WATER SYSTEMS PERFORMANCE NORTHRIDGE EARTHQUAKE, January 17, 1994

Le Val Lund, P.E., M ASCE

Civil Engineer
ASCE - Technical Council on Lifeline Earthquake Engineering

ABSTRACT

Lifelines played an important role in the emergency response and restoring the urban area affected by the Northridge earthquake. Although the earthquake was severe the lifeline disruption only represented a small percentage of the inconvenience to the population served within the large earthquake impact area. The 1994 event showed significant improvement in the seismic performance of lifelines (power, water, sewer, gas and communications) from the 1971 San Fernando event. The 1994 event also revealed some conclusions and new lessons learned in the seismic performance of lifelines which will require attention by lifeline agencies.

The Fifth U. S.-Japan Workshop
on Earthquake Resistant Design of Lifeline Facilities and
Counter Measures Against Soil Liquefaction
September 29 and October 1, 1994
Snowbird, Utah

INTRODUCTION

An earthquake occurred at 4:31 a.m., Pacific Standard Time (PST) on Monday, January 17, 1994. The epicenter was located 20 miles (32 kilometers) from the center of Los Angeles, in the Northridge community (San Fernando Valley) of Los Angeles, California, USA. The magnitude was M 6.7 (Caltech) or M 6.8 National Earthquake Information Center (NEIC). The impact of the earthquake was wide spread in western Los Angeles and eastern Ventura Counties. The earthquake had significant impact on lifelines, in addition to damage to residential and commercial buildings, and freeways. The estimated damage was approximately $15 billion and there were approximately 58 fatalities.

Lifelines

Lifelines are those services vital to the health and safety of the community and the functioning of an urban and industrialized society. Lifelines are critical for the emergency response and recovery of a community after a disaster such as earthquake. Lifelines include electric power, communication, transportation (highways, airports, railroads and harbors), water, sewage, natural gas and liquid fuel systems.

Lifeline Seismicity

No surface rupture that can be associated with the main shock has been found by field geologists from California Division of Mines and Geology (CDMG), US Geological Survey (USGS) and other organizations. Buried pipelines were subjected to both strong shaking and acceleration, and tectonic movement, even though there was no surface faulting.

WATER SYSTEMS

Supply

Water supply to Southern California is provided by local groundwater basins, water reclamation and imported supplies from the Colorado River and Northern California. The earthquake disrupted five of the major pipelines from northern California serving the Santa Clarita, Simi and San Fernando Valleys which supplied four water treatment plants. Three plants were in operation and the fourth was under construction.

The breaks in 54 (1371), 77 (1956), 78 (1981), 85 (2160), and 120-inch (3048-millimeters) diameter steel and concrete pipelines and concrete conduits were repaired in two to 67 days. Some of the repairs were temporary to restore service and permanent repairs will made by summer 1994.

Until these pipelines were repaired water utilities received supplies from local groundwater basins, storage reservoirs and Metropolitan Water District of Southern California (MWD) Colorado River Aqueduct and State Water Project - East Branch.

Supply Pipelines

The State Water Project-West Branch supplies the Jensen Water Treatment Plant from the Castaic Reservoir via the Newhall and Balboa Tunnels. At the south portal of the Balboa Tunnel the 170-in (4320-mm) line branches into two-85-in (2160-mm) by 13/16-in (20-mm) welded steel inlet pipes (WSP) to the treatment plant. The west pipe performed satisfactorily; however, the east pipe circumferentialy cracked on the curved portion of a long bell. The pipe was joined by an inside welded bell and spigot joint. The northerly part of the round crack moved horizontally about 3-in (76-mm) east with respect to the southerly part. Vertical movement was about 1/2-in (38-mm).

An approximately 10-feet (3.0-meters) of the damaged pipe was removed and replaced by two-5-ft (1.5-m) lengths of pipe rolled at the MWD yard. The closure was made by three welded butt straps joints and completed the evening of January 19th. The MWD East Valley Feeder and pumping plant was activated to provide supply from the Colorado River Aqueduct/ State Water Project - East Branch to the areas in western Los Angeles County and eastern Ventura Counties, affected by this outage.

