WATER STORAGE FACILITIES

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VULNERABILITY

The loss of surface, buried, and elevated water storage tanks can seriously affect the ability of a water supply system to provide sufficient water for fire suppression and to maintain a potable water supply for emergency facilities, such as hospitals, fire and police facilities, emergency operating centers, and individual consumers. In addition, collapse of a tank could cause injuries and property damage both from the fallen structure and the rapid release of water. Damage to potable and wastewater treatment storage facilities could have similar effects.

OBSERVATIONS OF DAMAGE

Considerable damage to storage facilities occurred in the 1964 Alaska earthquake. Typical types of failure were total collapse of tanks, roof buckling, failure at roof to shell connections, and shell buckling.

Damage to storage tanks in the 1971 San Fernando, California, earthquake focused primarily on welded or riveted steel tanks ranging in age from 1 to 42 years. The principal modes of damage were buckling of the steel shell, especially at the base; horizontal displacement from the foundation; and failure of the inlet-outlet piping connections. The latter effect was noted as well at a concrete tank.

In or near the cities of Brawley, Imperial, El Centro, and Calexico, three elevated water storage tanks sustained damage in the Imperial Valley, California, earthquake of 1979. A 100,000-gallon elevated tank south of Imperial, built in 1962, experienced minor damage to diagonal bracing at the upper level; a gusset plate pulled out of a leg section and a horizontal strut buckled slightly. An El Centro water tower, having been built in the 1930s and having survived the 1940 El Centro earthquake, experienced stretching of diagonal tie rods in the upper level, buckled horizontal struts, and stretched anchor bolts at the column base plates. South of Brawley, a 100,000-gallon elevated tank, constructed in 1961, collapsed. Failure appeared to have been initiated by one or a combination of the buckling of horizontal braces, tearing of gusset plates from the legs, and failure of the tie rods at the upset ends.

In the 1983 Coalinga, California, earthquake, minor damage occurred to an elevated storage tank.

GENERAL HAZARD MITIGATION TECHNIQUES

Water storage facilities (surface, buried, and elevated) are a portion of the water supply lifeline system and should continue to function after an earthquake. In order to evaluate alternative storage plans for gravity and pumped water systems, seismic consideration should be given all the integral parts of the distribution system such as pipelines, pressure regulators, water wells, pumping plants, and treatment facilities. The following also should be considered for storage facilities:

1. Locating the storage facility as close as possible to the area where the water will be used, since this reduces the likelihood of an outage between the storage facility and the distribution system.

2. Locating the storage facility outside the zone of deformation associated with active faults and away from the potential path of landslides and rock falls.

3. Locating the storage facility away from areas with unstable soils such as certain slopes and fill areas, areas with natural or man-made underground voids, areas with high liquefaction potential, and areas underlaid by sensitive clays. The geology also should be investigated so that the storage facility will not be located in areas with adverse bedrock planes (i.e., bedding, jointing, fault, shear, etc.) of weakness.

4. Providing setbacks from any potential failure surface.

5. Providing the facility with an adequate spillway and emergency blow-off drain system.

6. Designing the tank to include a leak detection system beneath the bottom of surface and buried tanks in order to identify any unusual leakage that could cause saturation of the foundation for the tank.

7. Protecting all metal surfaces, both internal and external from corrosion.

8. Providing for redundancy and/or flexibility in the water system in case one or more links in a system are out of service. This can be done by providing multiple storage facilities to spread the storage in smaller facilities in separated areas and/or by providing multiple supply lines to provide alternative routes of supply to the tank.

9. Providing additional pumping facilities to maintain the water supply for firefighting and emergency facilities in case of the complete outage of the storage facilities. This can be done by providing additional electric pumping units or emergency internal combustion pumping units with a backup power supply provided by emergency internal combustion generators or alternative power sources. Also, fire hydrant connections between an upper and lower service elevation levels can be used by fire department pumpers to provide a means of supply when the pumping facility is totally out of service.

