CHAPTER IV

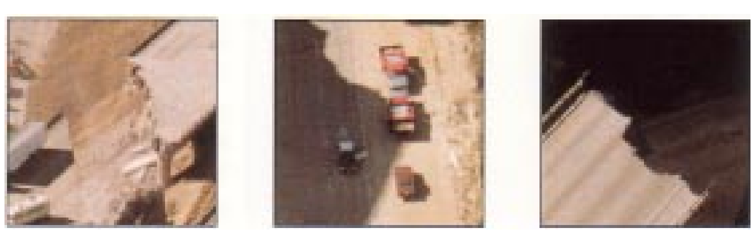
Achieving Seismic Safety in Lifelines

Lifeline network systems—water supply, electric power, transportation, natural gas, and communications—provide critical services to all of us. When these systems are damaged in a disaster, the safety and livelihood of people in affected communities are imperiled directly.

The Northridge earthquake caused failures in all types of lifelines. A number of freeway bridges collapsed, crippling transportation for months after the event. Broken pipelines and equipment deprived utility customers of gas for heating and cooking; water supplies were cut or contaminated. Many emergency power systems were inadequate. Difficulties with communication systems hampered emergency response immediately after the event—when they were most needed.

Lifeline systems are, in many ways, more vulnerable than buildings or other structures. Because a system is typically spread over a large area, it is susceptible to a wide range of earthquake hazards. Different parts of the system can experience very different levels of shaking or ground deformation in the same event. The performance of a system is tied to the weakest of its hundreds or thousands of components. In addition, because many lifelines are buried, damage is difficult to detect and repair, particularly when several components of the same system are damaged.

Seib, Los Angeles Times



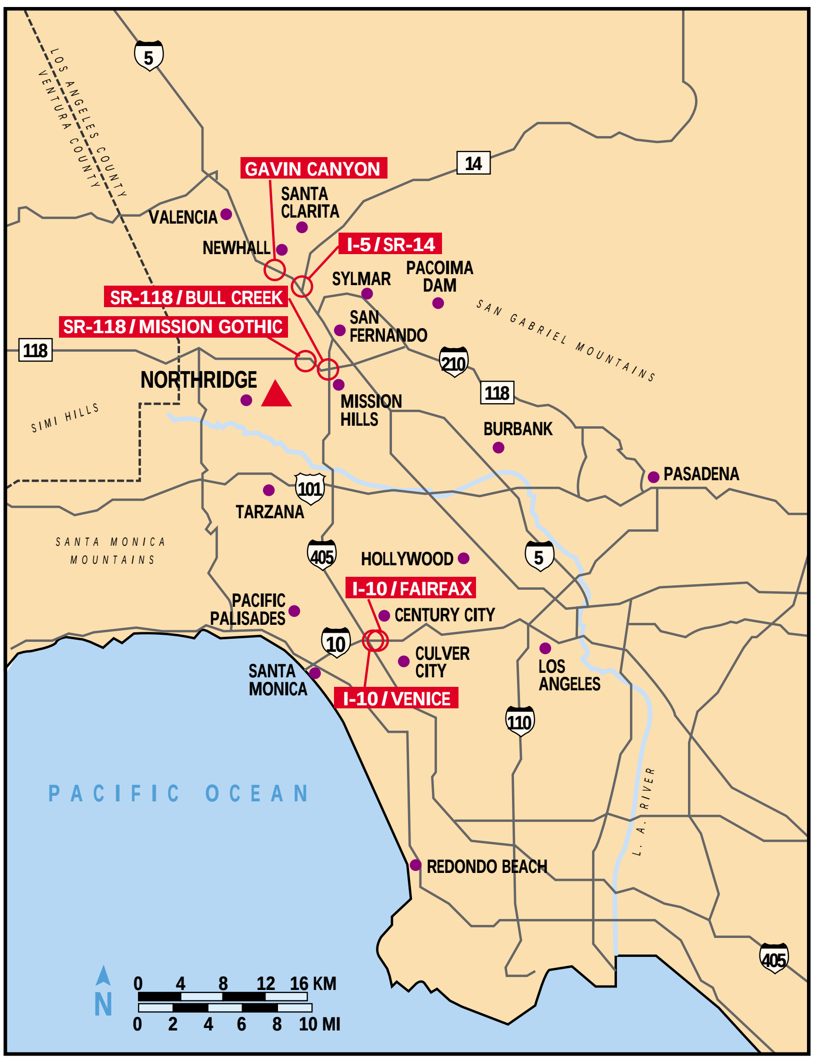
Roadbed sections of part of Interstate 5 fell off their supports.

The organizations that own and operate lifelines cannot ensure absolute reliability and do not accept responsibility for guaranteeing service during emergencies. Therefore, those who need these services during emergencies must anticipate their temporary loss and take appropriate precautions, including working with utilities to ensure better performance. The Commission believes that state and local agencies and the private sector can take a number of additional actions to improve reliability and reduce the vulnerability of lifelines to earthquakes.

Freeway Bridges

The Northridge earthquake caused the collapse, or partial collapse, of seven freeway bridges; over 250 others were damaged. One life was lost as a result of these failures, and traffic was extensively disrupted for months. The repairs, which were completed very rapidly considering the extent of the damages, cost over $350 million. Shaking as intense as that recorded near the epicenter of the Northridge earthquake will always cause some damage to large freeway structures, but they should not collapse.

Figure 68. Location of collapsed overpasses.



The Caltrans Seismic Advisory Board's report *The Continuing Challenge* sets forth a number of findings and recommendations based on the board's review of the effects of the Northridge earthquake. The Commission concurs with the recommendations of that report.

