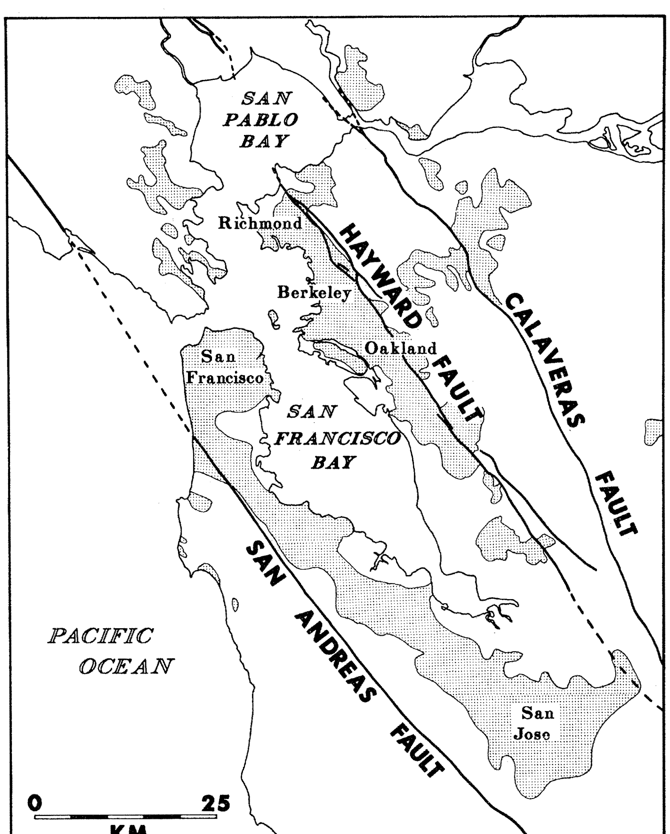
The data on the San Francisco earthquake illustrate important points to be considered in estimating damage from earthquake shaking. One point is to allow for things that do not happen in earthquakes as well as for those that do. So much attention is directed to damage that one is apt to overlook the overall statistics. It is important to know all the facts and, as far as possible, the reasons for them. A second point is that by no means were all of the buildings demolished in the 1906 earthquake. Several factors of reserve strength in most buildings must be taken into account to reconcile earthquake resistance with ground motion. Another point is that earthquake shaking is highly variable from place to place and from earthquake to earthquake. In another great earthquake, many of the buildings that survived the 1906 earthquake might be severely damaged, not solely because of possible deterioration with time but also because of the randomness of earthquake phenomena.

Although essentially none of the steel frame, concrete, or masonry buildings that survived the 1906 San Francisco earthquake would pass modern building codes, this does not mean that the codes are too severe for the types of building being constructed today. There are great differences between the massive-walled traditional building and the contemporary high-rise building without noncalculated elements, as was noted years ago (*15*). Older buildings were generally more rigid and stronger but more brittle. They were satisfactory as long as their strength was adequate, but were dangerous when forced into the range between initial distress and failure. Contemporary buildings are generally more flexible but tougher and more ductile. They may be expected to sustain damage but generally to survive, with some exceptions.

Even among contemporary buildings there are many variations. Codes and design philosophy have varied from time to time, from place to place, and from engineer to engineer. One cannot say that certain buildings meet earthquake standards without specifying the standards. These considerations and others make it difficult to estimate the effects of earthquake shaking on buildings. However, acceptable estimates can be made if the various conditions are taken into account.

San Francisco Bay Area in a Future Great Earthquake

The San Francisco Bay region is bounded by two major faults: the San Andreas on the west and the Hayward on the east (Fig. 5). Both faults are seismically active. The 1906 San Francisco earthquake ruptured a 430-km segment of the San Andreas fault, including the part shown in Fig. 5. Horizontal fault offsets of up to 6 m were measured north of San Francisco. The Hayward fault experienced two major earthquakes in the last century, in 1836 and 1868. The 1868 shock is assigned a magnitude of 7 ± ½ and caused horizontal offsets as large as 1 m. There is every rea-



