CHAPTER II

Geologic and Geotechnical Aspects of the Northridge Earthquake

The Northridge earthquake occurred at a depth of approximately nine miles beneath the earth's surface on a buried, or "blind," thrust fault. It produced intense shaking and caused extensive damage that reaffirmed the potential risk from this type of fault—and the need to mitigate that risk.

The earthquake was the most recorded earthquake that has ever occurred in California. Figures 5 and 6 show two perspectives of the data obtained. Strong-motion instrument recordings were obtained at 257 sites. Over 11,000 aftershocks have been recorded by these instruments. By maintaining and enhancing data collection programs and identifying areas that have faults capable of causing earthquakes, California can learn to better reduce its seismic risk.

The Northridge earthquake also caused secondary hazards, the most prominent of which was localized amplification of the ground motion caused by local geologic conditions. The identification and mitigation of secondary hazards, such as landslides, liquefaction, and areas that may amplify shaking, need to be integrated into land use planning programs, building codes, and engineering practices.

◄ **Sand boils caused by the earthquake at Redondo Beach.**

Most of the hazard associated with earthquakes typically comes from strong shaking.

The Northridge earthquake provided many geologic, seismologic, and geotechnical data that are still being compiled and analyzed. A significant value of the Northridge earthquake data is their use in the development and calibration of methods for assessing seismic hazard for planning and engineering applications. For example, the Northridge event occurred on a buried fault, highlighting the need to characterize and include earthquakes on this type of fault in the analysis of the ground motion component of the overall seismic hazard. It also reaffirmed that most of the hazard associated with earthquakes typically comes from strong shaking.

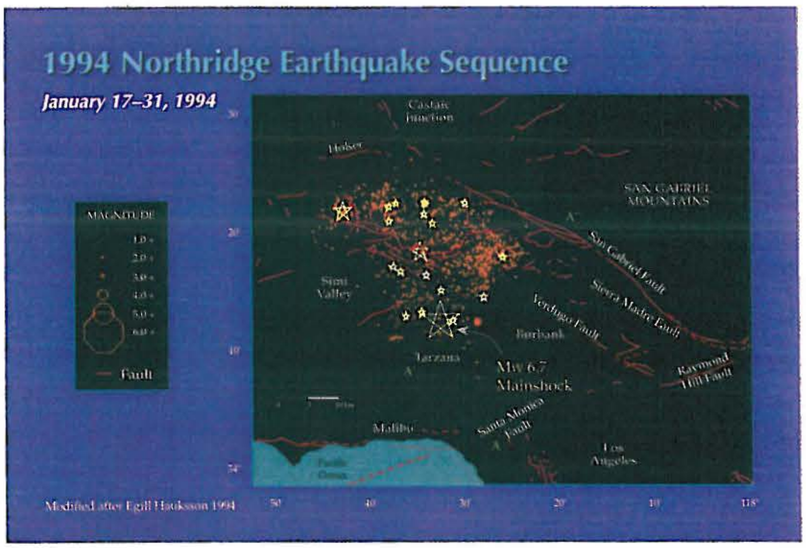

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Figure 5. Map showing Northridge earthquake sequence over a two-week period.

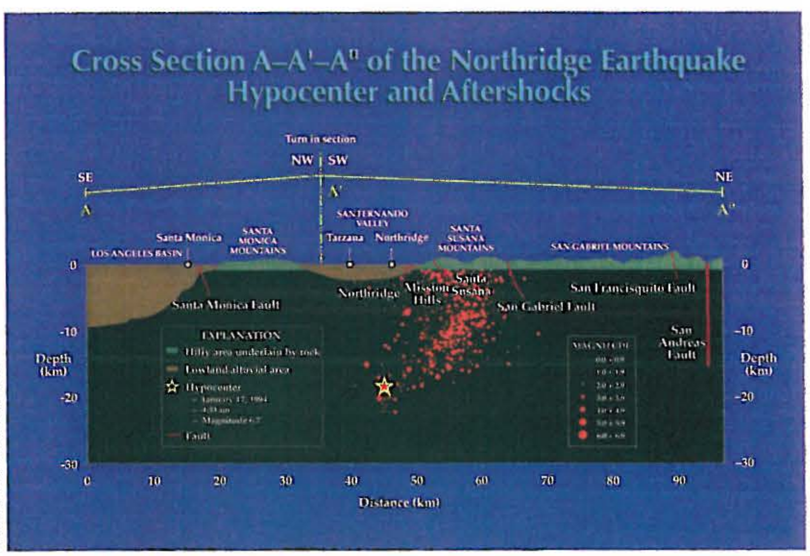

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Figure 6. Cross section showing Northridge earthquake hypocenter and aftershocks.

Using Geologic Information

Seismic hazard analyses are becoming more useful as our knowledge of the geologic aspects of hazard and source characteristics increases. Local conditions can affect the level of hazard significantly. It is now more common in ground motion hazard analyses to represent seismic sources as three-dimensional faults and to characterize the faults by their possible rupture dimensions, slip rates, and recurrence rates. Simplified approaches may be adequate, and in some cases necessary, for national-scale seismic hazard studies, but they can be enhanced for regional hazard assessments. Seismic hazard analyses for particular sites (such as for critical facilities) have long included details of potential nearby earthquake sources and other site-specific information.

