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Seismic Upgrade of Prestressed Concrete Water Tanks

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SUMMARY

Most of the East Bay Municipal Utility District's distribution water tanks are located near a major earthquake fault. Many of the tanks are above grade, prestressed concrete tanks that were built prior to the 1970's before the onset of modern seismic codes. The potential failure modes for these tanks include sliding and uplift of the tank wall over the existing foundation, and hoop overstress of the wall prestressed steel, causing loss of contents. The retrofit design criteria and analysis methods are based on the AWWA Standard with modifications to included near fault and site-specific soil effects. Retrofit schemes for sliding include interior curbs connecting the wall to the floor slab or exterior cables connecting to a new foundation. To prevent uplift either seismic cables or rock anchors were used. Retrofit schemes for hoop overstress involve the addition of prestressed wire wrapping or post-tensioned tendons or bars and a cover of shotcrete. Many tanks were upgraded with the tanks in service to reduce impacts to the system and cost. Many non-seismic components of the tanks such as seals, ladders, piping, valves and telemetry were rehabilitated or replaced in conjunction with the seismic upgrade work. Remote controlled seismic isolation valves with flow meters were included at selected reservoir sites to provide a means of saving water in those tanks after a pipe break following an earthquake. The upgrades have proved cost effective compared to replacement of the tanks. The program should greatly improve the post earthquake performance of the District's water system.

INTRODUCTION

The East Bay Municipal Utility District has over 170 water distribution reservoirs and wash water tanks. Included in these are 67 prestressed concrete tanks ranging in size from 200,000 gallons to 11 million gallons. Most of these tanks are above grade and were built prior to 1965. The majority of these are located near the two major earthquake faults that traverse the district's service area. 58 of the 67 prestressed concrete tanks have been identified with an unacceptable risk of failure following an earthquake with a 10% probability of exceedence in 50 years. The District is currently in the 9th year of implementing a ten-year, $189 million Seismic Improvement Program to seismically strengthen its water distribution system. Over $40 million will be spent to seismically upgrade the vulnerable concrete tanks.

Seismic Hazards

The District's service area covers approximately 325 square miles on the east side of San Francisco Bay. The adjacent Figure 1 shows the two major earthquake faults, the Hayward and Calaveras Faults, in the District's service area and a third fault, the Concord Fault, which is just to the east of the service area. Most of the District's 1.2 million customers are located in close proximity to either the Hayward or Calaveras Faults.

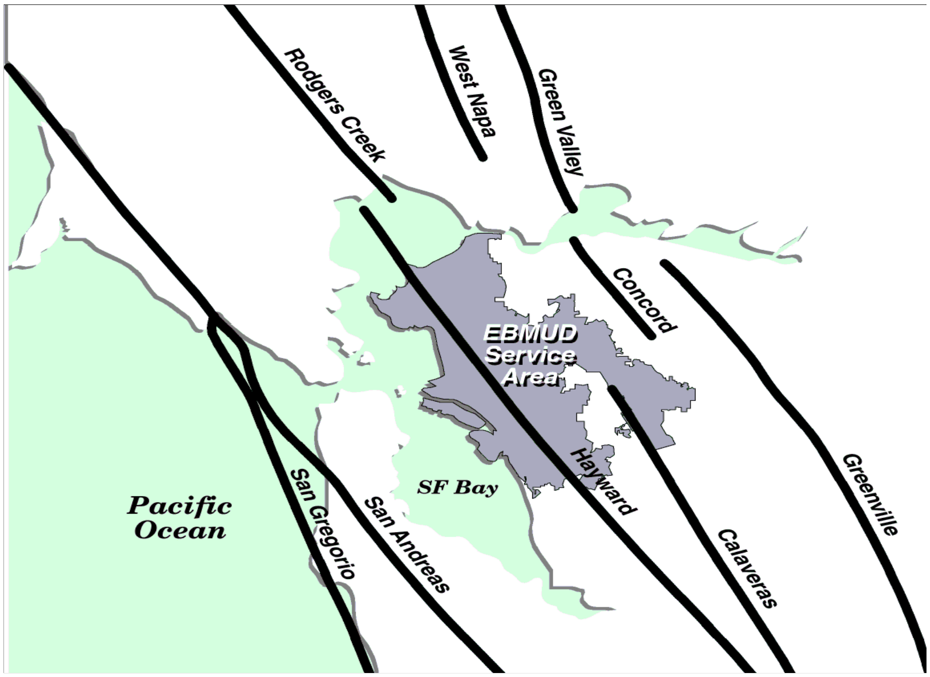

Figure 1. Major Faults

In 1990, the California Working Group on Earthquake Probabilities assigned a probability of 28% that a magnitude 7 earthquake would occur on the northern segment of the Hayward Fault within 30 years.

