SEISMIC-RESISTANT DESIGN OF NEW TREATMENT FACILITIES AND PUMP STATIONS

Donald B. Ballantyne
Kennedy/Jenks/Chilton, Federal Way, Washington

This paper discusses new treatment facilities, wells, and pump stations including seismic and geotechnical evaluations, foundations, siting, intakes, outfalls, vaults, conduits, channels, equipment, instrumentation and controls, and power supplies. It is divided into five technical sections: system planning; foundations and buildings; channels, large conduit, vaults, and piping; equipment; and wells, intakes, and outfalls.

Each technical section considers available criteria, methods, and techniques for the design and construction of seismic-resistant facilities. Any ongoing activities are mentioned. General reference sources are identified in a sixth section.

The seventh section addresses problems and issues in need of attention. The final section makes recommendations to address the problems previously identified in terms of what should be done, how it should be done, who should do it, and the associated cost.

Retrofitting of existing facilities is not discussed nor are geotechnical considerations including lateral soil pressures, liquefaction, settlement, and slides. Power supply is addressed only as it relates to on-site emergency power generation and redundancy. Communication facilities are included only to the extent needed to indicate their critical nature. Neither tanks nor tank appurtenances (buried, ground level, elevated, of steel or concrete) are addressed herein.

SYSTEM PLANNING

Siting

Seismic concerns in siting facilities are one of many considerations to be taken into account. Potential surface ruptures, magnitude of ground motion accelerations, and local soil stability all must be considered. Assessments must be made comparing potential sites for their relative seismic risk and the costs associated with achieving the level of resistance to an earthquake event. Extensive work in siting facilities has been done in the nuclear industry. Although in siting facilities much can be learned from this work, the level of effort should relate to the magnitude and importance of the project and the risk.

System Reliability

The term "system reliability" as used here refers to a treatment plant or a pump station system, not to a complete water supply system. The reliability required for a pump station or treatment facility depends on where the particular component fits in the overall system (e.g., whether or not it is the only treatment facility supplying water to the system). Once the level of reliability is established, decisions can be made concerning how to provide that reliability. These decisions focus on such items as seismic loading criteria, level of redundancy of system components, and level of readiness for quick system repair. Methods for establishing loading criteria are currently available. Determinations concerning level of system redundancy and repair readiness are still qualitative decisions.

Documents are available that address general system reliability including *Design Criteria for Mechanical, Electric and Fluid System and Component Reliability* from the Environmental Protection Agency (1974) and the *Recommended Standards for Water Works*, which presents 10 state standards (Great Lakes-Upper Mississippi River Board of State Sanitary Engineers, 1976). Both of these documents are general in nature and do not specifically discuss potential seismic damage potential.

Prioritization of Facilities and Components

Each facility and each component of each facility should be assessed in terms of its expected performance following an earthquake. Priority criteria must be set for post-earthquake system operation using a rational approach (e.g., whether the plant can go without sludge processing for 24 hours). This prioritization can become very complicated. Adopted or normal standards for drinking water quality and levels of sewage treatment may not be warranted if a seismic event has only a 100-year recurrence. A determination must be made as to whether the particular facility or component is required to meet the system criteria for operation following an earthquake.

Environmental Quality System Inc.'s (EQSI) *Earthquake Design Criteria for Water Supply and Wastewater Systems* (1980) discusses an approach to prioritizing components of a treatment facility.

Once facilities and their components are prioritized, criteria for their design can be established. Loading design criteria may be different for different priority facilities. Other design criteria also may differ where costly design is employed for particular facilities.

Both the *Uniform Building Code* (UBC) (International Conference of Building Officials, 1985) and the Applied Technology Council (ATC,

1976) establish different seismic loading design levels for essential and nonessential facilities and equipment.

Structural Loading Criteria

Structural loading may be established from area-wide planning documents such as the UBC (1985) or may be done on a site-specific basis. Site specific analysis is more appropriate for critical facilities. The ATC (1976) presents maps that account for both lower and higher frequency seismic motions. Geotechnical engineers can provide response spectra for specific sites if the project magnitude so warrants.