In addition to integrated representations of seismic hazards, such as ground motion maps for a particular return period, geologic information can be used to develop earthquake scenarios that can be useful for many applications. The California Division of Mines and Geology (CDMG) has prepared earthquake scenarios to evaluate emergency response in the San Francisco Bay Area, southern California, and northwestern California. With appropriate modifications, such scenarios also could be used to assess potential damage to residential, commercial, and industrial development, as well as estimate loss of lives and damage to the infrastructure. The scenarios could include details of earthquake effects for engineering purposes, as well as expected damage for emergency response and land use planning purposes.

At present, California is implementing a program to mitigate surface fault rupture hazards (the Alquist-Priolo Earthquake Fault Zone Act), but is only in the early stages of developing maps under the Seismic Hazards Mapping Act (SHMA) to address the shaking, landsliding, and liquefaction hazards. The Northridge earthquake emphasizes the need to address these higher-priority hazards; the Commission believes accelerations in this earthquake were especially high, most spectra generally agreed with those recommended by site-specific geotechnical studies as the basis for the design of special structures. Similar response spectra have been calculated from data from numerous earthquakes since the 1971 San Fernando event and should be expected in future events.

CDMG's Strong Motion Instrumentation Program proved its worth during this earthquake and its aftermath.

Engineers use *design* spectra to determine the design parameters to use when designing structures. The values for design spectra are not the same as those of response spectra computed from measured ground motion. Design spectra are modified from response spectra to reflect safety factors and the performance of materials and structural systems observed in past earthquakes.

Because of the damage from this earthquake, questions have been raised concerning the adequacy of the building code's definition of the forces that earthquakes can impose on buildings. Code writers and designers know that code spectral values will likely be exceeded in large earthquakes and that this was anticipated when the code was written.

The recorded data from the Northridge earthquake are still being evaluated and are subject to different interpretations. Strong motion instruments also were not located in many of the areas that suffered the most severe damage. Generally speaking, the motions recorded near the Northridge epicenter were compatible with those used as the basis for the code, but the motions exceeded those assumed in the code in some cases. At some locations, particularly in the near-source area and in areas with unique local geology, shaking exceeded the assumptions underlying design values in the short- to mid-period range. This shaking appears to have affected low- and mid-rise buildings and caused response in higher modes of vibration for tall buildings. Velocity- and displacement-sensitive structures also may have been affected by the velocity pulses described earlier. Near-source and local geologic effects must be considered in the design of structures. There is no compelling evidence that changes to the code's assumed force levels are necessary. However, changes are necessary regarding the treatment of the effects of near-source and local geologic conditions.

Strong-Motion Instrumentation

The timely release of strong-motion data, especially during the days immediately following an earthquake, is invaluable to building owners, emergency responders, and those who will revise codes and design practices. Much of the evidence of an earthquake's effects disappears quickly as demolition, repair, and reconstruction take place. The opportunity to compare building performance and earthquake effects with actual motion data helps practicing engineers and researchers understand their observations, which in turn helps strengthen building codes and reduce future earthquake damage.

The Commission believes that the CDMG's Strong Motion Instrumentation Program (SMIP) proved its worth during this earthquake and its aftermath. Within a day of the main shock, SMIP had issued a "Quick Report" containing copies of strong-motion records obtained by four of its stations; copies of records for nine additional stations were released the following day. By the third day, copies of records for 28 stations had been made available, and by January 25, five quick reports had been released, providing peak acceleration data for 68 stations. In mid-February, SMIP issued a report containing pertinent station information, known geologic site conditions, peak acceleration data, and traces of recordings from 193 stations. SMIP also processed significant records rapidly and released processed data from five stations during the first week of February; additional releases followed at three- to four-week intervals. Processed data for more than 70 stations were released by December 1994. The timeliness and quality of these data were extremely valuable.

The U.S. Geological Survey (USGS), utilities, dam owners, and researchers funded by the National Science Foundation (NSF) operate networks of hundreds of free-field and structural strong-motion instruments scattered throughout California. A considerable public investment

DEFINITIONS OF NEAR-FIELD AND NEAR-SOURCE

The terms "near-field" and "near-source" are often used interchangeably by engineers and others to represent an area near the fault where earthquake shaking has characteristics that differ from the shaking expected at greater distances. However, some seismologists use the term near-field differently from the way many engineers do. To clarify these terms, the following definitions are used in this report:

Near-Source Area: The near-source area is the area of the ground surface lying above and adjacent to the fault rupture plane. Its horizontal extensions from the fault are about the same as the depth of the rupture on the fault.

Near-Field: Near-field is a mathematical term used in seismology to describe the characteristics of waves propagating from a fault rupture.

Near-Source Effects: Ground motion in the near-source area may be characterized by high accelerations, large velocity pulses, and permanent tectonic displacement. The nature of ground motion is related to the direction and mechanics of the fault rupture as well as the path of the seismic wave to the site. The characteristics of near-source shaking may be quite different from those of more distant earthquakes and may not follow the "normal" attenuation relationships used to describe shaking at more distant points. The ground surface in the near-source area may experience slow deformation before the earthquake and will be warped permanently by the rupture of the fault during the earthquake.

causes significant high-frequency motion and allows permanent coseismic displacement of the fault and surrounding area. Known as source-effect phenomena, these factors affect the amplitude and frequency content of shaking.