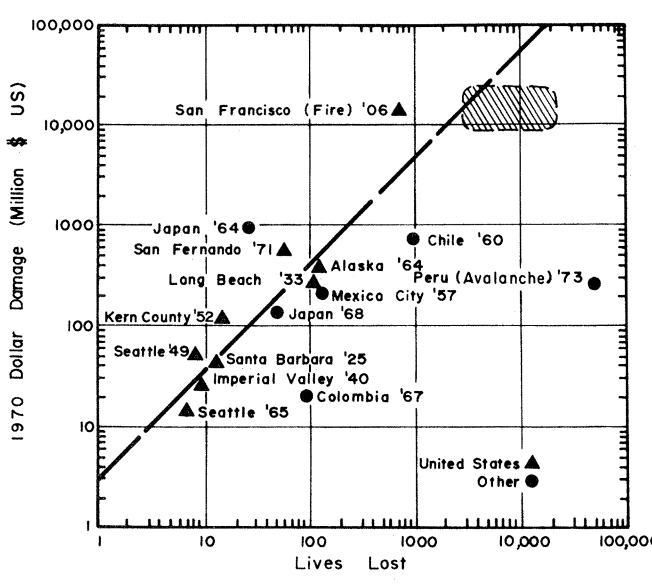


Fig. 5 (left). Map of San Francisco Bay region showing populated areas (shaded) in relation to the main active faults. Fig. 6 (right). Earthquake damage versus fatalities.

son to suppose that similar-sized earthquakes will recur on the two faults.

Major population centers lie adjacent to both faults. The entire city of San Francisco lies within 15 km of the San Andreas fault. The San Jose metropolitan area lies within about 25 km of the San Andreas, Hayward, and Calaveras faults, and the cities of Oakland, Berkeley, and Richmond all lie within 10 km of the Hayward fault. Some 2 million people live on the San Francisco Peninsula within about 15 km of the San Andreas fault. About 4 million people live in the 30-km-wide zone between the San Andreas and Hayward faults.

To assess the seismic risk in the San Francisco Bay region, we need to estimate the nature of ground shaking within 30 km of a magnitude 7.5 shock on the Hayward fault and a magnitude 8.25 shock on the San Andreas. In the absence of instrumental data, we can provide only an educated guess of what the motion will be. Extrapolating from the available strong-motion data for smaller shocks and relying on simple physical models of the faulting process, we arrive at the following estimates of peak horizontal motions on rock. For a magnitude 8.25 earthquake on the San Andreas fault, peak accelerations on rock could exceed 1.0*g* in San Francisco and in the cities on the San Francisco Peninsula and peak velocities could exceed 125 cm/sec; accelerations on rock in cities on the east side of the bay could be as high as 0.6 to 0.9*g*. For a magnitude 7.5 earthquake on the Hayward fault, peak accelerations on rock could exceed 0.8*g* in cities on the east side of the bay and be as high as 0.3 to 0.6*g* in San Francisco and the cities on the peninsula, and peak velocities could exceed 100 cm/sec in cities on the east side of the bay.

The influence of surficial geologic deposits on ground motion will depend on the thickness and physical character of the deposits. Typically, peak ground accelerations will be less at soil sites than on rock, peak velocities will be equal or larger, and durations will be significantly longer. Amplification of seismic waves in the soil layers overlying rock will be selectively damaging to structures with natural frequencies close to that of the soil-bedrock system.

These expected ground motions and even considerably smaller motions will cause landslides in certain hilly areas, especially if the soil is saturated from rains, and there will be subsidence of loose soils and poorly compacted filled ground. In addition, areas of saturated loose sand and silt will be subject to liquefaction and temporary loss of bearing strength. Some dams and reservoirs may fail and release the stored water. Waterfront structures will sustain vibrational damage, and tsunami or seiche effects may also contribute to damage along waterfront areas.

Damage to buildings and elevated freeway systems will be extensive, with some collapses and many near collapses. Especially vulnerable are the older buildings of masonry or concrete bearing walls and poorly connected wood floor and roof construction. However, small, wood frame residential buildings should generally perform well, although few if any would be undamaged. New structures built according to seismic codes should generally escape severe damage, although there could be disastrous exceptions. Some of the older buildings of the more classical type should be damaged but not collapse, while others could be more severely damaged.