Los Angeles Aqueduct No. 1 supplies the Los Angeles Water Filtration Plant from the Owens Valley by two aqueducts. Aqueduct No. 1 had damage at four locations; however, it was operated at very low flow for about week after the earthquake to allow repairs to be made to Aqueduct No. 2, then was shut off for repairs. After temporary repairs were made, it was operated again at one-half capacity, for about two weeks at the end of March, during a planned MWD shutdown. It was shut down shut down April 1st and was out of service until July for permanent repairs.
Both aqueducts were shut down for a period of three weeks, the last week of February and first two weeks in March, to allow for the repair of the

open concrete channel supplying the water filtration plant. The channel was fractured in many locations requiring replacing concrete sections, low pressure grouting the voids behind the walls and patching the cracks.

At the south end of Aqueduct No. 1 Soledad (inverted) Siphon at two locations occurred the partial cracking of the curved portion of the bell of an 120-in (3050-mm) by 3/8-in (10-mm) welded steel pipe. The pipe was welded on the outside of a bell and spigot joint and was above ground and supported by concrete saddles. The circumferential cracks were about 5-ft (1.5-m) long on the top of the pipe. The repair was made by removing a coupon of the damaged joints and replacing it with a welded steel plates. At Quigley (inverted) Siphon there was split in the top of the 120-in (3050-mm) riveted steel pipe which was welded shut.

At two locations, Whitney and Elsmere Canyons, the 120-in (3050-mm) cast-in-place reinforced concrete (inverted) siphons were shattered, and temporary repairs were made by plugging the cracks from the outside. Permanent repairs were made by placing a steel liner inside the pipe and injecting the cracks with sealing compound from tapped holes in the liner from the inside of the pipe. The steel liners were fitted with a "O" ring gasket at each end. Creek flow was a dewatering problem at Elsmere Canyon. Tunnels were inspected and found in satisfactory condition except for minor cracking and the tunnel through Terminal Hill, which had circumferential cracking at the south end. The cracks were sealed with urethane resin.

Los Angeles Aqueduct No. 2. was out of service for the first week after the earthquake for repairs, and placed in service until the shutdown of both aqueducts for the open channel repair during the last week in February for three weeks. It was put back in service in mid March until April 8th at which time it was removed from service for non earthquake related reasons.

At Terminal Hill the 77-in (1955-mm) welded steel pipeline was shut down twice to repair two pulled mechanical couplings and an eight-inch long split in the wye branch stiffener. This required draining and filling the pipe twice during the first week after the earthquake. The pulled couplings were temporarily repaired by welded butt straps. The wye branch stiffener was rewelded. Two-6-in (13-mm) compression bulges appeared on the north slope of Terminal Hill in the 77-in (1955-mm) pipe in above ground pipe supported on concrete saddles. This represented almost 2-feet (0.6-m) of compression in the pipeline. At these bulges there were no leaks although significant movement occurred.

At Quigley Canyon a circumferential tear in the top of the buried 77-in (1955-mm) welded steel pipe was repaired by welding a interior patch plate. A number of air and vacuum valves were damaged and required replacement.

Long travel times and traffic were a problem in gaining access to the repair sites north and south of the Interstate 5 and State Highway 14 damaged interchange. All repairs were made by agency personnel. Compliance was required with the Occupational Safety and Health Act (OSHA) for entering confined spaces (tunnels and pipes).

Santa Clarita Valley is served from the Castaic Reservoir, the terminus of the State Water Project-West Branch. The Castaic Conduit from the water treatment plant was video inspected and had 35 leak repairs in the 54 (1370), 39 (990) and 33-in (838-mm) modified prestresed concrete cylinder pipe (MPCCP). One repair occurred on the 54-in (1370-mm) MPCCP inlet pipe to the plant. Breaks occurred at welded fabricated compound (horizontal and vertical) bends and on long horizontal reaches where the rubber gasket joints pulled apart. A pipe manufacturer fabricated new compound bend sections and a contractor welded these sections together with butt straps. The pulled rubber gasket joints were welded in place. Backer rods were used to fill the annular space between the bell and spigot to facilitate the welding. The conduit was placed back in service March 25th. The supply to the Santa Clarita Valley after the earthquake was supplied from local groundwater.