Of critical importance to the design of engineered structures is that near-source effects combined with local geologic effects can adversely alter the seismic performance of a wide range of structures, including highrise and base-isolated buildings. Data recorded during the Northridge earthquake clearly indicate the need to incorporate measures to mitigate this hazard in building codes. High-velocity pulses in the near-source area are believed by some to be a cause of much of the damage. These pulses were the largest in the northern San Fernando Valley and Santa Susana Mountains. They were also significant in the southern San Fernando Valley.

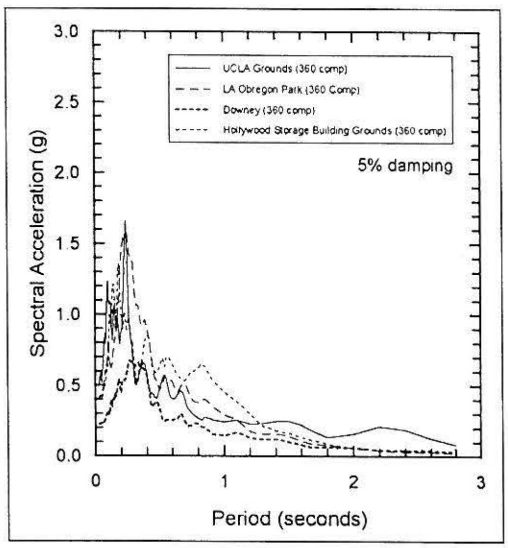
Duration of Strong Motion

The longer ground shaking lasts, the greater the damage to structures, natural slopes, and fills. When strong shaking ceases, there is a reasonable possibility that the damage will not continue. However, if the shaking continues after damage has been initiated, structures will continue to degrade and may eventually collapse. Damage caused by seismic consolidation and liquefaction also increases as duration increases. The duration of intense shaking during the Northridge earthquake was relatively short, on the order of nine seconds or less. Had the earthquake's magnitude been larger, there is little doubt that strong shaking would have lasted longer and the damage would have been greater. Strong shaking has lasted minutes in some other events.

The duration of intense shaking, like near-source effects, is not explicitly considered in our building codes. Because an urbanized area of California has not yet been exposed to long-duration near-source effects, the effect of duration on various types of structures is not fully understood.

Response Spectra

Response spectra are graphs that display the response of structures to ground motion associated with earthquakes (Figure 9 is an example). A spectrum graphically depicts the variation of spectral accelerations (velocities or displacements) experienced by simple structures with different stiffnesses or periods of vibration (expressed in seconds). Although some recorded



Earthquake Engineering Research Center, 1994

Figure 9. Example of Northridge earthquake response spectra.

There was initial speculation that much of the damage in the Northridge earthquake was caused by abnormally high vertical accelerations. Vertical accelerations tend to be comparable to or exceed horizontal accelerations near the area of fault rupture. Although vertical accelerations were high in some locations, so was the horizontal acceleration. The ratio of vertical to horizontal accelerations was consistent with previously recorded data. Modern building codes are based on assumptions that the maximum vertical accelerations will be two-thirds of the peak horizontal acceleration. An analysis of CDMG's Northridge records indicates that, although this ratio was exceeded at a number of locations, on average, it held true (Shakal et al., 1994). The Commission has not received evidence that vertical accelerations played an unusual role in the damage caused by the Northridge earthquake.

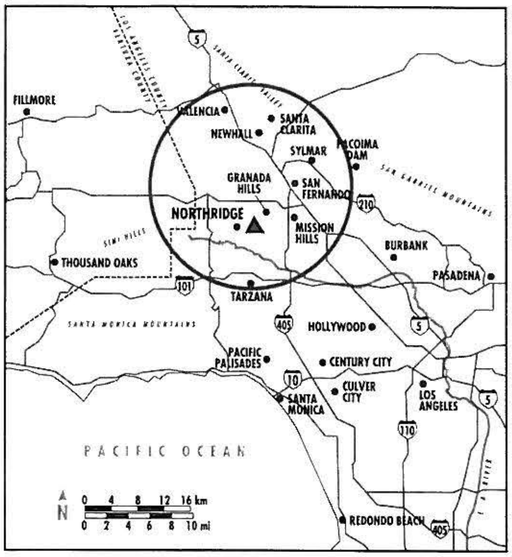


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Figure 8. Map showing preliminary near-source area (circle) for the Northridge earthquake.

Velocity and Displacement

The intensity of shaking is typically described by acceleration recordings. The Northridge earthquake also produced high velocities and displacements not described in acceleration data. A velocity of 56 inches per second was recorded in a parking lot at the Sylmar County Hospital, and a velocity of 72 inches per second was recorded at the Rinaldi receiving station. Peak velocity is important because it is a good indicator of an earthquake's demand potential (or energy) on multistory structures.

Ground displacement also is a significant factor in the design of structures, especially for seismically isolated structures. Ground displacement of 31 inches was measured at the Sylmar County Hospital parking lot. Base-isolated structures are normally separated from the surrounding soil to allow room for movement. Although seismically isolated structures are isolated from high-frequency shaking during an earthquake, they may collide with building foundation stops or barriers if actual displacements exceed the anticipated or design displacements. Such collisions would result in high impact forces that can cause significant damage and even collapse.