OTHER CONSIDERATIONS

Storage facilities should be constructed on competent natural ground or bedrock and not on fill; however, when a tank is constructed on fill, the fill material should be of uniform thickness and compacted to a degree that will ensure comparatively high soil shear strengths, little future consolidation, and essentially no differential settlement. If a tank is sited in an unstable soil area, the soil may be stabilized using vibroflotation or chemical or cement grouting. The tank also could be supported on piles.

Flexible connections should be provided between the storage facility and its inlet-outlet pipeline. These connections or joints can be mechanical, restrained expansion, rubber, ball and socket, or gimbel restrained bellows type couplings. The American Water Works Association's (AWWA) D100-84 (1984) recommends that a minimum of 2 inches of flexibility in all directions be provided for all piping attached to the shell or bottom of steel storage tanks. If major movement greater than 2 inches is expected, a more elaborate flexibility system should be designed. Shutoff valves, check valves, blow-off valves, and bypass facilities should have adequate flexibility to withstand movement.

All roof, hatch openings, ladders, and other appurtenances should be appropriately designed and constructed to resist seismic forces.

DESIGN GUIDELINES

The following are recognized standards for construction of tanks:

1. The structural design of steel tanks (surface and elevated) should be in accordance with the American Water Works Association's *Standard for Welded Steel Tanks for Water Storage*, ANSI-AWWA D100-84 (1984).

2. The structural design of concrete tanks should consider the provisions of the American Concrete Institute's (ACI) *Concrete Sanitary Engineering Structures*, ACI-74-26 (1977), with appropriate seismic consideration. All concrete should be designed to limit flexural deflection, and where the concrete is exposed to severe and frequent freezing and thawing, air entrainment should be used.

3. The seismic design of tanks should consider provisions of the Structural Engineers Association of California's (SEAOC) *Recommended Lateral Force Requirements and Commentary* (1980).

4. The structural design of prestressed concrete tanks should be in accordance with the AWWA's *Proposed Standard for Circular Prestressed Concrete Water Tanks*, AWWA D110-81 (1981).

5. The structural design of the tank appurtenances should consider provisions in the Applied Technology Council's (ATC) *Tentative Provisions for the Development of Seismic Regulations for Buildings*, ATC 3-06 (1978).

6. The seismic design of the storage facility should exceed local building and safety code requirements. They should be classified "essential" facilities and assigned an occupancy importance factor of at least 1.5.

7. The design should use the appropriate <u>seismic zone coefficient</u> as shown in the ATC's *Recommended Comprehensive Seismic Design Provisions for Buildings*, ATC 3-05 (1977), or a <u>response spectrum</u> developed for the specific site.

8. An evaluation should be made of the area of inundation (path of discharge) of the water through the surrounding area in case of failure of the storage facility or its piping system.

RESEARCH

Research studies have been performed recently on the dynamic analysis of liquid storage tanks:

1. At the Earthquake Engineering Research Center (EERC) at the University of California, Berkeley, Ray W. Clough and George C. Manos have tested the response of several small-scale tanks mounted on a shaking table subjected to simulated earthquake motion.

2. At the Earthquake Engineering Research Laboratory (EERL) at the California Institute of Technology, Pasadena, George W. Housner and Medhat A. Haroun have conducted theoretical and experimental investigations of full-scale tanks to seek possible improvements in design of tanks to resist earthquakes.

SURFACE FACILITIES

Surface storage facilities generally are cylindrical in shape with bottoms that are supported directly by the ground with little or no burial that could provide lateral support. The majority are constructed of welded or riveted steel plates; however, there are some reinforced and prestressed concrete storage tanks. Reinforced fiberglass tanks are used for chemical storage. The tank bottom may be supported on gravel or sand layers inside a concrete ring wall which supports the tank shell.