Simi Valley receives water supply from the MWD Jensen Treatment Plant. The supply is transmitted by two pipelines to the storage reservoir at the west end of Simi Valley. The common tunnel at the east end was inspected and found undamaged. At the west tunnel portal in Simi Valley the pipeline separates into 78-in (1980-mm) and 51-in (1295-mm) prestressed concrete cylinder pipelines with rubber gasket joints. Alternate supply was available from reservoir storage and groundwater.

The 78-inch North Branch Feeder (1980-mm) had 15 to 20 major pulled joints and approximately 500 cracks requiring chipping and patching with cement mortar. The rubber gasket joints were welded shut and some of the joints were pressure grouted from the inside behind the weld. External repair plates (diapers) were used at some locations.

Replacement was required of 22 damaged air and vacuum valves. The replacement valves were air freighted by the manufacturer within two days. The 78-in (1980-mm) line was placed back in service on March 4th.

The 51-inch Calleguas Conduit(1295-mm) remained in service intermittently after the earthquake. The earthquake damage occurred at three corroded blind flanges and bolts at future service connections. The flanges, bolts and valves were replaced. Also an air and vacuum valve was damaged.

Lifeline Collocation

An interesting collocation of nine lifelines occurred on Balboa Boulevard, north of Rinaldi Street, in Granada Hills, an apparent tension and compression zone. Located within the street were 3-gas , 3-water, 2-sewer and 1-oil underground lines; 34.5 kv and 4.8 kv power, telephone, and cable TV overhead lines; and ornamental street lighting. Ground movement caused the breakage of some of the underground pipelines. A fire occurred in the street which ultimately burned the overhead lines and five homes. At this location there appeared to be a ground separation (tension) at a location on Balboa Blvd. south of Lorillard Street of approximately 9 to 12-in (230 to 305-mm). Approximately 1,000-ft (300-m) to the south there was ground compression of an equal amount. At both of these locations the gas, water and sewer pipelines were damaged.

Large Diameter Pipelines

Two of the three water lines in Balboa Blvd. were the Granada Trunk Line 48-in (1220-mm) WSP and MPCCP and the Rinaldi Trunk Line 68-in (1727-mm) WSP. The Granada line had four major pulled mechanical couplings and two tension and compression failures on the curved portion of the bell, of the bell and spigot joints. Repairs were made by connecting a short length of pipe with butt straps in the tension zone, a butt strap in the compression zone and interior butt straps (WEKO seals) at other locations. A creek caused dewatering problems at one location. The line was put back in service on January 29th. The Rinaldi line had three pulled welded bell and spigot joints at the bell curve and a tension and compression failure on Balboa Blvd. Repairs were made by connecting a short length of pipe with butt straps in the tension zone, a butt strap in the compression zone and interior butt straps (WEKO seals) at other locations.

There were approximately one dozen other large diameter pipeline failures for the same reasons as described above. Repairs were made using the same methods, requiring the use of similar materials, equipment and personnel.

Distribution System

The most significant damage to the smaller distribution pipeline network was within the earthquake affected area. It was reported (4-1-94) there were approximately 1,400 leaks in mains and services by the water utilities in the San Fernando Valley and approximately 300 in the Santa Clarita and Simi Valleys. Pipes were broken by compression and tension and some pipes weakened by corrosion due most likely to vibration and tectonic movement. The most affected were older cast iron with rigid joints and older steel subjected to corrosion. There also were broken fire hydrants and air and vacuum valves.

The repairs were time consuming requiring draining prior to repair, the repair, the filling the pipe for testing, and chlorination and invariably another leak was observed, requiring the repeat of the process. In a number of cases this process was repeated many times and was more time consuming in larger diameter pipes which required more time to drain and fill. In some areas dewatering of excavations was necessary. Food, water and housing were a problem to the restoration workers in the damaged areas, because of the loss of commercial power and potable water to restaurants and motels.

Water Treatment Plants

The operating plants have a capacity of 25 (95), 550 (2080), and 600 million gallons per day (mgd) (2270 million liters per day) (ml/d) The treatment plants received minor damage, such as ground settlement around the plants; leaks at construction and expansion joints; leaks in plastic chlorine solution lines, overturned filing cabinets and book cases; falling ceiling tiles; and sloshing damage to gratings and wood baffles in the basins. Supply was available in most areas from storage and the other regional sources, but was not immediately available from the treatment plants because of the damage to the distribution systems. The Simi Valley water treatment plant (50 mgd) (190 ml/d) was not in operation and is still under construction.