Performance of Bridges

Caltrans summarized damage to bridge structures from the Northridge earthquake (Housner, 1994):

Collapsed or partially collapsed	7
Major damage	39
Other damage requiring repair	194
Hinges requiring repair or replacement	46

North and South Connector Overcrossings

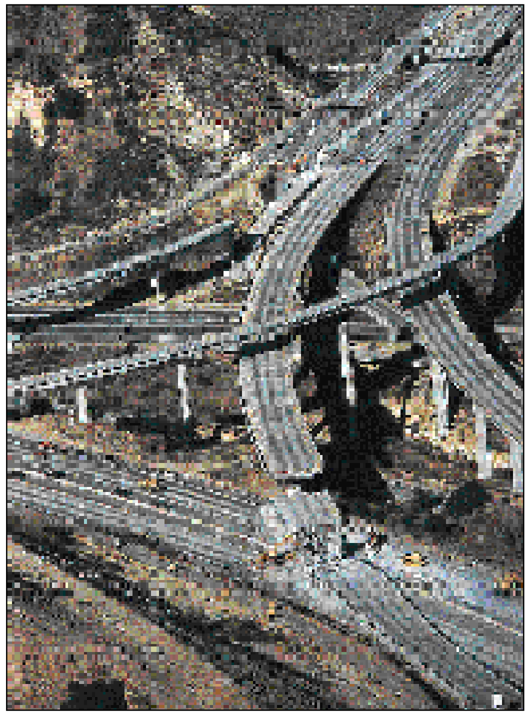
The interchange of State Route 14 and Interstate 5 (see Figure 68 for locations) was badly damaged in the 1971 San Fernando earthquake, but the two structures that collapsed in the Northridge earthquake, the North and South Connector overcrossings, were designed before 1971. At that time it was believed that improved hinge restrainers would be adequate to prevent collapse. Though they contain some pre-1971 design details, hinge restrainers were added to both bridges. During the Northridge earthquake, brittle shear failures in short stiff columns next to the abutments initiated the collapse of both bridges as shown in Figure 69. After the columns failed in shear and were crushed by the weight of the decks, the decks were pulled from their supporting abutments. As the decks fell, they failed by bending at the adjacent piers. These failures demonstrated that retrofitting such structures with hinge restrainers alone may not be adequate. Retrofitting the single-column piers to prevent brittle shear, moment, and foundation failures may also be needed. Caltrans has incorporated this observation in the design of both retrofitted and new projects.

Gavin Canyon, Fairfax & Washington, and La Cienega & Venice Undercrossings

Although these three bridges survived the San Fernando earthquake, they had the same deficiencies that allowed bridges to collapse in 1971: short seat widths at abutments and expansion joints and a lack of steel reinforcing ties in the columns. The Gavin Canyon Undercrossing also had an irregular shape that allowed a twisting movement as it shook and short seat widths at midspan expansion joints that made it possible for one end of each of two deck sections to fall off their supports, leading to the collapse shown in Figure 70. The joint restrainers installed in 1974 were not strong enough to prevent the deck sections from falling; had they been stronger, shear failures in the shorter columns would likely have occurred. Shear failure in columns demonstrates that the use of reinforcing steel ties spaced 12 inches apart may be inadequate to confine the core concrete within the main reinforcing steel. Caltrans has integrated this observation in the retrofit program and in the design of new structures.

Mission & Gothic and Bull Creek Canyon Channel Undercrossings

These two bridges on State Route 118 were designed and constructed after the 1971 San Fernando earthquake but before 1980, when Caltrans introduced major design changes. They collapsed because the columns failed in shear. In both cases, the effective lengths of the columns had been shortened; in other words, the columns responded stiffly, as if they were shorter than their actual length. The wide, moderately reinforced column flares of the Mission & Gothic Undercrossing and the channel wall at the Bull Creek Canyon Channel Undercrossing caused these shortening effects, which produced greater shear stresses than had been calculated in design. Since these two bridges had been evaluated by Caltrans as not requiring retrofit, their failures indicate a need to reconsider the criteria for selecting structures for retrofit, which could have prevented these failures.



Tobinn

Figure 69. Two overpass collapses at the I-5/SR-14 interchange were started by failures in short, stiff columns.

Steel-Girder Bridges

Although no steel-girder bridges collapsed during the Northridge earthquake, four bridges of this type, in a three-mile segment of Interstate 5 near the City of Newhall, sustained significant structural damage (Astaneh-Asl et al., 1994). These bridges are the Pico-Lyons Overcrossing, the Santa Clara River Bridge, the Valencia Boulevard Overcrossing, and the Old Road Bridge over the Santa Clara River.

Seible

Figure 70. Deck sections fell off their seats at the Gavin Canyon Undercrossing on I-5.

Seismic Design Specifications

Before the San Fernando earthquake, no California bridge had collapsed because of earthquake shaking. However, the damage to bridge structures during that earthquake made it very clear that many of the approximately 18,000 state, county, and city bridges had deficiencies that made them hazardous and that the 1963 seismic provisions were outdated. Caltrans made major changes to the seismic provisions of its Design Specifications, doubling the 1963 code force for all bridges supported on spread footings and increasing it by a factor of 2.5 for those on pile foundations. Design changes were also implemented to improve:

Shaking as intense as that in the Northridge earthquake will always damage freeways, but they should not collapse.

- *Expansion joints*—increased support seat width and separation restraint at expansion joints to prevent decks from falling.
- *Columns*—increased steel reinforcing tie and size and reduced tie spacing to prevent shear and flexure failures in columns.
- *Column caps*—increased steel reinforcing bars to tie column caps to box-girder decks.
- *Column foundations*—increased anchorage of steel reinforcement in the columns to their foundations.
- *Abutments and wing walls*—increased the strength of abutments and wing walls to resist backfill earth pressures and deck loadings.

In 1975 improvements were made to expansion joint restrainer designs, and in 1977 the Design Specifications incorporated elastic spectra rather than prereduced spectra. Load reduction factors were specified for individual structural components, depending on the toughness of the corresponding components. About 1980 Caltrans introduced the concepts of plastic hinging and shears into the design process. All provisions in the Design Specifications are now being reviewed by the Applied Technology Council (ATC), and Caltrans has already adopted significant changes to improve the seismic design criteria. Recent test results indicate that most of the new design details are effective, although further substantiation is needed.

The Commission believes Caltrans has addressed design standards to incorporate the lessons of past earthquakes and that the current ATC review will result in additional improvements.

Current Performance Criteria

Caltrans has adopted criteria to describe how bridges should perform in earthquakes. Bridges are classified into two categories: *important* bridges and *minimum-performance* bridges. The bridges in each category are expected to satisfy performance requirements when subjected to two levels of earthquake shaking: a *functional-evaluation level* that has a 40 percent probability of being exceeded during the usual lifetime of the bridge, and a *safety-evaluation level* that is based on either the maximum expected earthquake or an earthquake having a return period in the range of 1,000 to 2,000 years. The functional-level motion is less intense; the safety-level motion is less frequent.

A bridge is classified as *important* if one of three conditions is met:

1. The bridge is required to provide secondary life safety, such as access to an emergency facility.
2. Loss of use of the bridge after an earthquake would create a major economic impact.
3. The bridge is designated as critical by a local emergency plan.

The performance requirements for *important* bridges are:

- The bridge may have minimal damage when subjected to functional-level shaking, but it must be able to be restored to service immediately.
- The bridge's damage must be repairable when it is subjected to the safety-level shaking, and it must be able to be restored to service immediately.