Following the 1989 Loma Prieta earthquake, the District undertook a comprehensive study of the seismic vulnerability of district facilities. This study identified the vulnerabilities, presented a capital improvement program and established upgrade goals to maximize system performance following a major earthquake. The evaluation was system-based to model overall system performance. Each facility was evaluated for the various ways an earthquake can cause damage, including: Ground Shaking; Fault Rupture; Seismic induced Landslides; Liquefaction; Ground spreading and lurching. Scenario earthquakes with a 10% in 50-year probability of occurrence were used in the study and included magnitudes 7.0 on the Hayward fault, 6.75 on the Caleveras fault and 6.5 on the Concord fault.

Ground shaking and landslides are the primary seismic concerns for the prestressed concrete tanks. Fault rupture is rarely an issue because the tank sites typically avoid known fault locations. Liquefaction and ground spreading and lurching tend to occur in weak soils found in low-lying areas of the District. To provide the required pressure for water delivery to customers, tanks are located on higher ground with better foundation materials (typically stiff-soil or weak-rock). Each tank was prioritized based the following factors: life safety (adjacent or “downstream” habitants), importance to the system, damage susceptibility, and current condition.

Failure Modes

The primary failure modes for prestressed concrete tanks subjected to seismic loads are sliding, hoop overstress and wall uplift causing damage and loss of contents. One or more of these modes apply to each of the vulnerable tanks. The tank aspect ratio (i.e. the height to diameter ratio) is a key index for the anticipated types of failure. Higher aspect ratios lead to uplift problems while sliding is a greater concern for lower aspect ratios. Damage to tank piping can also cause failure.

Sliding
The tanks were built with little connection between the wall and ring footing or interior slab. The wall base was designed to move radially outward with increased water inside the tank. The outer edge of the interior slab sits on the footing with a continuous "ring" joint between slab and the interior face of the tank wall. Figure 2 shows a typical wall section. Beginning in the early 1950's radial keys were cast in the ring footing (and bottom of core wall) to resist tangential in-plane wall movement but allow radial outward movement. However, the shear capacity of the keys is well below the expected earthquake forces. Excessive movement of the wall would breach the ring joint seal causing severe leakage. Pounding against the interior slab would cause excessive stress in the slab and wall resulting in damage and possible permanent deformation.