Booster Pumping Stations and Groundwater Wells

There was no reported damage to booster pumping facilities or groundwater wells, other than loss of commercial power. Many wells did not have emergency power. Pumping stations with emergency power supply worked well. There was minor damage to the enclosures housing these facilities.

In some areas, fire department engine pumpers were used to maintain pressure in area in which the leaks had been repaired. The pumping between fire hydrants by the engine pumpers was used when the primary supply was not available.

Storage Tanks

The Santa Clarita Valley (Valencia-Newhall area) is north of and about eight miles (13-km) from the earthquake epicenter in Northridge. Severe tank damage occurred in this area in that six of the seven Newhall tanks were damaged and were rendered nonfunctional following the earthquake. Principal modes of damage were broken inlet-outlet piping and valves, roof and rafter damage, and shell buckling/elephants foot failures. Lateral movement or sliding/shifting did not appear to occur frequently or, if it did occur, it was in the order of two to four inches (5 to 10-cm).

Similarly, there were two structural failures in the Valencia area, with a third tank suffering damage from an adjacent tank failure. Failure modes were severe shell buckling and uplift, inlet-outlet piping failure, roof/rafter damage and in one case shell ripping at the tank bottom. The two tanks with structural failures have been removed.

The Simi Valley area lies 10 to 12-miles (16 to 20-km) west of Northridge. This area also experience a significant number of functional tank failures, the causes of the failures again being shell buckling and inlet-outlet piping and valve damage . In addition to the these tanks, there were an additional ten tanks in the Simi Valley area which were damaged and rendered nonfunctional; however, many of these tanks were repaired and returned to service.

Those tanks in the San Fernando Valley which had significant damage were in the Santa Monica Mountains south of Northridge. Inlet-outlet piping and valve damage, erosion and roof problems were again the major causes of functional failure. All of these tanks have been repaired and returned to service. A damaged 1929 riveted steel tank in the Granada hills area has been removed. Good performance was observed by prestressed concrete tanks.

Observations from this earthquake are the significant number of tanks damaged and which became nonfunctional by not being able to contain water-the effects on fire protection of being immediate concern. The principal modes of function failure were inlet-outlet piping failure and roof damage. Also most of the failed tanks were not American Water Works Association AWWA D-100 design basis tanks. Many were of bolted construction and were of relatively small size. The Larwin tank was a used tank, rebuilt in 1986, with AWWA nameplate, tank was anchored, nevertheless suffered severe damage and was removed from the site. Although not mentioned in this report, there were a number of smaller industrial tanks near the Northridge/Canoga Park area which also failed.

Comparing the damage to water tanks during this earthquake with damage in previous earthquakes, this earthquake produced far more extensive and severe damage to water tanks than previously experienced. About 40 tanks were rendered nonfunctional by this earthquake. To the credit of operating and maintenance personnel, many of the tanks without severe damage were returned to service in a short time and the systems were not faced with prolonged outages.

Many of the steel tanks were not AWWA D-100 designed tanks, so its difficult to judge their design criteria. It is noted that roof damage seemed to be more apparent in this event; the occurrence of roof rafters falling off supports was noted at number of locations. The failure of the inlet-outlet piping was the principal cause of functional failure; the lesson here is to provide flexibility in the inlet/outlet piping and possibly use steel valves and fittings.

Reservoirs

There were 120 dams within 46-miles (74 -kilometers) of the epicenter of the Northridge earthquake. Most of the dams are water supply storage reservoirs. Others are flood control and are generally empty or have minimum stored water. 108 of these dams are under the jurisdiction of the California Department of Resources, Division of Safety of Dams (DSOD), the remaining 12 are owned by the federal government. All major DSOD dams were inspected by their owners immediately after the earthquake. Some of the major dams were further inspected by their staff or contract engineers. In the first five days 101 of the dams under state jurisdiction were inspected by DSOD engineers. The remainder were either dry, under construction, or outside the epicentral area. All were eventually inspected. All state and federal dams performed satisfactorily and no emergency situation existed.

Thirteen of the 108 dams nearest the epicenter had some minor longitudinal and transverse cracking, settlement, minor horizontal movement or increased seepage and one small storm water dam had a minor slope failure.