CHANNELS, LARGE CONDUIT, VAULTS, AND PIPING

Channels and Large Conduit

Channels and large conduits connecting process units at treatment facilities are subject to seismic damage from several mechanisms including differential movement from seismic wave propagation between the channel and connected structure, differential settlement, and increased lateral earth pressures. Liquefaction has been known to float structures in areas of high ground water. Damage can be mitigated by providing adequate soil stability and flexibility along the channel and at its connection points and by accounting for increased lateral loads in the structural design. Quantifying required flexibility, however, can be a problem.

Flexibility can be provided in channel walls using dumbbell-type water stops or fused or breakaway-type joints. Repair of these joints can be considerably simpler than repair of a full channel section. Large conduit can be fitted with rubber bellows joints to provide the required flexibility.

Providing flexibility in conduit is an established practice. However, although many designs have been suggested for channel flexibility, there is no standard.

The American Concrete Institute (ACI, 1977 and 1978) discusses design of treatment structures but says little about seismic-resistant design.

Yard Piping

Yard piping can be damaged by the same mechanisms associated with channels. Smaller diameter pipe is inherently more flexible than concrete channels. Differential movement caused by seismic wave propagation may be accommodated in pipe joints as discussed in other papers in these proceedings or by expansion or flexible joints. Providing an offset in alignment also may accomplish the desired flexibility although the offset bends themselves may fail. Differential movement between piping and connected structures/wall penetrations must be accommodated.

The U.S. Departments of the Army, the Navy, and the Air Force (1982) provide details for recommended wall penetrations that will allow for differential settlement. Other authors such as EQSI (1980) also provide details for recommended wall penetrations.

Quantification is once again a problem with differential movement since the movement is dependent on soil type, its relative compaction, and the magnitude of the seismic waves. Geotechnical engineers should be able to provide reasonable estimates for design after they have conducted a geotechnical investigation.

Plant Piping

The plant piping discussed here is the above ground piping supported by pipe supports.

Pipe supports should be designed to support piping in the three orthogonal directions. Pipe 2.5 inches in diameter or less may not require seismic support unless it is critical piping. Supports should be designed to carry the earthquake design load of the full pipe as well as all nonearthquake loads in accordance with governing codes. Separate supports should be provided for piping appurtenances that will respond differently than the pipe. Pipe spans should be designed to have a natural frequency of greater than 20 cycles per second (cps) to minimize the pipe's response to earthquake energy. Piping should be adequately spaced to keep pipes from pounding against one another or the wall during a seismic event.

A single rigid pipe system should be supported by a single rigid structure (i.e., do not support rigid systems across building expansion joints or from floor to ceiling).

The pipe support system should be designed by the engineer, not by the contractor.

Small diameter piping containing hazardous chemicals should be protected from falling debris.

Flexibility should be provided in piping systems between systems that will respond differently. Examples include between piping and equipment, between pipe sections supported by different structures, and at wall penetrations.

Flexibility can be achieved in one, two, or three orthogonal directions using one or more flexible joints or offsets. Flexible joints can include bell and spigot, mechanical joints, expansion joints, rubber or metallic bellows, and ball joints.

It is also important to allow for thermal expansion and to provide thrust restraint.

The National Fire Protection Association's (NFPA) Manual 13 (1979) is an accepted reference for piping up to about 8 inches in diameter. The

Army/Navy/Air Force *Seismic Design for Buildings* (1982) contains recommendations for pipe support and flexibility. Many pipe support supplier catalogues include guides on support design. However, in many instances they only provide for gravity loads.

The American Society of Mechanical Engineers' (ASME) *Pressure Vessel and Piping Code* provides detailed criteria for the seismic design of high-pressure piping systems found in power generation plants. Piping systems typically encountered in the water and sewage industry operate at below 100 psi. As a result, rigorous pipe and support designs are not typically used.