Surface tanks and their contents may be affected by earthquake motions in a number of ways. The response of the water inside the tank is the primary driving force causing the tanks to fail. The response of water inside the tank to horizontal ground shaking can be idealized for analysis as follows: A portion of the water moves with the tank in short period motions; another portion of the water, primarily the top layer, sloshes back and forth across the tank in long-period oscillations. Both effects contribute to horizontal forces on the tank wall. In response to these forces, depending on their magnitude, the tank may slide or tip. Sloshing also may cause the tank to rock back and forth. The horizontal forces will induce a bending moment on the tank shell, causing compressive stresses on the tank side wall that are at a maximum near the bottom of the tank. In addition to hydrodynamic forces, water inside the tank is constantly exerting an outward static force on the tank wall in proportion to water depth. This loading may be amplified if the tank is subjected to vertical accelerations. With the compressive and outward forces acting on the tank wall simultaneously, it may bend (bulge) outward--a phenomenon sometimes referred to as "elephant's foot" bulge. The stresses may be so extreme the seam between the plate sections may burst, allowing the discharge of water.

Another potential problem is tank foundation failure. One possible reason is the increased localized loading caused by the tank overturning moment. Earthquake motions may cause the soil structure to liquefy, lose shear strength, or simply consolidate (settle), depending on the soil conditions. This may allow the tank to tip or settle unevenly, causing the tank shell or roof to buckle and sometimes fail.

Specific design recommendations for surface storage facilities are as follows:

1. Provide a reinforced concrete ring wall footing on firm foundation to support tank shell to minimize differential settlement. Such a ring wall prevents lateral displacement of material supporting tank bottom.

2. Provide a stiffened or thicker floor plate (sketch plate) at floor perimeter under shell plate to transfer vertical forces from seismic overturning moments to the concrete ring wall footing.

3. Surface tanks may be anchored or unanchored to resist earthquakes but must comply with requirements in AWWA D100-84.

4. Place tank bottom plate on compacted sand or gravel layers.

5. Protect the underside of the bottom metal plate from corrosion. This is sometimes done by using oiled sand for the support of the bottom plate.

6. Maintain a height-to-diameter ratio between 0.3 and 0.7 to control the seismic loadings. The ratio can vary depending on seismic zone.

7. Design to transfer the vertical roof loading from the roof of the tank to the foundation through the shell and/or vertical columns.

8. Consideration should be given to designing the roof system as a diaphragm to take horizontal seismic forces to the shell.

9. Eliminate abrupt changes in the thickness of the shell and between the shell wall and roof plate.

10. Allow enough freeboard to prevent the sloshing wave from coming into contact with the roof to minimize roof buckling and broken roof-to-shell connections.

11. Provide positive attachment of the roof to the roof rafters or brace roof rafters laterally. Do not depend on friction between the roof and rafters.

12. Provide a full penetration weld from both sides of the shell to the annular bottom (sketch) plate.

13. Consider ultrasonic or X-ray inspection of the welded joints.

14. Consider designing the bottom plate around the edge of the tank to prevent uplift of the tank wall due to rocking.

15. Design anchor bolts for minor earthquakes so they will anchor the tank without yielding.

16. Design anchor bolts to yield before the anchor bolt attachment if the tank fails to prevent damaging the water integrity of the tank.

BURIED FACILITIES

Buried tanks are either cylindrical or rectangular; their bottoms are supported directly by the ground and their sides resist lateral earth pressure in a way similar to a retaining wall. The majority are constructed of reinforced and prestressed concrete. The design criteria should consider both empty and full conditions and provisions, such as drainage, should be made to prevent liquefaction of the foundation material.

Specific design recommendations are as follows:

1. Seismic design should consider settlement, active and passive soil pressures, flotation (increased for soil liquefaction), effect of the inertial and sloshing of the water, inertia of the tank structure and the soil it supports, and appurtenant

items. Sloshing and the inertial effect are earthquake-induced forces only; the other items, although normally considered in a nonseismic design, must now be considered in greater detail.

2. Control the type of backfill used behind tank walls during construction. A noncohesive soil is normally used as it is easier to attain a specified high compaction density with a minimum effort. The higher the relative density of the backfill, the lower the liquefaction potential of the backfill material. Liquefaction of the backfill is the most severe condition that must be resisted by a retaining wall. Following liquefaction, the backfill becomes a very dense fluid which lacks shear strength required to resist deformation of the wall.