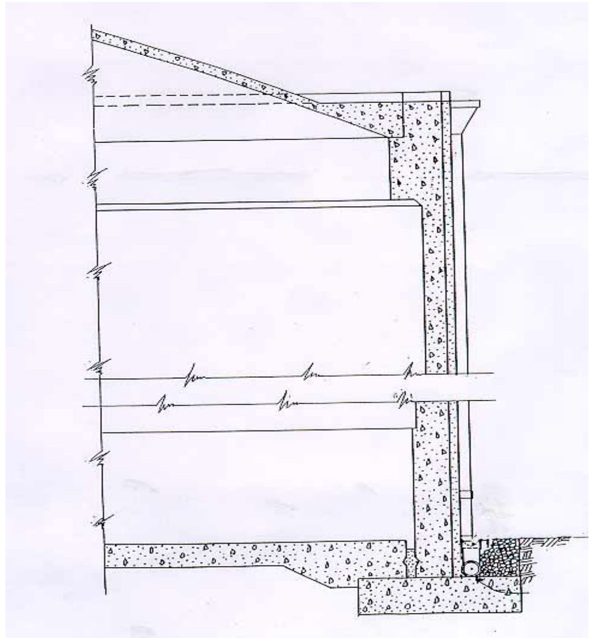

Figure 2. Typical Wall Section

Hoop Overstress
Hoop stress is dependent on the original design forces (with corresponding area of steel and applied stress levels), corrosion of the existing prestressing wires or bars and residual stress after long term creep losses. These factors are evaluated through a combination of field inspection and analysis. Prestressing bars were used until the early 1950's when wire-winding techniques were developed. The older tanks with bars tend have severely insufficient applied force and hoop capacity for the combined hydrostatic and hydrodynamic (seismic) loads. However the bars are not high strength material and have some ductility. In addition, little corrosion damage has been observed. Consequently, the expected damage is extensive wall cracking and excessive movement in the wall joints. By contrast, the newer prestressing wires are a higher strength material and were applied at higher stresses. However, they are more likely to be damaged or break if corroded. The wire-stressed tanks also have insufficient hoop capacity due to the low original design forces and would likely experience wall cracking. They could also experience local wire breakage and subsequent severe damage to the wall.

Most of the prestressed tanks have cast-in-place dome roofs. Each dome is supported at the top of the tank wall with a dome ring (tension ring) that has additional prestressing to resist dome thrust. These dome rings are typically overstressed under the combination of vertical loads and seismic forces, which can be either horizontal or vertical. Overstressing would result in cracking in the dome roof and partial or complete collapse of the roof. Even if the walls survived the quality and operation of the tank would be severely compromised.

Uplift
The hydrodynamic forces caused by seismic events include both the impulsive and convective (sloshing) components. The centroid of the convective force tends to be higher up the tank wall and greatly contributes to the overturning tendency. If the dead load of the wall and roof are not sufficient to resist the overturning the wall will uplift from the existing footing. This can produce pounding damage between the wall and footing as well as breaching the seal between these elements and result in complete loss of contents. Many of the high aspect tanks have small existing ring footings that are undersized for the additional bearing pressure caused by the seismic overturning forces. This can result in footing settlement and further damage.

Valve Pit and Piping Damage
In addition to the tank damage described above, failure can result from damage to the valve pit or the inlet/outlet (I/O) piping. Most of the valve pits are cast in place concrete structures located adjacent and connected to the tank ring footing. The I/O pipe enters into the tank through the tank floor and is encased in concrete under the tank to the valve pit. Many of the pits have pre-cast concrete roofs. The Pre-cast roof panels could fall and damage the valves and piping. The I/O pipe is susceptible to damage at the transition from the concrete valve pit wall to the adjacent soil. This is a particular concern for cast iron pipes or soft soils. If the tank roof is damaged and debris falls into the tank, the I/O pipe could get clogged and valves could be damaged.

Pipelines will break downstream from the many reservoirs and cause the tank to be drained within hours after a major earthquake. Refilling the reservoirs could take many days depending on the difficulty of the pipeline repairs. The danger of fires is also present in most pressure zones, 100 to 250 fires are anticipated to occur within the District Service Area in first 24 hours after a seismic event. This is particularly hazardous in zones that are remote or difficult to access.

Retrofit Schemes

The retrofit design criteria was established after the District completed a Seismic Evaluation Study of the entire Distribution system and presented alternative scenarios to the Board of Directors. It was determined that a level of funding could be justified to strengthen the tanks to prevent collapse but that further retrofit or replacement to a higher standard was not merited. The tanks may suffer damage such that the water may be exposed to the air and thus require boiling before drinking, and the damaged tanks may not be reparable after the earthquake. However, the tanks would survive to provide water for fire suppression and basic needs immediately after the event. For example, it is expected that some tanks will develop cracks and leak after an earthquake. However, the leakage rate will not be to great as to render the tank unusable.

The basis of the retrofit designs is the American Water Works Association Standard D110 (Wire-and Strand-Wound Circular-Prestressed Concrete) with modifications and additional requirements by the District to account for the high seismic region. The modifications include the use of UBC (Uniform Building Code) Seismic Coefficients for type and nearness of faults, and for soil profiles. A site-specific response spectra was used in the analysis of two tanks and a finite-element seismic analysis was performed on one of these tank. The finite-element analysis did not result in significant changes to the retrofit schemes but it did provide valuable information to better understand the wall and roof stresses. Retrofit methods were developed for each of the primary failure modes. The retrofit designs vary depending on the size, aspect ratio, location and condition of each tank.