EQUIPMENT

General Considerations

Each piece of equipment will respond to seismic motion as an independent structure. It is therefore necessary to:

1. Provide flexibility between the equipment and piping and electrical connections.

2. Select equipment that will have better response characteristics to seismic motion (i.e., low center of gravity, symmetrical, designed to carry the induced seismic load all the way to the base).

Anchoring

All equipment should be anchored using a rigid anchor system if possible. Rotating or otherwise vibrating equipment should be anchored using anchor bolts cast in place rather than expansion anchors. Anchor bolts/supports should be ductile. ACI presents its requirements for design of steel embedments as part of its *Code Requirements for Nuclear Safety Related Concrete Structures* (1978).

Equipment systems employing vibration isolation systems should use snubbers to limit the equipment response during a seismic event.

Secondary Support Systems

Systems required to operate a piece of equipment should have equal attention given to seismic design details as the equipment itself. Secondary systems of concern include batteries for starting, secondary power supplies, fuel pumps, engine cooling water, and bearing/seal lubrication.

Equipment Categories

Cast/Heavy Frame Equipment

Cast equipment typically has a high natural response frequency. Check stresses on long appendages such as the column and bowl assembly on vertical turbine pumps. Provide flexibility at connections to limit stress buildup in the casting.

Small Tanks

Supply rigid anchorage. Check buckling stress of the shell assuming the tank is full. Damping is extremely low in thin tall tanks. Avoid brittle cast iron support legs. Straps restraining tanks on saddles should be welded to the tank as tanks have slipped in past earthquakes, breaking their plumbing connections.

Frame/Sheet Metal Structures

Chemical feeders or electrical cabinets can support large masses. Check to make sure the structure can transfer horizontal loading to its base or that the back is anchored to a structural wall. Sheet metal sides act as diaphragms. Joints must be strong enough to transfer the loads. Maximize rigidity with cross bracing. Doors and removable panels break the equipment's structural continuity.

Immersed Equipment

Equipment immersed in sloshing water is subject to lateral hydraulic loading. Design to resist the loading or design for easy replacement. Baffles and launders, for example, could be designed for easy replacement. Account for increased lateral loads at the bottom of vertical turbine pumps hanging in tanks.

High-Pressure Gas and Hazardous Chemical Systems

Gas and chemical systems are particularly dangerous if damaged in an earthquake. Make sure all standard safety shutdown systems are installed and maintained. Equipment and piping should be protected from falling debris.

Chlorine cylinders should be strapped in place. Chlorine scales should be equipped with snubbers to resist lateral movement. Chemical feed lines should be kept as short as possible and operated at pressures as low as possible.

The Chlorine Institute provides guidelines for general chlorination system design but does not specifically address seismic design.

Cranes, Hoists, and Moving Bridges

Provide clips to keep wheels on tracks. Consider mechanisms to keep equipment from falling.

Massive Equipment

Sludge processing equipment such as centrifuges and filter presses and engine/generators should be located as low as possible in the building structure. The building may amplify earthquake ground motions. Separate equipment foundations may be used for critical units if flexibility is provided in connections across the foundation joint.

Instrumentation and Controls

Equipment controls should always include local manual controls in the event the central control room or communication is damaged. Precision equipment should be rigidly mounted to avoid amplification of seismic motions. Consideration should be given to the effect vibration will have on the equipment design. Communication and other critical equipment should have backup power supply. Consideration should be given to floor vibration isolation systems at large critical installations or separate foundations with base isolation.

Equipment Qualification

The owner should get assurance from the equipment supplier that the equipment will withstand the design earthquake. The supplier should provide the anchor design. A much more rigorous approach can be taken requiring some level of qualification.

Qualification can include shake table testing, either static or dynamic mathematical analysis, past experience, or design team judgment. Equipment qualification is used extensively in the nuclear industry.

FOUNDATIONS AND BUILDING STRUCTURES

Structure foundations should be compatible with the soils on which they are founded. Consideration should be given to the failure mechanisms associated with soils and foundations including liquefaction, surface rupture, slides, flows and differential settlement. A geotechnical investigation should be conducted to provide foundation recommendations. A wide range of foundation types are available to overcome various geotechnical problems. Soil stabilization and pile foundations are commonly used.