The performance requirements for *minimum-performance* bridges—all bridges not designated as *important*—are:

- When the bridge is subjected to the functional-level shaking, the damage must be repairable, and it must be able to be restored to service immediately.
- The risk of collapse is minimal when the bridge is subjected to the safety-level shaking, but the bridge may be closed for repairs, with only limited access, for a few days after the earthquake; full service may not be restored for months.

The Commission agrees that these performance levels and earthquake criteria are appropriate.

Retrofit Programs

Although the first-generation hinge restrainers installed at expansion joints following the 1971 San Fernando earthquake were deficient, those of current design have been effective in preventing the unseating of girders at their hinge seats. However, effective hinge restrainers often permit higher deck-level seismic forces, causing shear and flexural failures in the piers and failures in their foundations. Thus, piers and foundations may have to be strengthened for hinge restrainers to be effective.

The Northridge earthquake tested the column retrofit effort. A 1,037-foot-long structure at the junction of Interstate 10 and Interstate 405 is supported by single-column piers that were retrofitted with steel jackets in 1991. It is located only about four miles west of the Interstate 10 freeway structures that collapsed. A peak acceleration of 1.83g was recorded at the deck level, but the bridge did not suffer significant damage.

In all, 24 retrofitted bridges in the region experienced peak ground accelerations greater than 0.5g, and 60 retrofitted bridges in the region experienced peak ground accelerations greater than 0.25g. These bridges performed satisfactorily. The Commission believes that although Caltrans' current program to retrofit single-column-pier bridges was effective in the Northridge earthquake, future earthquakes with similar intensities but much longer durations than the nine-second Northridge event—perhaps up to 60 seconds—will provide much more severe conditions to test the effectiveness of the program.

It is too early to judge the effectiveness of Caltrans' program to retrofit multicolumn-pier bridges. The Commission believes it is important that Caltrans continue to subject these projects to peer review on a case-by-case basis and make full use of laboratory test results.

It is too early to judge the effectiveness of Caltrans' program to retrofit multicolumn bridges.

Priorities

The Commission believes Caltrans should reassess its procedure for setting retrofit priorities and revise it to reflect all key factors affecting vulnerability (such as flared columns and variable soil conditions) and the importance of the structure, or sequence of structures, to the region served. Caltrans had scheduled the retrofit for the North and South Connector overcrossings and the Gavin Canyon, Fairfax & Washington, and La Cienega & Venice undercrossings before the Northridge earthquake, but the work had not yet been done when the event occurred. These failures caused significant disruption to the entire region. In hindsight, the retrofit of these structures should have been a higher priority, reflecting their vulnerability and importance.

Pace of Caltrans Retrofit Programs

The Commission affirms Caltrans' goal to complete the retrofit of state highway structures by the end of 1997. The hinge-restrainer retrofit program for state and local bridges has been completed; the program for single-column-pier bridges is nearly complete; and the initial program for 1,039 multicolumn-pier bridges, now known as Phase I, will be completed by the end of 1995. Phase II, consisting of state-owned bridges evaluated after the Northridge earthquake, is underway with a tentative completion date of 1997. The toll bridge retrofit program has started. Retrofit of the San Francisco-Oakland Bay Bridge is to be completed by December 1997, but the completion goal for six other toll bridges has not been set. The Commission believes that toll bridges should be accorded the highest priority because of their importance to the regions they serve, the lack of alternative routes, and their vulnerability. Caltrans concurs with this position; the department is pursuing an abbreviated environmental review process for certain toll bridge retrofit projects and is actively investigating ways to accelerate the toll bridge retrofit program. The Commission supports these efforts but believes Caltrans must be given the necessary resources and be held accountable for meeting these deadlines.

Recommendation

The Commission recommends that:

- The toll bridge retrofit program be accelerated because of the critical importance of those structures and that Caltrans' efforts to do so be supported.

Steel or Concrete Girders

Engineers continue to debate whether steel girders are preferable to prestressed concrete-box girders. Commissioner Chang submitted a paper strongly urging the use of steel girders for the repair of damaged bridges and construction of bridges in seismically sensitive areas (SSC, 1994a). Many factors contributed to the damage of bridges, including inadequate seat widths, skew, curved alignments, local soil conditions, and outdated design. The Commission encourages Caltrans to consider all possible performance factors in its retrofitting, repair, and construction of bridges.

Recommendation

The Commission recommends that:

- Caltrans perform seismic performance probabilistic risk assessments of both concrete and steel designs as part of its continuing program of evaluation and improving the seismic safety of bridges.

New Technologies

New technologies and systems such as seismic isolation, energy dissipation, and damping systems can be used on bridges to reduce earthquake forces and motions or to absorb earthquake energy. Use of these systems should be considered and studies completed to evaluate site characteristics affecting the nature of anticipated ground motion and the structural characteristics of each bridge.

Recommendation

The Commission recommends that:

- Caltrans study different types of seismic isolation and damping systems to protect bridge girders and columns from earthquake damage and take into consideration the effects of local soil conditions and near-source ground motion.

Use of Seismic (Base) Isolation

Seismic isolation technology can be used to reduce seismically induced forces in a bridge structure if the isolation system:

- Has suitable force-displacement and damping properties that will be maintained over the life of the structure.
- Will remain stable under the combined static and seismic loadings during the shaking of a safety-evaluation seismic event.
- Can safely tolerate the associated large shear displacements produced in the isolation system.

Since the use of isolation increases the fundamental period of the overall system, peak free-field ground acceleration is no longer critical to the seismic response. However, free-field velocity becomes more critical and, with sufficient increase in period, peak free-field displacement can become the most critical parameter. Because of the sensitivity of seismic-isolated bridges to the longer periods of free-field motion, such isolation should be avoided at very soft sites such as those in the San Francisco area. Additional studies are needed to evaluate the effects of near-source motions on seismic-isolated bridges.

Recommendation

The Commission recommends that:

- Caltrans undertake a study of the effects of near-source motion on seismic-isolated bridges before building or retrofitting any seismic-isolated bridges.

Strong-Motion Instrumentation

Since 1971 Caltrans has been placing strong-motion instruments on bridges as part of the state's Strong Motion Instrumentation Program (SMIP), conducted by the California Division of Mines and Geology. Though none of the seven bridges that collapsed or the 39 that sustained heavy damage during the Northridge earthquake were instrumented, records were obtained on six bridges located within a 115-mile radius of the epicenter and free-field surface motions were recorded by 132 instruments located within a 100-mile radius. If the state-of-the-art of predicting the performance of bridges during earthquakes is to be advanced, it is essential that more bridges be fully instrumented, particularly the toll bridges and other large bridges with complex shapes.