Estimates of damage and loss of life for a recurrence of the 1906 earthquake are made by extrapolating from experience in past earthquakes. Figure 6 shows the damage in 1970 U.S. dollars plotted against lives lost in several destructive earthquakes within and outside the United States. Although there are many parameters to be considered, including population density and type of construction, it is clear that more lives are lost as damage increases. Building damage rather than ground shaking generally threatens life. Avalanches or dam failures can also cause great loss of life; for example, in the Peruvian earthquake of 1970, an avalanche killed 25,000 to 30,000 people. The line in Fig. 6 approximates a least-squares fit to the U.S. data, excluding the 1906 event in which fire caused four times more damage than did the earthquake itself. If allowance is made for fire loss, the 1906 damage level may be brought down to the line. The United States has so far experienced a low ratio of lives lost to dollar damage, mainly because of the time of earthquake occurrence and, to some extent, the type of construction.

Recognizing that the exposed population in the San Francisco Bay area has increased sixfold since 1906, that the investment in structures has increased tenfold, and that the fire loss in 1906 is not expected to occur again, $10 billion to $20 billion of damage is estimated for a repetition of the 1906 earthquake. The loss of life, if the occurrence were again during nonbusiness hours, is estimated at approximately 3000 to 5000. However, if the earthquake occurred during business hours, the loss of life could be many times greater, up to 10,000 or 20,000 (*16*). The shaded area in Fig. 6 mainly represents the potential damage and loss of life for building failures. Any dam failures causing floods would cost additional lives and property damage.

San Francisco does not have to wait for another magnitude 8.25 earthquake to sustain damage. A magnitude 5.3 shock in 1957 did $1 million of damage. An earthquake of magnitude 6 to 7 would cause considerable damage if close by, and one of magnitude 7 to 8 would cause a major disaster. In addition, tall buildings, whose natural periods of vibration are long, can be expected to respond considerably to great earthquakes some distance away. The frequency of earthquake occurrence increases as magnitude decreases so it is only a matter of time before damaging seismic activity recurs, whether or not the 1906 earthquake is repeated.

Conclusion

Ground shaking close to the causative fault of an earthquake is more intense than it was previously believed to be. This raises the possibility that large numbers of buildings and other structures are not sufficiently resistant for the intense levels of shaking that can occur close to the fault. Many structures were built before earthquake codes were adopted; others were built according to codes formulated when less was known about the intensity of near-fault shaking. Although many building types are more resistant than conventional design analyses imply, the margin of safety is difficult to quantify. Many modern structures, such as freeways, have not been subjected to and tested by near-fault shaking in major earthquakes (magnitude 7 or greater). Damage patterns in recent moderate-sized earthquakes occurring in or adjacent to urbanized areas (*17*), however, indicate that many structures, including some modern ones designed to meet earthquake code requirements, cannot withstand the severe shaking that can occur close to a fault.

It is necessary to review the ground motion assumed and the methods utilized in the design of important existing structures and, if necessary, to strengthen or modify the use of structures that are found to be weak. New structures situated close to active faults should be designed on the basis of ground motion estimates greater than those used in the past.

The ultimate balance between risk of earthquake losses and cost for both remedial strengthening and improved earthquake-resistant construction must be decided by the public. Scientists and engineers must inform the public about earthquake shaking and its effect on structures.

The exposure to damage from seismic shaking is steadily increasing because of continuing urbanization and the increasing complexity of lifeline systems, such as power, water, transportation, and communication systems. In the near future we should expect additional painful examples of the damage potential of moderate-sized earthquakes in urban areas. Over a longer time span, however, we can significantly reduce the risk to life and property from seismic shaking through better land utilization, improved building codes and construction practices, and at least the gradual replacement of poor buildings by more resistant buildings.