A single foundation type is recommended for any single structure so that it will respond in a uniform manner. For example, it is not recommended that a pile foundation be used for part of a slab and a mat foundation on the remaining portion. Avoid single structures founded on both fill and undisturbed soil.

Building structures should be designed as a minimum in accordance with codes. Design loads should be selected in accordance with the intended use of the structure. The UBC provides for higher design loads for essential facilities than for nonessential facilities. ATC 3-06 (1978) is currently under consideration for adoption by a number of agencies. It goes into great detail on seismic-resistant building design.

The building and enclosed facilities should be structurally compatible. A building should be rigid if it is to support a rigid system inside. Either the building and the attached structure should respond as a single unit or flexibility should be provided to accommodate differential movement.

WELLS, INTAKES, AND OUTFALLS

Wells

Well casings will move with the surrounding soils. Critical well installations may be double cased to a depth below where differential horizontal movement is expected (e.g., install a 12-inch casing inside a 24-inch casing). Select stable well sites if possible. Submersible pumps/motors have a greater probability of remaining in service if the casing is offset than do pumps connected to motors at the surface with driveshafts. Well casings will respond differently than the surrounding well house slab. A 1-inch flexible separation should be provided between the casing and slab. A flexible joint should be provided between the pump discharge header and the discharge piping.

Sanding of wells has been a problem in older wells subjected to earthquakes. Modern screen design should minimize this problem.

The major problem that has put wells out of service following an earthquake is contamination from sewage. Nearby sewers should be designed to resist earthquakes using ductile iron pipe. Septic tanks and cesspools should be pumped out, backfilled with sand and abandoned.

Intakes and Outfalls

Tall cylindrical concrete structures such as intakes may require a complex structural analysis. As submerged structures, they are subject to hydrodynamic forces of sloshing water.

Unstable embankments have led to severe damage to several intakes during earthquakes. Embankment stability and considerations for buries piping should be taken into account for sewage outfalls. Outfall diffusers also are subject to hydrodynamic forces.

RELATED REFERENCES

The American Society of Civil Engineers Technical Council on Lifeline Earthquake Engineering (ASCE TCLEE) has assembled a number of very relevant publications:

- *Advisory Notes on Lifeline Earthquake Engineering*, 1983
- *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*, 1984
- *Annotated Bibliography on Lifeline Earthquake Engineering*, 1981

Several ASCE conference proceedings have provided additional input:

- *The Current State of Knowledge of Lifeline Earthquake Engineering*, 1977
- *Lifeline Earthquake Engineering: The Current State of Knowledge*, 1981
- *Lifeline Seismic Risk Analysis*, 1986

The National Science Foundation has funded a number of major studies that have resulted in significant reports:

- *Earthquake Design Criteria for Water Supply and Wastewater Systems* by Environmental Quality Systems, Inc., 1980 (NSF Grant No. AEN 77-22617, available through NTIS).
- *Tentative Provisions for the Development of Seismic Regulations for Buildings* (ATC 3-06) by the Applied Technology Council.
- *Seismic-Resistant Design of Bridges* (ATC 6) by the Applied Technology Council.

The *Uniform Building Code* includes seismic-resistant design provisions for buildings and equipment.

The American Society of Mechanical Engineers (ASME) has developed standards for piping that include seismic considerations. ASME journals and proceedings often include papers on special design considerations for seismic resistance.

The American Water Works Association (AWWA) has included provisions for seismic-resistant design of water tanks at grade and elevated tanks in its *Standard for Welded Steel Tanks for Water Storage*, AWWA D100-83 (1983).

PROBLEMS AND ISSUES IN NEED OF ATTENTION

Need For Single Authoritative Document

Reference information is scattered. Standards have been written for the nuclear, highway, and building industries. Highway design has little relevance to the water and wastewater industry. Building design has some application. Standards for the nuclear industry, while considering many of the same subjects, are much more rigorous than those needed for the subject industry.