As of June 1994, over 300 strong-motion sensors have been placed on 28 state-highway bridges, including five toll bridges. Additional sensors are now being added to these and other bridges as rapidly as possible. The Phase II three-year instrumentation program is budgeted at $1 million per year (1994-1996 fiscal years). It will place 23-sensor arrays at 12 bridge sites, nine-sensor arrays at 18 sites, additional free-field instruments at previously instrumented bridges, and 42 sensors underground at seven locations. By December 1994, the Golden Gate Bridge and Highway Transportation District will install 79 strong-motion sensors at the Golden Gate Bridge: 70 on the bridge, six underground near the bridge, and three sensors on the ground surface near the bridge. Additional instrumentation is expected to be installed following completion of the retrofit program. The Commission believes that installing and maintaining strong-motion instrumentation is being carried out properly and that the effort must be continued beyond the end of Phase II in 1996.

To ensure satisfactory performance of new bridges during functional-level and safety-level seismic events, more research is needed, particularly experimental. The results of this research will allow the development of more realistic analytical models to assess the seismic performance of complex bridge structures. It is important that the models and associated performance evaluations be made for complete systems, including the interaction between the type of soil and the type of structure. In doing so, realistic free-field ground motions for these events need to be considered on a site-specific basis. Caltrans is encouraged to monitor prestress losses in bridge girders under static and earthquake loading conditions and to measure internal forces in highly redundant bridges, as appropriate, to understand the distribution of effective seismic loads to individual structural members.

To ensure the satisfactory performance of new bridges, more research is needed.

Recommendations

The Commission recommends that:

- The bridge instrumentation program be expanded to install strong-motion instruments, including dynamic strain gauges and load cells on selected strategic bridges.
- Caltrans continue to tie seismic research funding to its capital outlay program rather than the Transportation Planning and Research Act.

Multimodal Transportation Systems

Earthquake damage to major elevated highway structures threatens public safety and causes long-term disruption to the commerce and functioning of the affected region. Alternative transportation systems such as rail, light rail, buses, and ferries provide critical transportation options during the emergency response and recovery periods. The presence of these systems and emergency transportation plans provide emergency managers with important resources to manage the response and recovery effort. Earthquake risk-reduction and risk-management benefits of multimodal transportation systems should be considered along with the economic and environmental reasons for implementing the state's transportation policies emphasizing multimodal transportation.

Recommendation

The Commission recommends that:

- Multimodal transportation and emergency rerouting issues be considered by Caltrans in all seismic design, planning, and policy decisions.

Railroads

Railroads support California's economy by providing year-round transportation for the public and commerce. Since they might also be called on to play a major role in relief efforts after a major earthquake, their ability to remain operable or at the very least to recover rapidly after a major earthquake is important.

In the Northridge earthquake, a westbound freight train of 29 cars derailed on the Southern Pacific's Coast Line in Northridge. The derailment caused the release of several thousand gallons of sulfuric acid from a tank car and also spilled diesel fuel from a locomotive. The damage was over $600,000, not counting cleanup or damage to freight. No injuries were reported as a result of the spills.

The Public Utilities Commission's (PUC) review of this incident revealed that Southern Pacific had earthquake-response procedures in place, but in this instance the moving train was too close to the epicenter to allow enough warning time. Under more typical situations, when trains are several miles from the epicenter, earthquake warning systems should prevent similar derailments and spills. The PUC's review of railroad earthquake-response programs statewide found that many railroads in California do not have adequate response and risk-reduction programs.

Recommendation

The Commission recommends that:

- The PUC review the earthquake response and risk-reduction programs of California's railroads and adopt regulations, including deadlines, for such programs by December 31, 1995.

  The response program shall include the use of an earthquake-notification system and criteria for operational response (for example, stopping, lowered speeds, inspections). The risk-mitigation program shall include mapping seismic hazards along rail line rights-of-way, evaluating the vulnerability of structures (for example, bridges and tunnels), and retrofitting those subject to failure.

Natural-Gas Supply

The Northridge earthquake caused several significant fires when natural-gas pipelines ruptured and mobile homes and other structures moved. Although these fires produced relatively few injuries and no casualties, the Commission believes the number of fires started by natural-gas ignition during this earthquake should have been lower. The danger from fire following earthquakes is extreme. Had weather conditions been less favorable or firefighters delayed, fires could have caused deaths and billions of dollars of additional losses.

Transmission and Distribution Lines

All reasonable efforts to reduce the potential sources of fire must be considered. Although the gas utilities have significantly upgraded their systems to improve earthquake performance, the long-term improvements have not been completed, and the remaining vulnerabilities await either repair or the next earthquake.

According to Southern California Gas Company (SoCalGas) reports, the Northridge earthquake caused the following pipe failures or leaks:

Steel transmission pipelines	35
Steel distribution pipelines	154
Plastic distribution pipelines	27
Leaks on meter sets	6,461
Leaks on customer facilities	15,021

The Northridge earthquake illustrated once again that pipelines are more likely to rupture in areas of ground deformation and displacement, and pipelines carrying hazardous materials should be routed through areas where significant disruption is less likely whenever possible.

The Northridge earthquake also illustrated, as have previous earthquakes, that modern pipe of steel and other materials performs well even when subjected to intense shaking and moderate levels of ground displacement. Most of the problems in transmission pipe appear to have been related to weld failures in oxyacetylene-welded steel pipe installed before 1932, when welding procedures were inferior to those currently used (O'Rourke and Palmer, 1994). The natural-gas fire on Balboa Boulevard, Figure 71, was from an older pipeline in an area where significant ground deformation occurred; the resulting fire engulfed five nearby homes.

There are a large number of older, vulnerable transmission and distribution pipelines in highly urbanized areas throughout the state. California gas utility companies have programs to replace or strengthen these older pipelines according to priorities that consider seismic vulnerability. The Commission believes that a review of these programs is needed to incorporate new information regarding active faults and the resulting ground motion and deformation expected as well as new mitigation approaches. Older transmission and distribution lines in densely populated neighborhoods, near critical facilities, or near special occupancies such as schools and hospitals should receive the highest priorities for replacement.

According to SoCalGas statistics, as of 1993 there were 3,803 miles of steel transmission pipelines, 26,809 miles of steel distribution mains, and 14,935 miles of medium-density polyethylene distribution pipe. With so many miles of pipeline, breaks during future earthquakes must be anticipated. To minimize the threat of fire, measures must be developed to detect and respond to failures rapidly.