Near-Source Effects

The near-source region of an earthquake can be defined as the region within several miles of where the projection of the fault rupture plane meets the ground surface. Figure 8 shows the approximate near-source area of the Northridge earthquake. Within this region, the ground motion may be characterized by pulses of high velocity that are potentially damaging to certain types of structures. The near-source area in a strike-slip earthquake would have a different shape (generally longer and narrower, extending on both sides of the fault rupture for the length of the rupture), and the nature of the near-source strong motion would also vary, depending on other nonsource effects such as local geologic conditions.

Although seismologists have known of the influence of near-source effects on seismic shaking for some time, near-source effects first gained the interest of California engineers following the 1971 San Fernando earthquake. Failure of the Olive View Hospital in 1971 was attributed, in part, to a large, long-period near-source "seismic pulse." Near-source effects have been considered in the design of some critical facilities for a number of years. However, the implications of near-source effects have only recently been studied for use in the design of conventional structures because previous earthquakes have not struck well-instrumented urbanized areas and, therefore, produced few recorded motions from areas close to the source. At present, near-source effects are not explicitly considered in the building codes except for seismically isolated structures.

Near-source effects of engineering interest are related to the direction and mechanics of the fault rupture. The numerous localized, relatively rapid failures of "patches" of the fault surface that the SHMA program is a vital part of the state's efforts to mitigate seismic risk and should be funded at a higher level to accelerate its progress. The Alquist-Priolo and SHMA programs are discussed in more detail in Chapter V.

The Commission believes that a broad base of support for the hazard mapping program must be established in the earth sciences, engineering, financial, and planning communities so that its products will be used effectively. Better lines of communication must be established among scientists conducting hazard analyses, engineers using the results in design and review, and planners who implement the results for land use planning. The Commission believes it is also important that the results of the mapping program be implemented at the planning stages of land use and not solely at the later building and safety stages. Recommendations addressing these concerns are also included in Chapter V.

Recommendations

The Commission recommends that:

- CDMG use independent peer review by acknowledged experts representing scientists, hazard analysts, and users throughout the Seismic Hazards Mapping Program.
- CDMG draw on resources outside state government to conduct the mapping program.

Strong Ground Motion

The Northridge earthquake was a moderate earthquake that produced strong ground motions and intense shaking. The term "moderate" describes the *magnitude* of the earthquake, which in this case was 6.7. Moderate earthquakes (less than magnitude 7.0) generally produce localized shaking of an intensity (that is, amplitude of motion and frequency content) on stiff structures similar to that of major earthquakes (magnitudes of 7.0 and above). However, a more extensive area experiences intense shaking in a higher-magnitude earthquake and the *duration* of the shaking, the length of time the strong motion lasts, generally increases with increases in magnitude. Since a higher-magnitude earthquake affects a larger area and lasts longer, it can be expected to cause greater damage. Figure 7 compares areas subjected to intense shaking from four earthquakes, including Northridge.

A number of factors affect the amount of damage to structures in an earthquake, but the intensity of shaking is of paramount importance. Shaking intensity is affected by the magnitude of the earthquake, its style of faulting, local geologic conditions, proximity to the fault rupture, and the rupture geometry along the fault. The Northridge earthquake's strong-motion records reveal extensive information about the nature of the shaking, including acceleration, velocity, displacement, duration, and frequency. The consensus of earth scientists and geotechnical engineers is that the earthquake's motions were not unusual for a thrust-fault earthquake of this magnitude. However, this earthquake clearly points out the importance of near-source effects and local geologic conditions on shaking intensity and the need to incorporate these phenomena in seismic design and construction.

Accelerations

Peak accelerations, which are not necessarily the best measurement for correlating ground motion with the forces in structures, typically ranged from 0.4g to 0.8g in the regions that suffered significant damage. Recorded peak horizontal accelerations typically ranged between 0.1g and 0.5g at distances between 12 and 30 miles from the rupture zone, although some higher accelerations were recorded due to local geologic or topographic conditions. Horizontal accelerations exceeding 0.9g were recorded in the San Fernando Valley and in Santa Monica, nearly 14 miles away from the epicenter. The highest recorded free-field accelerations, 1.82g horizontal and 1.18g vertical, were at the Cedar Hill Nursery in Tarzana, three miles south and west of the epicenter. Instruments near an abutment to the Pacoima Dam recorded peak accelerations of 2.3g horizontal and 1.7g vertical, although the free-field accelerations on alluvial materials near the base of the dam were less than 0.5g.

Figure 7. Map showing the area of intensity level VII and greater for selected historic California earthquakes.

has been made in developing and maintaining USGS- and NSF-funded strong-motion networks. For example, the USGS strong-motion network in southern California consists of nearly 100 stations, while the University of Southern California network originally consisted of 80 free-field stations. Many of these instruments are old analog-type devices; the data they collect require considerable processing before they can be used. Because these arrays complement the SMIP instruments and record motion in different areas, data from these networks are vital to understanding the distribution and severity of shaking resulting from the earthquake. The USGS released photocopies of records obtained from 150 individual accelographs in February 1994. However, data from the USGS- and NSF-funded networks were not processed in a timely manner following the Northridge earthquake. USGS data were released to the scientific and engineering community in December 1994, but NSF-funded data were not released as of that date. This situation is unacceptable; a mechanism is urgently needed to correct this problem.

Recommendations

The Commission recommends that:

- The state continue its strong support of SMIP as a valuable part of California's effort to reduce the risk from earthquakes.
- SMIP exert leadership by organizing a workshop involving the other operators of strong-motion instrument networks in California to coordinate the deployment and operation of these networks.