Progress toward reducing risk from seismic shaking through better building design is slowed by deficiencies in our knowledge about the nature of damaging ground motion and the failure mechanisms in structures. For example, lacking observational data, seismologists must rely on simplified theoretical and numerical models of the earthquake process to estimate near-fault ground motion, especially for earthquakes as large as magnitude 7 and 8. Because such models have not been adequately tested against data, their reliability is unknown. Engineers lack detailed information about failure processes in structures during an earthquake. Although many structures have been instrumented to measure their response to an earthquake, few records have been obtained from buildings that actually sustained significant structural damage and few structures are properly instrumented to measure all the modes of deformation that are likely to contribute to failure. Moreover, the fact that many structures have withstood ground motion more intense than that assumed in their design indicates that conventional methods of design do not take into account important contributions to earthquake resistance by nonstructural elements and by the ability of structural elements to deform inelastically without necessarily causing failure of the structure. It is fortunate when such reserve resistance exists, but better understanding of the sources of reserve strength is needed to determine how large a margin of safety they confer and how they might be affected by changes in construction practices and materials with time.

In the next few years we look forward to significant advances in knowledge and to more effective application of what is already known, largely because of substantial funding of research related to seismic engineering by the National Science Foundation (*18*). The increasing number of strong-motion seismographs operating in seismically active regions (*19*) will likely provide for the first time a number of records of damaging levels of ground motion. Significant effort is being directed toward obtaining near-fault records, although many probable sites of future large earthquakes remain inadequately instrumented, especially outside the conterminous United States. New and more complete information on building response and damage mechanisms will be obtained by improved instrumentation of structures and through laboratory investigations of failure in structures and structural elements. Further developments in computer technology and in computer modeling techniques will permit more realistic simulations of the seismic response of soils and structures that take into account their inelastic behavior and their strain-dependent properties. Earthquake design codes will continually be revised to better utilize existing knowledge concerning the nature of strong ground motion and the dynamic behavior of buildings during earthquakes and to incorporate new knowledge and also experiences gained from future earthquakes. We believe that application of new knowledge, improvements in earthquake-resistant design and construction, and remedial strengthening or replacement of weak existing structures can significantly reduce our current level of exposure to earthquake hazards.