EERI

Figure 71. Fire and flood produced calamity at Balboa Boulevard's ruptured gas and water mains.

Recommendations

The Commission recommends that:

- California utilities accelerate their upgrade and replacement programs to improve the performance of seismically vulnerable gas transmission and distribution lines. Priority should be given to those pipelines in the vicinity of essential facilities, special occupancies, and dense population, and in populated areas with potential ground deformation.
- Emergency response procedures be improved and valves installed in areas where ruptures are more likely so that breaks can be rapidly detected and lines depressurized to reduce the potential for explosions or gas-fed fires.
- The PUC issue recommendations and regulations to ensure improvement in the safety and seismic performance of gas transmission and distribution lines, including implementation schedules and priorities and the use of automatic shut-off valves, as appropriate, by June 30, 1996.

Mobile Home Gas Service

Although the earthquake caused only 54 fires in other types of structures, gas-fed fires destroyed 172 mobile homes. Most of the gas leaks were caused when mobile homes collapsed onto their meter sets or sheared gas connections as they fell or by interior lines rupturing when water heaters fell. In most cases the gas could not be shut off and continued to feed the fires. Because mobile home parks are particularly vulnerable to fire, the gas service must be easily and rapidly controllable in earthquakes.

The threat of fire from natural-gas leaks following earthquakes is a substantial risk.

Although new mobile home installations are required to meet seismic resistance standards, existing mobile homes are not. Mobile home owners need reliable information on seismic vulnerability and the steps they can take to mitigate their risk. Reducing mobile home seismic vulnerability is also discussed in Chapter III.

Recommendations

The Commission recommends that:

- Automatic gas shut-off valves be mandatory at the service entry point at all mobile home parks in California.
- The PUC conduct hearings and workshops to determine the best method for providing shut-off valves for mobile home parks and appropriate performance standards for such valves and to prepare draft legislation mandating shut-off valves for mobile home parks by September 1, 1995.
- The Department of Housing and Community Development develop and institute an education program for mobile home owners and park managers to encourage and guide installation of seismic bracing for mobile homes, proper bracing for water heaters in mobile homes, and measures to reduce the risk of gas-fed fires in mobile homes and mobile home parks.

Residential Gas Service

There have been relatively few serious fires caused by interior gas leaks in past California earthquakes. Current mitigation techniques for such leaks and fires include anchoring appliances such as water heaters, using flexible connections, and installing fire alarms and sprinkler systems. Although recent building codes have mandated some of these measures, the majority of existing structures and their occupants are not as well protected.

Whether mandatory or voluntary, the use of earthquake-activated gas shut-off valves involves a number of issues including long-term reliability and maintenance, resetting, and cost. Utility customers who have installed them as added safety devices should still anchor appliances and fix structural weaknesses in their buildings.

The Commission believes that the threat of fire from natural-gas leaks following earthquakes is a substantial risk to entire communities. The PUC, gas utilities, and the State Fire Marshal should recommend a course of action to reduce this risk.

Recommendations

The Commission recommends that:

- The PUC sponsor a task force of representatives from the California Utilities Emergency Association (a division of the Office of Emergency Services), utilities, construction, manufacturing, emergency and fire services, and local governments to evaluate the damage data from the Northridge earthquake and other recent earthquakes, define the risks of fire and potential for damage and injury, and review alternative mitigation methods, including the use of earthquake-activated shut-off valves.
- The Division of the State Architect (DSA) review the adequacy of its criteria for earthquake-activated gas shut-off valves and revise them to improve reliability.
- The PUC use the task force results to adopt requirements by June 30, 1996, to reduce natural-gas earthquake risks to an acceptable level and recommend actions for utilities outside the PUC jurisdiction.

Electric Utilities

Over two million electric utility customers in the Los Angeles area lost power and lights at 4:31 on the morning of January 17, 1994. Thanks to redundant transmission and distribution lines and substations, most of these customers had power restored within a few hours, 93 percent within 24 hours, and 99 percent within three days of the event.

Damage to brittle porcelain insulators and bushings in higher-voltage substations was the primary contributor to power outages and the cause of a power surge that affected seven western states and Canada. Although there was much damage, most of the substation equipment performed well, especially the components that were designed to the latest seismic requirements. There was no damage to circuit breakers that met current criteria. Damage to transformer bushings, wave traps, and circuit switches appears to have been caused by either lack of compliance with current criteria or inadequacy of the criteria. An earthquake producing a strong motion of a greater duration might have further reduced system redundancy and extended restoration times. Electric system strengths and weaknesses should be investigated to identify areas for improved risk management.

In earthquakes prior to the Northridge earthquake, high-voltage transmission towers generally performed well, experiencing little or no damage; wind-loading requirements for designing transmission towers also provide protection against strong shaking. However, during the Northridge earthquake, two steel-lattice transmission towers collapsed involving a total of six towers. The towers were located on ridge crests, and the collapses were caused by movement of the footings due to slope failure. Tubular steel towers were also significantly damaged where soft ground conditions amplified motions and permitted displacement of the footings. Site-specific geologic and geotechnical evaluation studies of tower sites along essential transmission lines are needed to reduce the potential for the failure of towers from weaknesses in their foundations.

A number of public and municipal electric and gas utilities in California participate in the Inter-Utility Seismic Working Group to exchange earthquake risk and emergency-planning information and to develop consistent criteria among west coast utilities. In addition, California utilities have undertaken to reduce seismic risks through research and mutual-assistance pacts following earthquakes and other emergencies. These and other utility-initiated activities have resulted in improved seismic standards and performance. The PUC oversees seismic vulnerability reduction programs of the investor-owned utilities; municipally owned utilities such as the Los Angeles Department of Water and Power (DWP) are not within PUC jurisdiction but some, like DWP, participate on a voluntary basis. The Commission believes these types of programs are important in reducing the overall risk from earthquakes in California.

Recommendations

The Commission recommends that:

- Measures be taken by investor-owned and municipal utilities to improve the performance of substations and transmission lines.
- The PUC investigate and evaluate the causes of substation equipment damage and transmission tower failures; the actions utilities are taking to identify the potential for similar failures and improve substation equipment and transmission tower performance; the use of site-specific geologic and geotechnical information for locating and designing utility facilities; and the adequacy of current utility risk-mitigation programs.
- The PUC determine whether mandatory regulations are required for design and location of substation equipment and transmission towers to ensure adequate component and system performance. If regulations are deemed necessary, the PUC should issue such regulations by July 1, 1996.
- Electric utilities not under the jurisdiction of the PUC, such as municipal utilities, cooperate with the PUC and other utilities in reviewing their seismic mitigation programs, and the governing boards of those utilities adopt regulations and practices at least as stringent as those mandated by the PUC for private utilities.