  As a result of the workshops, SMIP should compile a list of all strong-motion instruments and their locations in the state and find ways to improve the overall performance of the systems. Furthermore, a mechanism should be developed to provide the processed data from earthquakes in a timely manner. These tasks should be completed by July 1995.
- Public funds not be used for the purchase, deployment, or upgrading of strong-motion instrument networks operated by private organizations unless there is a plan for the maintenance of the instruments and an agreement for the timely release of data to the public.

Reference Stations

Most free-field strong-motion stations were installed in locations near active faults to collect data for use in understanding the physics of earthquakes to be better able to estimate ground motion in future earthquakes. Such studies are vital to an understanding of the earthquake process, and such instrument deployments need to continue. However, there is also an urgent need for free-field strong-motion data as references to establish the levels of ground shaking experienced by buildings and other structures. Without such data, engineers cannot assess whether buildings performed as intended and determine the changes needed in codes and design practices to improve performance. For example, there were few free-field instruments in the immediate vicinity of damaged steel-frame buildings, so the levels and character of shaking experienced by these buildings are not well understood. The lack of reliable ground-motion data makes it extremely difficult to understand the causes of these failures and find acceptable solutions. None of the existing programs is directed toward obtaining the reference ground-motion data that are needed.

A mechanism is urgently needed to ensure the timely release of strong-motion data after an earthquake.

Recommendation

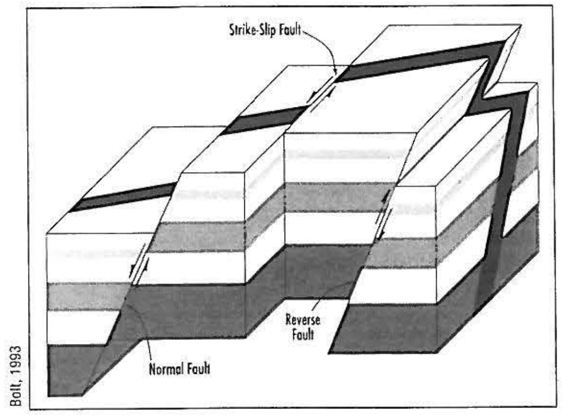
The Commission recommends that:

- SMIP give high priority to establishing a network of reference stations to measure ground motions in major urban areas of California.

  The reference station network should provide ground shaking data for use in the evaluation of building and structural performance after damaging earthquakes. Instruments deployed in this network should provide data that require a minimum amount of processing and will be available to building officials and engineers on an urgency basis.

Buried Faults

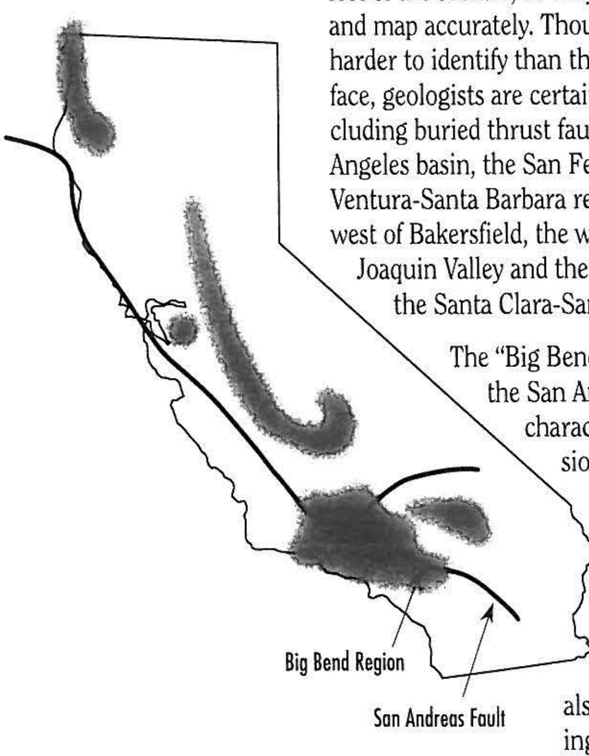
Like the 1983 Coalinga and 1987 Whittier Narrows earthquakes, the Northridge earthquake resulted from slip on a buried, or "blind," fault. Unlike surface faults, this type of fault remains completely buried deep in the earth's crust.



Many faults break the surface; examples are reverse-slip faults of the type involved in the 1971 San Fernando earthquake and strike-slip faults such as the San Andreas, Hayward, and San Jacinto (Figure 10). Buried faults do not reach the surface even though they may be active. Buried faults can remain deep within the earth's crust, often at depths greater than six miles, or may extend to within a few hundred feet of the surface, so they are difficult to locate and map accurately. Though buried faults are harder to identify than those that break the surface, geologists are certain that buried faults (including buried thrust faults) lie beneath the Los Angeles basin, the San Fernando Valley, the Ventura-Santa Barbara region, areas south and west of Bakersfield, the west sides of the San Joaquin Valley and the Sacramento Valley, and the Santa Clara-San Jose area (Figure 11).

Figure 10. Diagram showing the three main types of fault motion.

Figure 11. Regions of California with known buried faults.



The "Big Bend" (Figure 12) region of the San Andreas fault system is characterized by compressional features, including reverse faulting and folding in the Los Angeles Basin. Buried faults are significant components of the system. Other fault zones also are important, including zones of incipient faults (faults that are in the early stages of development) and subtle faults in alluvial regions. These faults show little direct evidence of existence on the surface but may be deep-seated, buried strike-slip or oblique-slip faults or their lateral extensions.