3. Allow for lateral forces acting on the tank shell structure including the earthfill above the tank, which may contribute substantially to the lateral forces during earthquakes.

4. Consider that earthquake motion may cause liquefaction of backfill and natural ground immediately adjoining the tank structure, which may cause the tank to float (water displacement vs. liquefied soil) even if it has been designed to resist flotation from high groundwater.

5. Buoyant forces causing flotation can be controlled in several ways:

   - Providing a positive drainage system.

   - Providing a positive tie-down mechanism, which requires designing the tank floor to structurally resist the buoyant forces.

   - Where piles are required to support the tank, they also may be utilized to resist uplift. This requires a thickened concrete floor which also would be the pile cap.

   - Increasing the weight of the structure by using mass concrete, heavy aggregate concrete, or adding to the overburden on top of the tank.

6. Avoid abrupt changes in structural configuration, including sharp interior angles.

7. Recognize accidental structural continuity in the construction of the floor to wall connection. Note that most prestressed tanks use a hinge connection between the wall and floor which may, in fact, have the potential for transfer of bending stresses to the adjacent structural elements.

8. Provide water stops at all reinforced concrete construction joints of the following types:

- Imbedded water stop.
- Internal "diaper" seal.

9. Provide annular space for movement when a pipe penetrates through the valve vault walls.

10. Consider flexible pipe joints outside the tank walls within inlet-outlet control valve vault.

ELEVATED FACILITIES

Elevated storage facilities are generally cylindrical or ellipsoidal in shape and are supported either by a braced frame or a pedestal. The frames or pedestals are commonly constructed of steel; however, there are some concrete elevated pedestal tanks in use.

Elevated tanks may fail because of foundation failure or rupture of the tank itself; however, the primary failure mode encountered is failure of the tank support structure. The structure responds to horizontal earthquake motions essentially as a single degree of freedom system (i.e., a mass oscillating on a spring). While a portion of the water inside the tank may respond independently, the effect on overall structural response is normally neglected. The system has a moderately long period. The earthquake horizontal accelerations will induce stress on the various members of the supporting structure. The structure may be simultaneously subjected to vertical earthquake accelerations, responding as if it were rigid. The stresses from both the horizontal and vertical ground shaking should be combined. If stresses are great enough to induce yielding, deformations may become so large that failure occurs. Once a member has failed, its load is transferred to other members with possible ultimate tank failure occurring by the "domino effect."

The tank structure (pedestal type), having a long period of response, may have a large horizontal displacement, sometimes referred to as "drift." This may substantially redistribute the vertical loadings on the support structure, a condition that may not have been considered in the design. The effect of eccentric vertical loading on the support structure from the weight of the supported object at an extreme horizontal displacement is sometimes referred to as the "P-delta" effect. Unless considered in design, these P-delta effects may cause the supporting structure to fail.

Specific design recommendations are as follows:

1. The design of an elevated tank should adequately transfer the loading from the tank to the foundation. Particular attention should be given to the overturning moment inducing an upward force on one side of the footing and P-delta effect of horizontal displacements.

2. Rigid cross-braced steel elevated tanks should be designed to withstand greater horizontal forces from seismic events than (energy absorbing) moment-resisting structures.

3. The connections shall be designed for the full capacity of the member rather than the design load of the connection. The objective is the yielding of members before failure of the connections.

PROPOSED RECOMMENDED RESEARCH

Multiple Shaking-Table Systems

In lifeline earthquake engineering, there is no experimental facility in the United States to study lifeline system performance in earthquakes, which includes both spatial and temporal distribution. It is suggested that several relatively small shaking tables (3 foot by 3 foot) be built with only one horizontal motion component; however, the system should have the flexibility to be modified at a later date to include vertical motion. This test facility would allow the testing of several components of the water distribution system to be studied at the same time under different motion.

Passive Field Verification

Currently there are several strong motion array networks in the United States and other parts of the world to study free-field ground motion characteristics. It is suggested that lifeline instrumentation within the strong motion array networks be installed so that responses of these lifeline systems can be correlated directly with the free field ground motion characteristics.