Virtually all aspects of emergency response and coordination depend on power generation.

Emergency Power

Electrical power is critical following an earthquake. Virtually all aspects of emergency response and coordination depend on normal, emergency, or standby power generation.

90 percent of L.A.'s water is imported from northern California and the Colorado River.

Unfortunately, many of the emergency power systems that were called into service following power outages in the Northridge earthquake did not perform their intended function. Most failures were not related to major system components; instead they were due to system logic, interfaces, and operational anomalies. Major mechanical equipment such as engines, turbines, generators, fuel oil tanks, and boilers did not sustain significant damage during the Northridge earthquake; engineered electrical equipment such as transformers, motor control centers, switchgear, and batteries generally functioned well, though cooling system damage resulted in several system failures. Some of the problems encountered were not necessarily related to the earthquake; instances of overheating generators and inoperable transfer switches for connecting loads to emergency services were similar to problems encountered during the 1977 New York blackout (OTA, 1990).

Actions to correct problems with emergency generators could include:

- Establishing service agreements between building managers of critical facilities and vendors of emergency power generators, utilities, or other qualified organizations to provide personnel and equipment for assistance in servicing and repairing emergency power equipment.
- Collaboration between electric utilities, California Utilities Emergency Association, and local jurisdictions to maintain up-to-date information on critical and essential facilities so that these facilities can be given the highest priority for restoration of power after earthquakes.
- Mandatory programs to address proper sizing, design, and installation of emergency power systems; periodic testing and inspection of the generators; and training of building superintendents and facility staffs to maintain and operate their emergency power systems.

Since the electric utilities are not responsible for providing service under emergency conditions, they should inform customers—especially those who operate emergency communications, essential, and hospital services—about the potential loss of electric service following an earthquake. The availability of power to operate critical facilities, lifelines, and communications is an integral part of the ability to respond appropriately during an emergency. Without power, a community's ability to respond effectively is greatly reduced.

The Commission believes that decisive actions are needed in the area of emergency power. For example, hospital representatives testified before the Commission that air quality maintenance district restrictions prevent testing of emergency power generators. They are concerned that the lack of testing affects the reliability of emergency power.

Recommendations

The Commission recommends that:

- Legislation be enacted to require those who own essential communications and emergency services facilities or hospitals to provide for reliable backup power in conjunction with utilities.
- The Air Resources Board investigate claims that local air quality maintenance district restrictions prevent regular testing of emergency generators and resolve any conflicts to allow testing.

Water Supply

As a result of damage caused by the Northridge earthquake, piped drinking water was unavailable in some heavily damaged areas for over two weeks. A number of earthquake-caused fires had to be fought by drafting water from swimming pools or bringing in tanker trucks.

Though 10 percent of the Los Angeles area's water supply comes from local wells, 90 percent is imported from northern California and the Colorado River. The earthquake damaged five major pipelines and severely disrupted water service to Santa Clarita, Simi Valley, and the northern part of the San Fernando Valley.

Breaks in major aqueducts generally occurred at joints. Both steel and concrete pipelines were affected by ground movement or severe ground shaking. Although damaged aqueducts were returned to service within approximately 40 days of the earthquake, some pipelines needed further repairs during the summer to replace the temporary repairs made immediately after the earthquake.

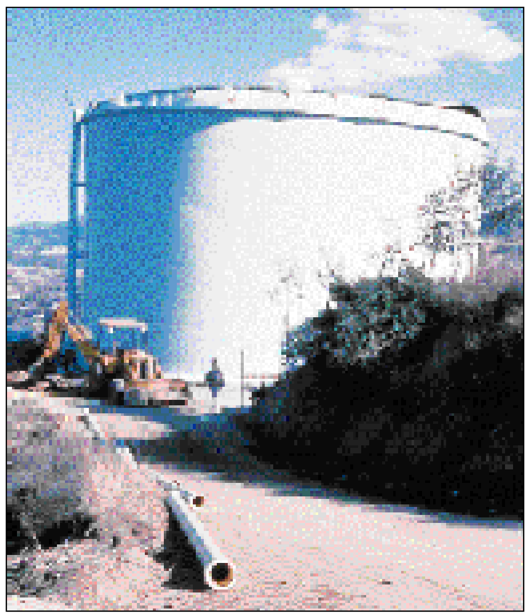
Significant repairs were also required to local water distribution systems after the earthquake. DWP reported approximately 1,400 repairs to mains and services within their system. Simi Valley and Santa Clarita reported an additional 300 repairs to their systems. Most of the distribution pipes affected were either cast-iron pipes with rigid joints (for example, cement- or lead-caulked joints) or steel pipes weakened by corrosion.

There was also extensive damage to older aboveground steel water tanks. In several cases, the entire contents of the tank were lost because of failures of inlet-outlet piping, which generally occurred because the ground shifted under the tanks. Other failures included buckling at the base of tanks, buckling of the shells, and roof damage. Because these storage facilities may represent the only immediate water supply for local systems, special measures must be employed to ensure their integrity after earthquakes (see Figure 72).

Several organizations are addressing the effects of earthquake hazards on water systems, including the California/Nevada Section of the American Water Works Association and California Utilities Emergency Association. Several large water utilities are also part of a California Water and Power Earthquake Engineering Forum, which meets periodically to discuss seismic issues and develop and disseminate regional mitigation strategies.

Large California water districts, which are usually publicly owned, are not regulated to the same degree as are the large investor-owned gas and electric utilities, which must respond to the PUC. The PUC's jurisdiction is limited to privately owned water companies which, while numerous, serve but a small fraction of the state. Many water utilities within the state do have seismic mitigation programs, though they range from sophisticated to rudimentary. For many, identification and mitigation of seismic vulnerabilities is not taking place in a systematic fashion. This is a situation that is a major concern to the Commission. Each water utility should be responsible for developing plans to address seismic vulnerabilities in a systematic manner.