Geologists are able to recognize geomorphic features, such as broad ripple-like folds, or pressure ridges, and Riedel faults at or near the surface as evidence for the existence of buried faults. These folds and buried faults are produced by tectonic compression over millions of years. However, most fault studies have emphasized locating the surface traces of active faults. At the state level, the emphasis has been on identification of active strike-slip faults to mitigate surface fault rupture hazards under the Alquist-Priolo Earthquake Fault Zone Act, discussed in Chapter V.

Though the shaking above a buried fault can be severe, the size of the region of strong shaking is not typically as large as that from a large magnitude earthquake on a fault like the San Andreas. Regardless of the size of the affected areas, the tectonic compression causing thrust fault earthquakes is continuing, and many such faults are located under highly urbanized areas. Buried faults pose a serious hazard to the citizens of California.

Buried and other obscure faults are not a new threat. They have been considered in the design of certain critical facilities for over two decades. However, building codes do not explicitly address specific types of faults or near-source effects. Similarly, buried faults, near-source effects, and local geologic conditions have not been properly considered in hazard-mapping efforts, land use planning, or environmental reviews.

The Commission believes buried faults, near-source effects, and local geologic conditions need to be recognized as a significant part of the seismic hazard in California. The results of studies on these features should be incorporated in regional seismic hazard analyses and considered in the design of important buildings and structures. For example, the SHMA program and the Building Seismic Safety Council's effort to develop seismic shaking hazard maps for the 1997 National Earthquake Hazard Reduction Program's *Recommended Provisions for the Development of Seismic*

Regulation for New Buildings should incorporate provisions for sites near buried faults as well as near-source effects and local geologic conditions.

Recommendations

The Commission recommends that:

- CDMG identify areas where active buried faults exist that may cause serious damage and loss of life. By December 31, 1995, CDMG should conduct short-term, focused studies including:
  - Mapping of geologic and geomorphic indicators of buried faults (for example, pressure ridges and sag ponds).
  - Compiling subsurface geologic, geophysical, seismological, and geodetic data and analyzing these data and knowledge of active tectonics.
- CDMG form an advisory working group of knowledgeable earth scientists to develop cost-effective methods for assessing the locations as well as the significance of buried faults, the potential for earthquakes of various magnitudes, and motion parameters.

Site Conditions

Local site conditions, regional geologic conditions, and geomorphic features play an important role in the frequency and intensity of earthquake shaking and the potential for liquefaction, landslides, and subsidence. A significant part of the SHMA program is directed at mapping urban areas of the state that are subject to earthquake-induced landslides, liquefaction, or amplified shaking due to local conditions. The Commission believes it is important to complete this work quickly and competently, using the best technical resources available.

The amplification of strong ground motion because of geologic conditions is of major concern. In the Northridge earthquake, a section of Los Angeles' busiest freeway collapsed. The Santa Monica Freeway was built over an area aptly named "La Cienega"—Spanish for "the swamp." The motions that brought this section of the freeway down were, in all probability, amplified by the underlying soft soils and local geologic conditions.

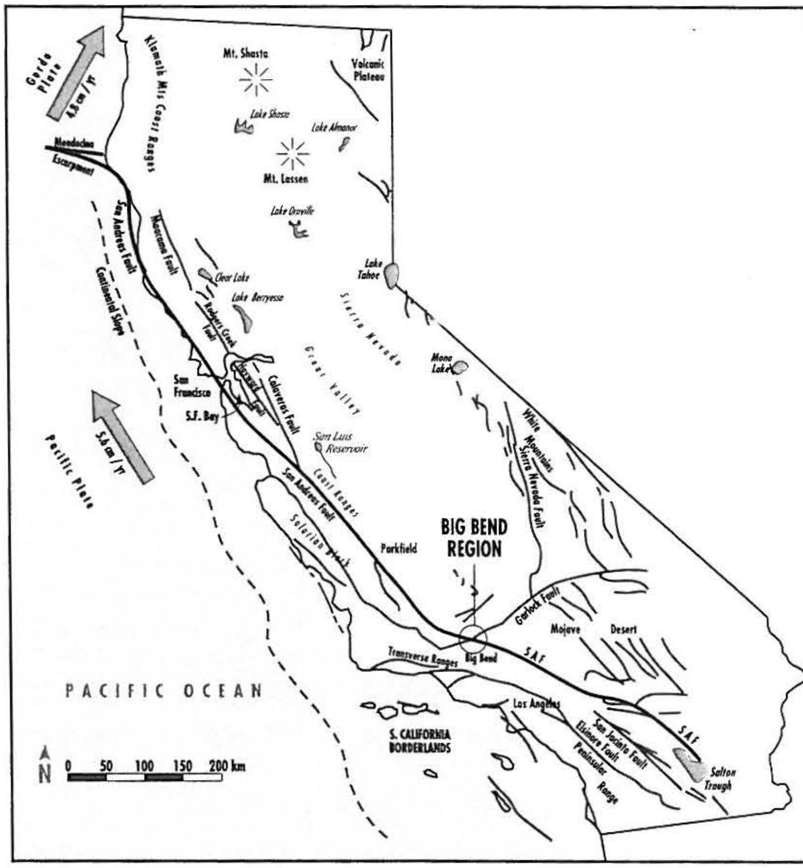
Decision makers and regulators must be aware of local geologic conditions and take them into account when planning, zoning, designing, and constructing buildings and other structures.