Pacoima Dam had cracking in both abutments and damage to its access ramps and stairways. The upper left abutment strong motion instrument recorded an acceleration of 1.5 g or greater on the horizontal and 1.4 g on the vertical component. At the same location in the 1971 San Fernando earthquake the record was 1.25 g on the horizontal and 0.7 g on the vertical component. Peak accelerations exceeding 2.0 g were recorded on the dam structure. The total capacity of the flood control basin is 3,770 acre feet, but storage capacity was temporarily limited to 1,000 acre feet, while civil engineers made further investigation of the abutments. The dam performed satisfactorily in the earthquake. Water is released from this dam to enhance the water supply by recharge into the San Fernando groundwater basin.

Dams performed well in the Northridge earthquake. Since the 1971 San Fernando earthquake, most major dams in the state have been dynamically analyzed for the maximum earthquake that could be imposed on the dam. Some dams met this seismic criteria, others were rebuilt, modified, operating at a reduced level or have been removed from service.

Water Quality

This earthquake disrupted treated water to many water systems including Santa Clarita, Fillmore, Moorpark, Simi Valley, Malibu and San Fernando as well as Los Angeles. Water supply was available, some treated and some untreated, from groundwater basins, storage, MWD Colorado River Aqueduct and East Branch of the State Water Project.

Three filtration plants were out of service due to pipeline damage; this meant a loss of over one billion gallons (3.8 billion liters) of water treatment capacity. As a precaution, water purveyors, in cooperation with the California Department of Health Services, Division of Drinking Water and Environmental Management (DHS), issued "boil water" notices immediately. Although some service areas were not affected, the boil water notices gave water purveyors needed time to assess the damage to their systems. A standard "boil water" notice had been prepared by DHS in advance for use by the water agencies in times of a emergency.

The notice generally stated customers should boil or treat their water before consuming. Rapid boiling for five minutes or treating the water with chlorine would disinfect the water adequately. Specifically, customers were asked to add unscented liquid commercial bleach to their water in the following amounts: 8 drops per gallon (3.8-liter) for water that appears clear, 16 drops per gallon (3.8 -liter) for water that appeared cloudy. Customers were told to mix the chorine and water and let the mixture set for 30 minutes before consuming.

The boil water notices were released by the water purveyors and DHS in the printed and electronic media. Local TV and radio stations became very important disseminators of changes in the boil water notice in the areas. A problem arose when customers from unaffected water systems began to unnecessarily boil water their water and call their water purveyors in panic. This required unaffected water purveyors to issue their own separate notice indicating their water was safe to drink. Even with the confusion water purveyors and DHS felt issuing "boil water" notices was better than taking a chance that someone might drink contaminated water.

In order to lift the "boil water" notice from any service area, the water agency requested permission from the local DHS district engineer. The authorization would only be granted after the water purveyor had completed the repairs to its distribution system, the distribution system was pressurized, had at least a 1 ppm (1 mg/l) chlorine residual in the distribution system and had received satisfactory disinfection and bacteriological testing. The testing took at least one day. It would be desirable to have mobile water quality Laboratory to make field testing of water quality and an expedited method for testing for contaminants in the water.

In areas like Santa Clarita Valley, where well water was chlorinated for the first time, some customers complained about the chlorine taste and odor. In Los Angeles, boil water area was gradually reduced as the system was restored and customers in the last boil water notice area were allowed to use their water on January 29th, in the Simi Valley on January 24th and in the Santa Clarita Valley on February 4th.

Emergency Water Supply

Emergency water supply was provided by bottled water, beer and soft drink beverage companies, MWD, U. S. Army Corps of Engineers, California National Guard and water agencies provided water using agency, contractors and rented tanker trucks. The tanker trucks were disinfected and fitted with taps and hoses for easy dispensing. During the height of the operation in Los Angeles, 72 trucks were being dispatched to nearly as many locations providing over 100,000 gallons (378,500 liters) of water each day. The Los Angeles International Airport was temporarily closed because it fell within the boil water notice area and no airplanes could take off with out potable water. The problem was solved by having the water tanker truck that normally supplies the planes dispatched to a location outside the boil water area to received its potable water for delivery to the aircraft.