Though the performance of water delivery systems at a regional level was generally acceptable in the Northridge earthquake, the Commission believes that the performance of certain water supply components in this and future earthquakes requires further investigation. In particular, large-diameter welded-steel pipelines with lap-welded joints must be analyzed to determine their threshold of earthquake failure. These pipelines are common within the water transmission system; if widespread damage to them were to occur, the water supply to the southern California region could be seriously disrupted. All the major pipelines bringing water into the Los Angeles basin from northern California cross areas where large damaging earthquakes are expected, and most of them



EERI

Figure 72. The walls of this water tank buckled; pipes ruptured and lost 800,000 gallons.

could be put out of service by a single event (Figure 73). Similar situations exist in northern California.

Figure 73. This four-foot-diameter water main under Balboa Boulevard buckled and ruptured when surrounding soils compressed it.

Moreover, a number of water districts rely on single pipelines to bring water to large urban areas. Should those pipelines be damaged significantly in an earthquake, the supply of water could be lost to the areas being served by those lines.

Investor-owned electric and gas utilities cooperate with the PUC and each other in developing mitigation programs for their systems. The mutually supportive work, along with PUC guidance, has been effective.

The Commission believes a state-level agency should encourage and support efforts to improve water supply systems by providing guidance and materials to water districts and by monitoring risk-reduction efforts. The Department of Water Resources is an agency that should provide the needed expertise and leadership.

Recommendations

The Commission recommends that:

- The Department of Water Resources issue a report to all water utilities describing the reasons behind the failures of large-diameter piping, distribution piping, water tanks, and other system components and providing representative risk-mitigation programs to identify and address seismic vulnerabilities.
- Legislation be enacted to require each water utility within California to prepare a seismic mitigation program consisting of a seismic policy and a statement of acceptable levels of risk; a description of potential earthquake damage and system impacts based on likely earthquake scenarios; a priority-based long-term risk-mitigation program; and a commitment to fund the program.

Communications

Many emergency and normal communications systems were disrupted by damage, loss of electrical power, increased call volume, and call convergence into and out of the affected region. The disruption ranged from delayed dial tones to nonfunctioning radio systems. Damage to structural and nonstructural elements of buildings housing communication systems compromised equipment and lines. Because electrical power is needed to operate equipment and dispatch consoles, these facilities need reliable backup power.

The Northridge earthquake's effects on communications systems included:

- *Telephones*—Pacific Bell and General Telephone Electric both experienced difficulties. Though their systems performed well, dial tone delay caused the impression that the telephones were out. The 9-1-1 system was minimally disrupted for a short time. Both companies were able to get facilities back into operation quickly and load-line controls were imposed to give priority users ready access. Commercial land-line companies managed increased call volume and convergence during the disaster by giving priority to predetermined phones used for essential services.
- *Cellular telephones*—cellular phones worked well, but experienced overload. Emergency managers and first responders in the public and private sectors depended on cellular phones immediately after the earthquake. The usefulness and reliability of these systems could have been enhanced by limiting access to cellular phones to essential-services personnel. However, the Federal Communications Commission (FCC) has not established priority access for cellular users similar to that for land-line users.
- *California Office of Emergency Services*—the OASIS system linking Sacramento and Los Alamitos worked as designed.

- *Public safety radio*—radio communication among various police and fire agencies in the affected area was hampered by too few mutual-aid channels, incompatibility of radio systems, and the use of exclusive frequency bands. Moreover, emergency services personnel from other jurisdictions who responded to provide mutual aid often had equipment incompatible with the systems in the affected region. Equipment is available to allow everyone access to all radio bands.
- *Emergency medical communications*—many hospital radios and phones were disrupted, so the Los Angeles Fire Department had to send units to each location to determine its status; paramedic and emergency medical services in the San Fernando Valley and the Northridge areas had major problems; the Los Angeles County Medic Alert Center broke down; the Hospital Emergency Administrative Radio system was inoperable in the area of earthquake impact; Reddi-Net, a computerized system owned by the Hospital Council of Southern California that links 86 hospitals, failed; and mistakes, equipment damage, and lack of training took their toll.

Communications failures during disasters result in breakdowns in service, misunderstandings, lack of information for making decisions, and sometimes loss of life and property. The loss of communications by hospitals and medical providers was a particular problem in this earthquake. The deficiencies of the telephone and radio systems must be reduced to improve emergency response following future earthquakes.

Land-line and cellular communications systems rely on central switching facilities. Although these systems have functioned after recent earthquakes and generally have redundant lines and equipment, their reliability depends on the earthquake resistance of the buildings housing the equipment.

Recommendations

The Commission recommends that:

- The owners of essential services facilities ensure the adequacy of backup power generation systems and assess whether these systems can resist earthquakes.
- The agencies that rely on communication systems during emergency response have reliable redundant backup systems.
- OES explore the possibility of identifying and licensing additional mutual-aid channels in both the VHF and UHF bands for police and fire service use statewide.
- OES continue to place high priority on working with the FCC to address standards for radio equipment that will enhance direct communications between police and fire agencies, including those assigned through mutual aid.
- The PUC work with the cellular industry to facilitate limiting access to cellular phones to essential services after declared disasters.
- The Emergency Medical Services Authority investigate problems with emergency medical communication systems and specify measures to correct inadequacies, including requiring testing of emergency communication systems and training personnel.
- The ESA be amended to require that switch facilities for land lines and cellular communications be located only in buildings constructed or retrofitted to seismic requirements at least as stringent as those found under the Essential Services Buildings Act.
- The Governor petition the FCC to:
  - Provide additional frequency spectra for public safety services and expedite the development of appropriate standards and protocols to facilitate direct communications between systems.
  - Limit access to cellular phone service to essential services after a declared disaster.

Dams

The agency responsible for dam safety in California is the Division of Safety of Dams (DSOD) in the Department of Water Resources. DSOD administers the 1929 Dam Safety Act, which was passed into law after the failure of the St. Francis Dam took more than 450 lives.

The shaking far exceeded the level that the designers of California's older dams even thought possible.

The act applies to all dams meeting certain height and water storage criteria. A total of 1,230 dams fall under state jurisdiction; 116 of these exceed 150 feet in height and 154 have reservoir capacities over 10,000 acre-feet. About 84 percent of the dams are embankment dams; the remainder are concrete. California's 174 federal dams and various other constructions such as levees are not covered by the act, but a modification to the law following the 1963 failure of the Baldwin Hills Reservoir expanded DSOD's jurisdiction to include off-stream water storage facilities.

Following the near-failure of the Lower San Fernando Dam during the 1971 San Fernando earthquake, DSOD undertook a reevaluation of all hydraulic-fill dams under its jurisdiction. This resulted in the placement of operating restrictions on all dams of this type located in highly seismic areas. Los Angeles County also conducted reevaluations of its dams after the San Fernando earthquake, and reservoir levels at several of those dams remain restricted. All the high-hazard dams under DSOD's jurisdiction have been reviewed since 1971.