Sliding
Two primary design methods have been developed and constructed to resist sliding. The first incorporates new interior perimeter concrete curbs with connections to the existing floor slab and the tank wall. For this method the tank must be drained for the upgrade. The curbs are poured tight against and dowelled to each vertical wall panel. The curb ends are separated by gaps at each of the vertical wall joints. The bottom rests on a slip pad and the floor slab connections consist of steel pipes inside tube steel sockets. The steel pipes are grouted into the floor slab and filled with grout. This allows for wall movement in the radial direction for normal hydrostatic and thermal loads but provides resistance in the tangential direction (i.e. parallel to wall) for seismic loads. The seismic sliding load is thus transferred to the slab is ultimately resisted by friction on the soil below the slab due to the weight of the contents. Figure 3 shows construction photos of a typical interior curb.

Figure 3. Interior Sliding Restraint Curbs

The second method includes an exterior ring footing addition with diagonal seismic cables attached to the exterior wall surface and extending into the footing. The ring footing addition is typically anchored to the foundation sub-grade with drilled concrete piers. This upgrade can be done even if the tank remains in service. The cables are high strength galvanized seven-wire strands and bond to a layer of new shotcrete on the wall under the new prestressing. The cables pass through a neoprene sleeve at the wall base to allow for perpendicular wall movement. Figure 4 shows construction photos of this method.

Figure 4. Exterior Seismic Cables & Ring Footing Addition

Hoop Overstress

To mitigate hoop tension overstress, new circumferential wire-wound, strand-wound, or tendon prestressing is applied to the tank. The degree of new prestressing depends on the area of steel, remaining force and condition of the existing prestressing. Elastic shortening will also further reduce the force in the existing prestressing. On most tanks, wound wires (or strands) have been preferred due to economics and quality control. The wires or strands are high strength steel, hot dipped galvanized and applied with an automated wrapping machine that continuously monitors the applied stress. Two inches of shotcrete cover is applied over the wires (or strands) to bond and protect them. Photos of the wrapping machine and shotcrete application are shown in Figure 5 below. Tendon prestressing has been primarily used on smaller tanks that have lower demand (i.e. less degree of hoop overstress) or for tanks that have little clearance around the tank or difficult access for a wire or strand-wrapping machine. The Tendons are typically epoxy coated 7 wire strands, greased and encased in plastic sheathing. They are applied by hand and tightened with hydraulic jacks at coupling anchors located at specific points on the tank circumference. The couplers are staggered between tendons and friction losses are monitored to ensure a uniform application of stresses on the tank. Figure 6 below shows a relatively small but tall tank with tendons installed prior to the application for shotcrete. The shotcrete is required for protection against corrosion and vandalism. This method is typically not as economical as wire or strand wrapping due to the automation of the wrapping and shotcreting.