Recommendation

The Commission recommends that:

- Building codes, standards for design and retrofit of lifelines, and land use planning incorporate measures to identify and set priorities to reflect adverse seismic effects of local site conditions.

Figure 12. Map showing "Big Bend" area of the San Andreas fault.



Modified after Ellsworth

Ground Deformation

A zone of ground deformation near the Northridge earthquake's epicenter was marked by linear patterns of failed gas and water lines; compression and extension of streets, curbs, and sidewalks; concentrations of high building dam-

Buried faults pose a serious hazard to the citizens of California.

age; and a pattern of northwest- and northeast-trending breaks in the ground's surface. Surface displacement was generally an inch or two of right-lateral slip and up to four inches of left-lateral slip. There was about 12 inches of both compression and extension deformation. This pattern of deformation may be of tectonic origin or the result of locally severe near-surface shaking related to the buried fault rupture propagating and concentrating more intense seismic energy in localized areas.

In the Granada Hills District of the San Fernando Valley, USGS reported evidence of permanent ground deformation consisting of pavement cracks, depressions in the ground, pavement humps and tented sidewalks, and left-lateral offset of curbs along an east-west zone approximately three miles long and several hundred yards wide (USGS, 1994a; USGS, 1994b). This zone may be coincident with the mapped trace of the Mission Hills fault (Angell et al., 1994). USGS commented that the deformation might be related to arching and extension above a concealed fault or to lurching and differential compaction from strong shaking.

There are significant questions regarding whether the mechanisms causing the zones of permanent deformation were tectonic or nontectonic and what geologic tools are available for identifying these zones in advance of future earthquakes. If patterns of ground deformation are nontectonic, they may be explained as being related to zones of strong shaking that caused yielding of the soils at depth, leading to cracking and deformation of the surface materials. But if these zones are related to subtle faulting, they may add slightly to the area's seismic hazard (Barnhart and Slosson, 1973).

Zones of ground deformation detected near the epicenter may be related to tectonic folds and faults or to strong shaking. This deformation may signify a zone of subtle faulting that is the surface expression of deeper-seated strike-slip faults or perhaps the lateral extension of such faults. The boundaries of the zones should be identified and the amount of surface displacement and ground deformation and the damage they might cause in future earthquakes should be estimated. Urbanized areas obscure the identification of subtle fault zones, but patterns of deformation (cracked streets and sidewalks), geomorphic features (pressure ridges, compression-extension strain patterns), and earthquake damage patterns may be interpreted to infer their presence.

Recommendations

The Commission recommends that:

- CDMG, as part of its SHMA program, evaluate the level of hazard presented by possible subtle faults, buried faults, and incipient faulting in alluvial basins in active tectonic environments and zones of compression.

  Other types of tectonic deformation noted above are recommended as priority long-term research projects.

- CDMG, as part of its SHMA program, and under the policies of the State Mining and Geology Board, expand the categories of seismic hazards to create a new hazard zone to address ground deformation and amplified shaking associated with folding and faulting.

Natural Slopes, Unconsolidated Sediments, and Engineered Fills

Landslides, soil liquefaction, and ground settlement occurred in many areas during the Northridge earthquake. Many of these ground failures occurred in urban areas and contributed significantly to property damage. An area susceptible to landslides, liquefaction, and settlement can usually be recognized by the existence of factors such as geomorphic features, folding of youthful geologic units, and groundwater levels.

Landslides

The Northridge earthquake triggered landslides and rockfalls over an area of about 3,600 square miles, causing many road closures and significant damage to homes and utilities:

- Landslides damaged hundreds of homes on the crest and north flank of the Santa Monica Mountains between Cahuenga Pass and Sepulveda Pass.
- The Porter Ranch portion of the Santa Susana Mountains also experienced landslide damage.
- In the coastal bluffs of the Pacific Palisades in Santa Monica, several homes were destroyed or condemned because of landslides.
- A section of the northbound lanes of the Pacific Coast Highway remained closed for at least four days following the earthquake because of landslides.
- Many road closures were reported throughout the San Gabriel and Santa Susana Mountains.
- At least two electric transmission towers collapsed as a direct result of rock slides.
- A major aboveground natural-gas pipeline was damaged (EERI, 1994b).

The number of landslides resulting from this earthquake was consistent with other earthquakes of this magnitude, and the types of slides (rockfalls and deep-seated slumps) were comparable to those observed previously in similar geologic units and slope conditions. Geologic maps of the northern San Fernando region indicate geologic units containing weak materials and old landslides that might be reactivated, so areas susceptible to landsliding because of earthquake shaking can be readily identified and mapped.

Liquefaction

Soil liquefaction and related lateral spreading associated with the Northridge earthquake occurred in many areas but made a relatively small contribution to structural damage because they occurred in areas away from most buildings. Along the coast, liquefaction-induced sand boils were observed as far north as Calleguas Bridge, near the Mugu Lagoon, and as far south as Redondo Beach-Kings Harbor and the Port of Los Angeles. Inland, liquefaction-induced sand boils were observed near the epicenter and as far north as the Santa Clara River valley. This type of ground failure may have contributed to reported service-line breakages and to roadway, curb, and structural damage. For example, liquefaction-induced lateral spreads associated with horizontal displacements of about three inches and settlements of a few inches contributed to significant structural damage to a shopping center in Woodland Hills and a commercial building in Studio City.