Mutual Aid

Volunteer mutual aid was provided by almost a dozen water agencies from the local area and one came from the San Francisco Bay area. Mutual aid agencies provided their own personnel, equipment and materials. Fifty-two people assisted Los Angeles in restoring their system. Contractors familiar with water utility work were also used. the mutual aid agencies had to deal with the limited housing and food in the epicentral area.

CONCLUSIONS

1. Lifelines played an important role in emergency response and restoring the community after the Northridge earthquake. Telecommunications, radio and electronic media played a valuable role in directing emergency response for essential services and the repairing of damaged lifelines. Water supply was necessary where available for public fire protection. Highways and roads were used to move rescue, repair, fire and medical teams and their supplies and equipment to the damaged areas. Although the Northridge earthquake was severe, the lifeline disruption only represented a small percentage of inconvenience to the population served within earthquake impact area.

2. The 1994 Northridge event showed significant improvement in the seismic performance of lifelines from the 1971 San Fernando earthquake. Among the facilities and equipment installed, using modern seismic codes,

which had good seismic performance, but not totally inclusive, is dams, steel and concrete tanks, wells, pumping stations and treatment plants. Also included is welded steel pipe with butt joints, ductile iron pipe with rubber gasket joints and polyethylene pipe.

3. The 1971 San Fernando and 1987 Whittier Narrows earthquakes experience has encouraged lifeline agencies to prepare emergency response plans. These plans have been tested and implemented by lifeline agencies. The regular earthquake exercises generally held, in April, of each year in various communities proved to be invaluable in this earthquake. The month of April is selected because it is the anniversary of the 1906 San Francisco earthquake.

4. Above ground tanks usually have either one or two pipes, with valves, rigidly connected to the tank to provide for the filling the tank and draining the tank to meet the peak water demands in the water service area. In the Northridge earthquake, there were cases were the piping or valves broke because the differential movement between the tank and the piping. Several methods have been developed for providing a more flexible connection between the tank and the piping to withstand the differential movement. There needs to be further study on economical and other methods of preventing storage tank inlet/outlet piping damage due to differential movement.

5. Older steel tanks not seismically designed and constructed suffered buckling at the bottom (elephants foot bulge), in the shell and roof. There is a need to seismically retrofit these older facilities.

6. Welded steel Tanks seismically designed and constructed under American Water Works Association (AWWA) Standards for Welded Steel Tanks for Water Storage (AWWA D-100) and prestressed-concrete water tanks designed and constructed under AWWA Standards for Wire-Wound Circular Prestressed-Concrete Water Tanks (AWWA D 110) performed very well.

7. Water supply lifelines use bell and spigot pipe almost exclusively for welded steel pipe. Bells are fabricated by using a mandrel to expand the cold pipe to create the bell. There were a number of instances in the Northridge earthquake were the large diameter bell was cracked at the curvature point where the bell changes diameter. There is a need to study the seismic strength of welded steel bell and spigot joints and how to improve the seismic performance of the joint. The joint performance

should be compared with the current (AWWA) Standard for Welded Steel Pipe (AWWA C-200)

8. Most damage to the water distribution system piping occurred in cast iron pipe with rigid joints and old steel pipe subject to corrosion. Although there is limited ductile iron pipe with rubber gasket joints installed, the seismic performance of this pipe was very good. Programs are needed, including funding, to replace this older pipe in seismically active areas.

9. Most of the emergency power supplies worked for pumping stations and treatment plants; however, there is a continuing need to regularly test these emergency generators under load; to have adequate fuel for a longer term commercial power outage; provision for transferring fuel from the storage tank to the day tank, when the electric pumps are out of service.

10. There are number of wells, pumping stations and treatment plants without emergency power or that do not have capacity to provide for all their essential operations. There is a need to enlarge the emergency generation capacity to cover all essential operations. Portable generators with "quick electrical connectors" would be of value.

11. Sloshing in large basins in water filtration and water reclamation plants caused damage in the 1989 Loma Preita and 1994 Northridge events. Although not critical, the damaged equipment can cause malfunction of other equipment. As an example sloshing caused the jamming of the chain drive sludge scrapers in seven out of 44 final clarifiers of a water reclamation plant. There is a continuing need to consider sloshing in the design of mechanical equipment and baffles in large basins of water and wastewater treatment plants.