It is uncommon to see nuclear plant design references on a sanitary engineer's desk. However, tank design and equipment qualification had their roots in the nuclear industry.

The *Advisory Notes* prepared by ASCE TCLEE is an excellent reference source. Unfortunately, it has no teeth and is not in a standard format that could be adopted by organizations such as ASCE or AWWA. It was developed by a small group of experts in the field but doesn't have wide acclaim. It needs publicity.

The Guidelines for the Seismic Design of Oil and Gas Pipeline Systems also is an excellent reference but would not typically be on a sanitary engineer's desk.

Earthquake Design Criteria for Water Supply and Wastewater Systems is a very complete study. It was developed on the basis of an extensive literature review by a small group of people, but it lacks industry-wide input from interested organizations such as ASCE, AWWA, the Water Pollution Control Federation (WPCF), and the American Public Works Association (APWA). It also is 6 years old.

As noted above, the National Science Foundation (NSF) has funded numerous studies concerning various aspects of seismic-resistant design of sanitary facilities. Reports of damage to water and wastewater systems from significant earthquakes throughout the world are available. In both cases, the documents deal with a specific subject and are of limited use to the designer. Many NSF documents are of a theoretical nature and not prepared with the design engineer in mind.

Need for Increased Public/Design Professional Awareness

California residents and design professionals are acutely aware of earthquakes. Many water and sewer agencies in that Earthquake Zone 4 state have assessed the seismic vulnerability of their systems. Numerous emergency response programs have been developed at local, county, and state levels. East Bay Municipal Utility District, a large water district east of San Francisco Bay, has developed its own seismic design criteria.

By contrast, the state of Washington, with most of its population in Earthquake Zone 3, is far behind. Some seismologists have suggested the area may encounter a magnitude 8 earthquake. The largest water purveyor in the state upgraded the seismic resistance of its dams several years ago in response to a dam safety law enactment. Little more has been done relating to the system's seismic vulnerability. The state's second largest purveyor has a single supply line connecting its main water source and the city over 20 miles away. Portions of that line were built in the early 1900s with wood stave pipe. They are hoping for no major earthquakes. In all fairness, both of these Washington water systems were exposed to magnitude 7+ and 6+ earthquakes in 1949 and 1965, respectively, and survived with only moderate damage. The 7+ event, however, was over 30 miles from the largest purveyor. The author suspects that this level of awareness and concern are common throughout most of the country.

Cost of Seismic-Resistant Equipment and Materials

The San Francisco Water Department uses restrained joint bell and spigot ductile iron pipe in its fire distribution system. This pipe offers joint flexibility in all directions making it the best for seismic resistance but the Department pays a premium for the material.

The nuclear industry requires seismic qualification of critical equipment. It to pays a premium for the equipment.

SOLUTIONS

Single Authoritative Document

A single "Manual of Practice" should be developed by an engineering consultant active in the design of water and waste facilities with input from across the industry including utility representatives, academia, consulting engineers, and equipment and material suppliers. A possible mechanism for facilitating this involvement would be professional organizations such as ASCE, AWWA, WPCF, and APWA. An engineering consultant driving the process is the most effective way of completing the project since volunteer assistance typically cannot provide adequate time.

Development of a "Standard" would go a step further and would result in a document that could be used by governmental and insurance jurisdictions.

A budget of approximately $500,000 would be required for manual development. While primary funding would be needed from the federal government, contributions from professional organizations would benefit the cause.

Develop Public/Design Professional Awareness

Public awareness should be increased through educational programs.

Community concern ultimately may pressure decision makers to implement mitigation programs.

Professionals' awareness should be increased through professional organizations' publications and information programs such as those provided by the ASCE TCLEE.

Seismic-resistant lifeline design should be included in basic design courses at universities. Professional engineering licensing exams in more states should include seismic design. Funding for these programs should come from existing sources.