Engineered Fill

Ground settlement without evidence of lateral spreading was observed at a number of sites following the Northridge earthquake. This settlement, which damaged many structures and service lines, may have been caused by soil liquefaction at depth, seismic consolidation, or induced compaction of engineered-fill materials or natural soil deposits.

Ground settlement, which damaged many structures and service lines, may have been caused by induced compaction of engineered-fill materials.

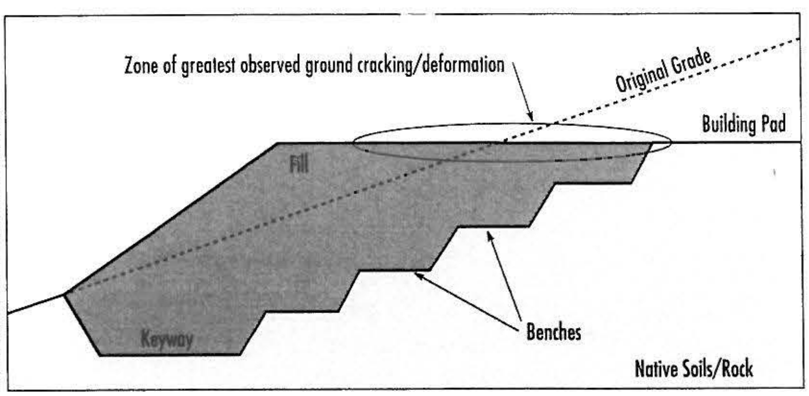
Structures located on engineered fills are common throughout California. A study by the Earthquake Engineering Research Center concluded (see Figure 13):

> The poor performance of modern wedge fills located on the faces of slopes during the Northridge earthquake is of considerable importance to the geotechnical engineering profession. The standards of practice in the construction of these fills have evolved considerably since World War II to address troublesome static failure, or long-term static distress, mechanisms such as landsliding and settlement. Modern design and construction practices in this region typically include drainage provisions and construction under the direction of licensed civil engineers. While these practices have generally improved the static performance of fills, the potential for poor dynamic performance has not been widely recognized. With the data collected following the Northridge earthquake, it appears that further evolution of the standards of practice may be necessary for the proper design and construction of wedge fills in seismically active areas (EERC, 1994c).

The Metropolitan Water District's Jensen Filtration Plant, located about six miles from the epicenter, was taken out of service after the earthquake as a result of the rupture of the influent conduit, an 85-inch-diameter steel pipe. The rupture occurred near the eastern boundary of the site in engineered fill placed in the late 1960s. Cracks ran generally parallel to the slope along virtually the entire eastern boundary of the site; most were less than an inch wide, but there were some up to three inches wide with six inches of offset. Offsets of up to six inches were also observed around structures located in the eastern portion of the site. Cracking continued to develop during aftershocks.

Many modern fills designed to current code were permanently deformed by the earthquake, causing severe damage to structures. Cracking of residential fills and related damage were observed at many sites in strongly shaken regions such as Valencia and Santa Clarita. Cracking was particularly evident in cut-and-fill transitions and where shallow fill was compacted on overcut areas. Little damage was observed where a deeper fill of uniform depth was placed on cut benches or where alluvial soils were removed prior to placement of fill.

Figure 13. Schematic of typical "wedge" fill geometry.



Earthquake Engineering Research Center, 1994

When fills are properly designed and constructed, they will resist earthquakes. Chapter 70 of the Uniform Building Code sets forth minimum rules and regulations to control excavation, grading, and earthwork construction. However, enforcement of good design and construction practices is not always consistent. Improved quality control measures will improve the performance of fills.

Recommendations

The Commission recommends that:

- State and local jurisdictions enforce provisions in Appendix Chapter 70 of the 1991 Uniform Building Code (Appendix Chapter 33 of the 1994 Uniform Building Code) as a minimum code for excavations and fills.
- Fills intended to support structures be designed and inspected by qualified professionals to ensure conformance with the current code and engineering practice; qualified technicians with proper certification inspect construction; the engineer of record certify that fill placement is in conformance with plan design; and when the fill is to be placed on bedrock, an engineering geologist inspect the geologic conditions before placement.
- Seismically induced deformations caused by seismic compaction of fill and underlying alluvium be considered in the design and construction of residential fills.

Continuing Education of Geosciences Professionals

Reduction of risk from seismically induced landslides, liquefaction, the failure of engineered fills, and other geologic hazards depends on the quality and skill of the professionals who must be capable of identifying and mitigating these hazards. After every earthquake, new knowledge is gained on how and why these hazards occur, their effects on structures, and the most cost-effective methods to mitigate damage. Professionals must be aware of advances in the state-of-the-art within their fields of expertise to remain competent. Continuing education is one way professionals can keep up with not only scientific advances but changes in law, land use planning, technology transfer, and other related subject areas. A strong continuing education program for practicing professionals would lead to improved professional practice and help reduce earthquake losses.

Recommendation

The Commission recommends that:

- The Department of Consumer Affairs' licensing renewal process require continuing education for geologists, geophysicists, engineering geologists, and geotechnical engineers.
- Licensing boards for geologists, engineers, and architects be required to hold hearings after each earthquake in the affected area to learn how their requirements can be improved.