12 Customer water, gas and electrical service was disrupted to a small (5% to 20%) portion of the population impacted by the earthquake and for a short period of time considering the intensity of the earthquake. Most of this disruption was due to distribution system damage and structural damage to residences and buildings. Redundancy was provided in distribution system networks and alternate supplies from other sources for electric and gas supplies and storage, groundwater basins and alternate aqueduct systems for water supplies. Redundancy continues to play an important role in the restoration of lifeline services.

13. The 1994 Northridge event demonstrated the vulnerability of lifelines within essential facilities, such as, hospitals, fire stations and emergency operating centers. Small breaks in water lines and automatic sprinklers caused flooding in lower floors. Roof top HVAC equipment was damaged which caused malfunction of other systems within the building. Internal lifelines in essential facilities require seismic design. There is a need for emergency electric and water supplies for essential facilities.

14. The Northridge earthquake identified several areas were there is a need for enhancing the ability of lifeline employees in their emergency response and recovery activities. This event cause transportation problems, because of the closed freeways, for lifeline employees to get from their homes to their work location. Alternate work locations or telecommuting where feasible should be considered.

15. There is need for emergency food, water and housing; and adequate cash to purchase these items, for lifeline workers in the epicentral areas. Because there is a potential for potable water, gas and electricity not being available, restaurants and motels may not be in operation.

16. There is need for a communications plan, which has been tested for lifeline employees and families to notify each other of their well being. This would allow employees to report directly to a restoration effort without worrying about their families. This was not necessary in the Northridge event because most people were still at home at 4:31 a. m. in the morning.

17. In advance of an emergency, non-emergency response lifeline employees, should be assigned and trained in emergency response activities. For government lifelines there is a need to document repairs for FEMA reimbursement which could be done by non-emergency response personnel.

18. A lifeline agency with its own engineering staff, not involved in the recovery operation, offered their services to help employees with their home earthquake inspections.

19. Consideration should be given to developing a mobile water quality laboratory to expedite, in the field after repairs have been made, the determination if the water is safe for drinking.

20. Currently bacteriological testing takes several days to determine whether water is safe for drinking. Research should be done to expedite this process so the boil notice may be lifted sooner.

21. The entering of large diameter pipes, conduits and tunnels requires compliance with OSHA requirements for entering confined spaces.

22. Air and vacuum valves on pipelines are an inverted pendulum above the ground surface. In the Northridge event many valves toppled, had cracked bodies or damaged floats (balls). The damage may have been caused by transient pressures in the pipeline. A study is required to improve the performance of these valves in an earthquake.

23. The Northridge event showed good performance of structures and equipment which had been seismically upgraded from the 1971 San Fernando event. Seismic upgrade of lifeline equipment, buildings and facilities is very costly, requires prioritizing, budgeting and some form of innovative financing. Innovative financing research is required to further improve the seismic performance of lifelines.

24. All lifeline agencies should make seismic vulnerability assessments of their facilities to determine vulnerability to damage of their system. The assessment should prioritize/schedule any required seismic mitigation.

25. All lifeline agencies should have an emergency response and recovery plan. The plan should be practiced and updated on a regular basis.

References

"Preliminary Reconnaissance Report - Northridge Earthquake, January 17, 1994, Lifeline Section, Earthquake Spectra, Earthquake Engineering Research Institute, Oakland, March 1994.

Persson, V. H., 1994, "Assessment of Damage to State Jurisdictional Dams Caused by the Northridge Earthquake (M_W 6.7) on January 17, 1994", Presented at the California Seismic Safety Commission meeting, March 3, 1994, Burbank, CA.

Lund, L., 1994, "How the Earthquake Affected Water Quality", Association of California Water Agencies, Water Quality Monitor, Volume 6, Number 1, January/February 1994, , Sacramento, CA.

Aqueduct, Metropolitan Water District of Southern California, Los Angeles, March/April 1994.

Intake, Department of Water and Power, Los Angeles, January/February 1994.

Water storage tanks by T. Cooper, ASCE - TCLEE.

Personal Communications and field investigations by L. Lund with numerous water and wastewater agencies.

II MECHANISMS OF LIQUEFACTION AND LARGE GROUND DEFORMATION