The biggest problem may be convincing the decision makers of the critical nature of the problem. Consideration should be given to developing a program similar to the National Flood Insurance Program. The federal government could subsidize an earthquake insurance program for lifeline facilities in Zones 2, 3, and 4. In order to get insurance, owners would have to upgrade facilities to some minimum level of seismic resistance. The private insurance industry already has influenced seismic-resistant design decisions in southern California.

Reduce Costs of Seismic-Resistant Equipment

It may be too expensive for a single owner to require seismic qualification of equipment. Equipment in this context should include all mechanical devices. A program could be instituted to perform shake-table testing on a line of standard equipment. Equipment weaknesses could be identified and the design could be improved at what would likely be a nominal cost. More seismically resistant equipment then would be available at competitive prices. Equipment design that could benefit most from shake-table testing may be structurally too complicated to otherwise analyze.

Similarly, a seismic-resistant pipe joint could be developed in the lab and manufactured as a standard. Pipe could be marketed that would respond well to earthquakes and be cost competitive. Money drives the manufacturing industry.

Consideration should be given to joint projects between equipment/material manufacturers and academia/consulting engineers to develop and market seismic-resistant equipment. Funding could be developed jointly between the manufacturers and the federal government. An investigation may be warranted to determine types of equipment that could be improved, relative improvement costs, and the relative benefits of the improvement.

SUMMARY

Since the 1971 San Fernando earthquake, extensive information has been developed as to how to design seismic-resistant water and sewage facilities. In the most highly seismic areas of the country that information has been applied to some designs but overall the nation falls far short in applying current seismic-resistant design technology to existing and new facilities. Although it is important to continuously develop better technology, it is essential to use now the considerable technology already available.

REFERENCES

American Concrete Institute, Committee 350. 1977. *Concrete Sanitary Engineering Structures*, ACI 74-26. Detroit, Michigan: ACI.

American Concrete Institute. 1978. "Proposed Addition to: Code Requirements for Nuclear Safety Related Concrete Structures (ACI 349-76)." *ACI Journal* (August):329-335.

Applied Technology Council. 1978. *Tentative Provisions for the Development of Seismic Regulations for Buildings*, ATC 3-06 and NBS Special Publication 510. Washington, D.C.: National Bureau of Standards.

American Society of Civil Engineers. 1977. *The Current State of Knowledge of Lifeline Earthquake Engineering*. New York: ASCE.

American Society of Civil Engineers. 1981. *Lifeline Earthquake Engineering: The Current State of Knowledge 1981*. New York: ASCE.

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering, Technical Committees. 1983. *Advisory Notes on Lifeline Earthquake Engineering*. New York: ASCE.

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering, Committee on Gas and Liquid Fuel Lifelines. 1984. *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*. New York: ASCE.

American Water Works Association. 1983. *AWWA Standard for Welded Steel Tanks for Water Storage*, AWWA D100-83. Denver, Colorado: AWWA.

Eguchi, Ronald T., Ed. 1986. *Lifeline Seismic Risk Analysis--Case Studies*. New York: ASCE.

Environmental Quality Systems, Inc. 1980. *Earthquake Design Criteria for Water Supply and Wastewater Systems*, Draft Report. Washington, D.C.: National Science Foundation.

Great Lakes-Upper Mississippi River Board of State Sanitary Engineers. 1976. *Recommended Standards for Water Works*, Bulletin 42. Albany: New York State Department of Health.

International Conference of Building Officials. 1985. *Uniform Building Code*, 1985 Ed. Whittier, California: ICBO.

National Fire Protection Association. 1979. *Installation of Sprinkler Systems, 1978*, NFPA 13. Boston, Massachusetts: NFPA.

U.S. Environmental Protection Agency, Office of Water Program Operations. 1974. *Design Criteria for Mechanic, Electric, and Fluid System and Component Reliability*, EPA 430-99-74-001. Washington, D.C.: EPA.

U.S. Departments of the Army, the Navy, and the Air Force. 1982. *Seismic Design for Buildings*. Washington, D.C.: U.S. Departments of the Army, the Navy, and the Air Force.