Immediately following any significant earthquake, DSOD runs a computerized search of all dams within a specified distance of the epicenter, contacts dam owners by telephone, and then dispatches inspection teams to the field. The program predicts those dam sites that experienced horizontal shaking greater than 0.05g. The search after the Northridge earthquake located 108 dams within 47 miles of the epicenter. All but three of these had been inspected four days after the earthquake. The remaining three were visited the following week, and follow-up inspections were made in February and March of dams closest to the epicenter.

Thirteen of the dams had some cracking or movement, but none were judged to be a safety hazard. Eight dams had only minor cracking—six earth dams, one rock-fill dam, and one reinforced-concrete. Only one of the six earth dams is hydraulic-fill, and it is kept empty by DSOD restriction except to serve for flood control.

The most serious effects occurred at Pacoima Dam, a 365-foot-high arch dam located in the San Gabriel Mountains about 11 miles from the epicenter. During the earthquake, the 3,700 acre-foot-capacity reservoir was 27 percent full, and the water surface was 131 feet below the crest. An array of 17 accelerometers at the site recorded motions on the dam and on the canyon walls adjacent to the dam. Peak horizontal accelerations on the abutments ranged from 0.5g at the foot of the dam to over 2.0g on the side walls near the crest. Variations in the abutment motions from the top of the canyon to the bottom and from one side to the other were striking.

Damage visible at the site was consistent with the strong shaking indicated by the accelerograms. Rock slides blocked the access road, damaged the tramway, destroyed many walkways, collapsed the protective cover on the lower spillway chute, and filled the chute with debris. The shotcrete covering the left abutment rock was extensively cracked, and some of the broken shotcrete slid down the canyon walls along with loose underlying rock. The contraction joint between the dam and the concrete thrust block at the left abutment opened by 2 inches at the crest level. The opening decreased to 1/4 of an inch at the bottom of the joint, 60 feet below the crest, and a large crack in the thrust block extended diagonally from the joint to the foundation rock. Survey measurements made after the earthquake indicate one portion of the foundation rock at the left abutment slipped about 2 to 3 inches horizontally and 2 inches down. This movement allowed the contraction joint to open.

Some damage also occurred to the body of Pacoima Dam. Two cracks were visible on the downstream face of the dam from 48 feet below the crest down to a point 90 feet below the crest. Several cracks were found on the uppermost portion of the dam near the crest, each of which ran diagonally from a shear key corner to either the upstream or downstream face. Post-earthquake measurements indicated that the dam crest was permanently displaced upstream by 2 inches.

The upper 65 feet of Pacoima Dam is most vulnerable to damage. Because the spillway intake is 65 feet below the crest, water would not be released unless a damaging earthquake happened to occur just after a flood. The part of the dam below the upper 65 feet should remain intact in any event.

The peak acceleration at Pacoima Dam was considerably stronger than that currently used in safety assessments of dams in California. Although the dam survived, the earthquake did not test it under stresses caused by a full or nearly full reservoir when the potential for damage in the dam and abutments would be greater. Current engineering capabilities have advanced over the years but are not able to reliably assess such an event or the complicated nature of motion in the canyon of a dam. Improvements in analytical methods, verified by experiments and earthquake shaking measurements, are urgently needed.

The Commission believes that although dam performance in the Northridge earthquake was acceptable, the earthquake was only of moderate magnitude and the duration of the strong shaking was quite short, on the order of nine seconds or less at most sites. However, recorded shaking far exceeded the level that the designers of California's older dams even thought possible. Moreover, a number of recent California earthquakes have also occurred on buried fault systems that were not previously recognized. To its credit, DSOD has been discussing and focusing on buried faults since the Coalinga, Whittier Narrows, and Loma Prieta earthquakes. However, as recommended in chapters II and V, identification and mapping of buried faults must receive a higher priority, and dam regulatory agencies should be involved in that process and use the findings in the reevaluation of existing dams.

DSOD's efforts to regulate the seismic safety of California dams have been successful. They have applied progressive engineering practices to achieve the good performance of dams in past earthquakes and prevent loss of life. However, like other matters of seismic safety in California, DSOD's critical function is underfunded. State funding for dam safety has decreased by 20 percent over the last five years as the number of dams has slowly but significantly increased, and aging dams require more attention. Resulting cutbacks in personnel have reduced the frequency of field inspections and curtailed studies to develop ways of applying research results to dam engineering. The frequency of major earthquakes during the past few years has stretched staff and funding to critical limits.

In its review of the performance of dams in this earthquake, the Commission also examined the question of other dams not under the purview of DSOD. The federal Bureau of Reclamation has responsibility for a number of federal dams in California. Though the bureau has been cooperative in the past, a decrease in its funding leaves a substantial number of its facilities needing repair and upgrading, including Folsom, Friant, and Bradbury (Cachuma) dams. Recent changes in the bureau's mission, which include an abrupt decrease in emphasis on dams and water projects, may well reduce dam safety practices and increase risk. The bureau recently began accepting risk analyses as a substitute for structural repair on potentially deficient dams and using incremental damage study techniques to justify its decisions. It also has not requested needed additional appropriations for its program for safety evaluation of existing dams.

Federal statutes preclude state control over federal agencies performing work related to dams. It may be time to reexamine this situation. Currently, new dams are being designed and constructed by the U.S. Army Corps of Engineers to slightly different standards from

The peak acceleration at Pacoima Dam was considerably stronger than that currently used in safety assessments of dams in California.

state requirements. A few dams, transferred to California sponsors and therefore now under state jurisdiction, have not been accepted by DSOD as meeting California requirements. DSOD is working with the Corps of Engineers and local project sponsors to resolve differences in this area and to ensure state involvement in projects before transfer.

Recommendations

The Commission recommends that:

- The owners of dams be required to fund a dam instrumentation program carried out by the Strong Motion Instrumentation Program at the direction of DSOD.
- DSOD review its current assessment procedures in light of the strong-motion data obtained from the Northridge, Loma Prieta, and Landers earthquakes and assess concrete dams in areas having a likelihood of intense shaking and where the release of water would have significant public safety consequences.
- DSOD be directed to conduct seismic reevaluations and to increase inspection frequency of high-risk dams in zones of high seismic hazard.
- Legislation be enacted to allow DSOD to establish a research program directed towards improving and verifying methods of analyzing the seismic performance of dams.
- The Governor petition the federal government to ensure that all federal dams in California are designed, built, inspected, and repaired to state requirements.