Connections and Construction Joints

It is suggested that research be conducted on inlet-outlet piping for tanks and construction joints for concrete tanks. These are vulnerable points and failures during earthquakes have occurred. Expansion and construction joints also are vulnerable to damage and failure.

Unanchored Tanks

Research is needed to improve the present method of analysis and design of tank behavior during intense earthquakes on tanks that are unanchored at their base. An improved analysis procedure is needed that properly accounts for the effects of sliding and uplifting of the base and that reproduces, with a reasonable degree of accuracy, complex, nonlinear response mechanisms that experimental laboratory programs have revealed. Also an economic analysis of anchored compared to anchored tanks could be included.

Soil-Structure Interaction

Soil-structure interaction and damping of tanks requires study, both for laterally and vertically excited systems. The objectives of the study would be an evaluation of the damping appropriate to the various modes of vibration of tanks and to increase the existing technology to reduce costly design analysis and construction.

Buckling of Walls

A better understanding is needed of the buckling of the walls of a steel tank under dynamic conditions of loading and of the effect of such buckling on the overall integrity of the tank. Both experimental and analytical studies should be conducted to define dynamic buckling sufficiently well so that design process can take it into account.

Liquid Sloshing

In evaluating the effects of liquid sloshing, the amplitudes of motion at the free surface of the liquid are considered to be sufficiently small that the response is linear. The influence of multiple short and long period liquid sloshing should be investigated, particularly as it affects the integrity of the tank (shell and roof) and appurtenances. Also, using the 1985 Mexico City experience, it should be determined whether the sloshing period is close to the natural period of the site; if so, the resulting response amplification should be determined.

Vertical Motion

Studies of the seismic response of tanks normally neglect or approximate the effect of the vertical component of ground acceleration. Except for some exploratory studies, this problem has not attracted the attention it deserves. A rational method should be developed for evaluating the response to vertical excitation.

Field Testing

A range of properly planned and executed field tests of full scale structures is needed to assess the adequacy of analytical predictions and to help guide future analytical developments and laboratory testing programs. A reasonable number of tanks in seismically active regions should be instrumented with strong motion recorders, strain gauges, central recording systems, etc., to provide control data on their behavior during actual earthquakes.

Technology Transfer

There are thousands of small water and sewer utilities that have little or no technical research expertise. Much research has been done;

however, it is not in a form usable by these small utilities. Work is needed to review existing research products and to translate the results into practical terms to be disseminated (manual, workshop, trade association guidelines, codes, standards, etc.). The resultant product could be a "Standard of Practice" for use by lifeline utilities for new construction or for retrofitting existing facilities.

Lifeline Workshops

Lifeline utilities need to have earthquake awareness and understand the potential impact of an earthquake on their facilities. The need is for planning, development, and implementation of a training program in the form of a workshop for lifeline utilities, trade associations, and local government. Elected officials, lifeline owners and managers, and decision makers should attend, and it should be presented in different seismically active regions throughout the United States.

Retrofit of Existing Facilities

Research is required to develop and implement simple cost-effective methods for retrofitting existing tanks. The proposed research and potential benefits should be directed into two areas. The first would be low-cost modifications that would be applied by a utility for its everyday maintenance program. The second area of investigation would be directed toward retrofitting projects of moderate costs. These modifications would increase the seismic resistance of a tank against collapse.

Funding for Research

There is a need to provide methods for funding research for lifeline projects. Traditional funding comes from federal agencies (NSF, NAS, USGS, FEMA), the AWWA, etc. It is proposed that a study be made to identify and implement innovative funding techniques to supplement the present funding sources. Consideration should be given to private sources, cost sharing, user fees, lotteries, etc.

Funding for Retrofit Implementation

Small public and private water and sewer utilities need to seismically retrofit their facilities; however, their funds to do this work are limited. There needs to be a study to plan, develop, and suggest methods for funding in addition to revenue from the sale of water. Consideration should be given to rate surcharges, taxes, bonds, tax exemptions, stocks, etc.

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