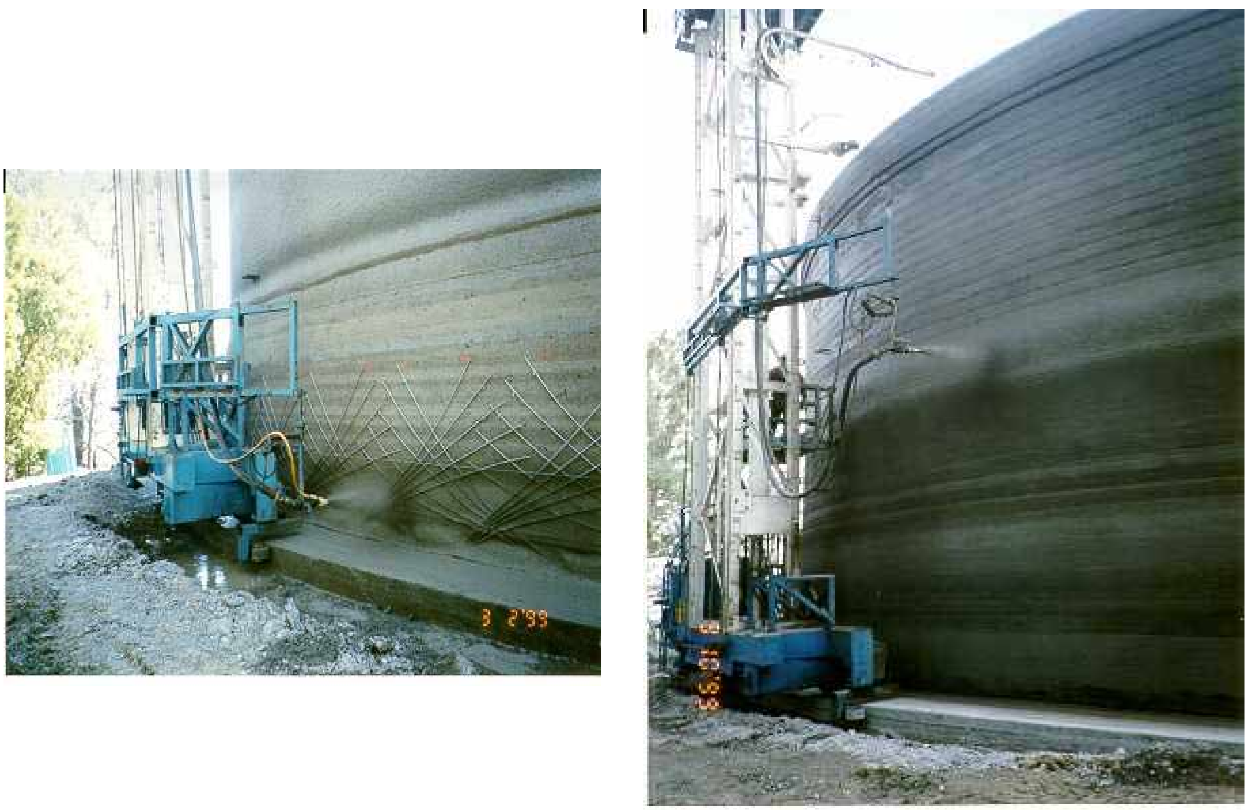

Figure 5. Automated Wire or Strand Wrapping and Shotcrete

Uplift

Wall uplift is typically also mitigated by the seismic cables, ring footing and drilled piers described above for sliding. The angle of the cables can be adjusted if the required force for uplift is greater than the sliding requirement. At some of the lower aspect tanks with lesser seismic uplift demands, the new interior sliding restraint curbs attached to the base of the tank wall described above provides sufficient additional dead load to resist uplift. At a few sites with high uplift demands and rock sub-grades, rock anchors consisting of grouted multiple strands, were used. The anchors were installed in grouted holes drilled tight against the tank wall & through the existing ring footing. The top of the strands were splayed out and attached to the tank wall prior to the application of shotcrete and strand wrapped prestressing. The new prestressing and shotcrete provide sufficient bond to anchor the strands.

Figure 6. Post-tensioned Tendons prior to final shotcreting
(Note: bottom of wall has new seismic cables that are encased in new shotcrete)

Valve Pit and Piping
To prevent damage to valves and piping the existing precast concrete valve pit covers were secured with galvanized steel hardware and epoxy anchor bolts in the valve pit walls. To reduce the risk of damage to the Inlet/Outlet pipes, a gap was typically chipped out around the pipe circumference in the exterior valve pit wall and flexible sealant material was placed in this gap. This will reduce or eliminate the "hard spot" where the pipe transitions from soil to the concrete valve pit. At sites where the soil around the pipe outside the valve pit is much softer than the foundation sub-grade of the tank and valve pit, a flexible expansion joint was installed which allows for both rotation and longitudinal movement.

To mitigate the potential for downstream pipe breakage, remote controlled reservoir isolation valves are being installed at certain reservoirs (typically only one reservoir per pressure zone), to maintain some water storage for emergency use. Battery powered valves were chosen to allow for remote operation even if the normal power supplies are down. The installation includes a flow meter downstream of the valve, to allow the operator to monitor the flow, and a hydrant upstream of the valve, to provide water from the reservoir for emergency vehicles.

Conclusion

Existing aging circular prestressed concrete water storage tanks located in an area of high seismic risk can be effectively and economically retrofit. Some tanks may be retrofit while they remain in service. Seismically upgrading and rehabilitating the tanks can be more cost effective than replacement. East Bay Municipal Utility District's tank retrofit program will greatly enhance the post earthquake performance of the District's water distribution system.

REFERENCES

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