References and Notes

1. *Report of the Los Angeles County Earthquake Commission, San Fernando Earthquake, February 9, 1971* (1971).
2. The U.S. strong-motion program, begun by the Coast and Geodetic Survey, has undergone a number of changes of organizational affiliation in the past 10 years. Most recently, in 1973, the program was transferred from Environmental Research Laboratories, National Oceanic and Atmospheric Administration, to the Office of Earthquake Studies, U.S. Geological Survey.
3. The 1.25g peak acceleration was recorded on a ridge, which probably amplified the peak acceleration; a lower value would likely have been recorded at a level site on rock [D. M. Boore, *Bull. Seismol. Soc. Am.* **63**, 1603 (1973); W. V. Mickey, V. Perez, W. K. Cloud, in *Proceedings of the Fifth World Conference on Earthquake Engineering* (Rome, 1973), pp. 755–762; R. B. Reimer, R. W. Clough, J. M. Raphael, in *ibid.*, pp. 2328–2337]. Without additional near-fault records from earthquakes of comparable size, one cannot accurately judge how anomalous the 1.25g value is for a magnitude 6.6 earthquake. At this time various arguments suggest that a value in the range 0.7 to 1.25g is representative of maximum near-fault accelerations during the San Fernando earthquake [Panel on Strong-Motion Seismology, *Strong Motion Engineering Seismology* (National Academy of Sciences, Washington, D.C., 1973), p. 4].
4. J. N. Brune, *J. Geophys. Res.* **75**, 4997 (1970).
5. M. D. Trifunac, *Bull. Seismol. Soc. Am.* **62**, 721 (1972).
6. The response spectrum is most easily defined in an operational sense. Given an input ground motion, the dynamic response of a suite of damped harmonic oscillators of varying natural frequencies but constant damping is calculated as a function of time. (The response may be expressed in terms of acceleration, velocity, or displacement.) A response spectrum is constructed by plotting the maximum response for each oscillator as a function of its natural frequency. Thus, a 5 percent damped acceleration response spectrum gives the maximum accelerations of a suite of 5 percent critically damped harmonic oscillators to the input motion of interest. For further discussion, see G. W. Housner, in *Earthquake Engineering*, R. L. Wiegel, Ed. (Prentice-Hall, Englewood Cliffs, N.J., 1970), p. 85.
7. International Conference of Building Officials, *Uniform Building Code* (International Conference of Building Officials, Pasadena, Calif., irreg. 1927–1973). This is a recommended code which provides minimum standards for design and construction of buildings and other structures to ensure public safety. Many municipalities and counties have enacted it, at least in part, by ordinance. The code is continually updated and revised to accommodate new design and construction methods. Since 1937, revised editions of the code have been published every 3 years; the most recent edition appeared in 1973.
8. Structural Engineers Association of California, *Recommended Lateral Force Requirements and Commentary* (Structural Engineers Association of California, San Francisco, ed. 3, 1973), p. 34. The earthquake provisions of the *Uniform Building Code* are primarily those recommended by the Structural Engineers Association of California.
9. J. A. Blume, in *Proceedings of the Second World Conference on Earthquake Engineering* (Tokyo, 1960), pp. 1061–1083.
10. ———, in *Proceedings of the Fifth World Conference on Earthquake Engineering* (Rome, 1973), pp. 2256–2265.
11. ———, *Bull. Seismol. Soc. Am.* **60**, 217 (1970).
12. For a discussion of the modified Mercalli intensity scale, see C. F. Richter, *Elementary Seismology* (Freeman, San Francisco, 1958), pp. 135–149.
13. I. Farhoomand and R. E. Scholl, John A. Blume & Associates Research Division, *Investigation of Ground Motion-Damage Relationships for Residential Buildings in Glendale, California: San Fernando Earthquakes, February 1971* [Report JAB-99-96 to the U.S. Atomic Energy Commission, Nevada Operations Office, August 1972; available from National Technical Information Service, Springfield, Va.].
14. R. E. Scholl and I. Farhoomand, John A. Blume & Associates Research Division, *Statistical Correlation of Observed Ground Motion with Low-Rise Building Component Damage: Project Rulison* [Report JAB-99-93 to the U.S. Atomic Energy Commission, Nevada Operations Office, January 1973; available from National Technical Information Service, Springfield, Va.].
15. J. A. Blume, *Trans. Am. Soc. Civ. Eng.* **125**, 1088 (1960).
16. The estimates for loss of life given here are somewhat greater than those presented in a recent report on earthquake losses in the San Francisco Bay area prepared for the Office of Emergency Preparedness by the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration [*A Study of Earthquake Losses in the San Francisco Bay Area* (Department of Commerce, Washington, D.C., 1972)]. In that report deaths, excluding those from failure of dams, are estimated at about 3,000 and 10,000 for nonbusiness and business hours, respectively (*ibid.*, p. 121).
17. In addition to the 1971 San Fernando earthquake, other examples of destructive moderate-sized earthquakes occurring in or near urbanized areas are the 1969 Santa Rosa, California, and 1972 Managua, Nicaragua, shocks. At Santa Rosa two shocks (magnitudes 5.7 and 5.6) caused $6-million damage to buildings [K. V. Steinbrugge, W. K. Cloud, N. H. Scott, *The Santa Rosa, California, Earthquakes of October 1, 1969* (U.S. Department of Commerce, Washington, D.C., 1970), p. 3]. Although only slightly larger, the Managua earthquake was much more destructive because the buildings were less resistant than those in the western United States. More than 11,000 people were killed, and property damage totaled more than $500 million [R. D. Brown, P. L. Ward, G. Plafker, *U.S. Geol. Surv. Prof. Pap. 838* (1973), p. 1].
18. Under the RANN (Research Applied to National Needs) program, NSF funding for research related to earthquake engineering, including the area of ground motion studies, has increased from $2.9 million for fiscal year 1972 to $4.8 million for 1973 and $8.0 million for 1974 (C. C. Thiel, personal communication).
19. Although the federal government is supporting much of this effort, the State of California under recently enacted sections of the Public Resources Code has inaugurated a program for recording strong motion in representative geological environments and in representative structures throughout the state.