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# EARTHQUAKE EXPERIENCE DATA ON GROUND MOUNTED ANCHORED VERTICAL STORAGE TANKS

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## SUMMARY

Data on the actual performance in past earthquakes ("earthquake experience data") of ground mounted, anchored vertical storage tanks were collected and compiled. These data show that such tanks from power plant and industrial facilities which are similar to nuclear plant tanks are capable of surviving significant earthquake ground motions without a loss of contents. Current methods were used to analyze selected data base tanks for estimated site ground motions. Implicit factors of safety in these methods were estimated.

## INTRODUCTION

Ground mounted vertical storage tanks are components important to nuclear power plant safety. Nearly all of these tanks in United States nuclear plants are anchored. Seismic design criteria for older tanks assumed that they are rigid and that the impulsive mode responds at the earthquake peak ground acceleration. Studies have shown that this assumption is typically unconservative because of tank flexibility. Changes to U.S. nuclear plant seismic design criteria may result in seismic loads greater than those considered in the original design.

Seismic reevaluations of older nuclear power plants are being conducted because of revisions to seismic design criteria and changing perceptions of the seismic hazard at certain sites. Actual performance in past earthquakes ("earthquake experience data") has been accepted as a means of assessing the seismic adequacy of several categories of equipment components for these reevaluations. In a study sponsored by the Electric Power Research Institute, earthquake experience data on ground mounted, anchored vertical storage tanks were collected to develop general conclusions on nuclear plant tank seismic adequacy, as appropriate. These data are presented in the following discussion. Ref. 1 describes their application to nuclear plant tanks in more detail.

## EARTHQUAKE EXPERIENCE DATA

<u>Sources of Experience Data</u> Readily available earthquake experience data on ground mounted anchored vertical storage tanks were collected from two sources: (1) Post-earthquake investigations performed by EQE personnel and (2) a limited literature survey of post-earthquake investigations performed by other engineers. These data were obtained from several earthquakes, starting with the 1971

San Fernando earthquake up to the New Zealand and Whittier earthquakes of 1987.

Tanks From Power Plant and Industrial Facilities The total population of ground mounted anchored tanks was screened to identify only those tanks considered applicable to the study of nuclear plant tank seismic adequacy. Screening eliminated the following data: (1) Tanks subjected to average horizontal peak ground accelerations less than about 0.15g, (2) tanks fabricated from fiberglass, (3) tanks with shell thicknesses less than 3/16 inches, and (4) tanks known or judged to be less than about 50% full. The tanks listed in Table 1 were judged to be applicable. They are generally from power plant and industrial facilities. An example is shown in Photo 1.

Aside from fiberglass and thinwalled stainless steel tanks (discussed below), damage to anchored tanks in past earthquakes is relatively rare. Observed damage is summarized in Table 1. It is mostly associated with tank anchorage (i.e., anchor stretch or pullout). There are only a few cases of reported buckling or minor leakage at a valve or pipe coupling. A rapid and total loss of contents was probable in only a single known instance. The primary cause was failure of a stiff attached pipe that experienced larger seismic displacements after anchor failure.

Data on the applicable data base tanks were compiled in terms of the parameters that are important to seismic adequacy. These parameters account for tank ground motion input, construction, size, configuration, materials, anchorage, and foundation conditions. In addition to individual tank parameters, a seismic capacity index (SCI) was defined. It combines several parameters to provide an overall measure of relative seismic capacity between different tanks. The normalized seismic capacity index was defined as the SCI divided by the average horizontal peak ground acceleration. It provides a better measure of the available seismic capacity relative to ground motion input.

The resulting parametric compilations are summarized in Table 2. They establish the extent and applicability of the experience data. The data base tanks were subjected to significant ground motion levels, with some horizontal peak ground accelerations up to about 0.6g. A wide range of parametric values are covered. Parameters from a sampling of U.S. nuclear plant tanks were similarly compiled. The data base and nuclear plant tanks were found to be comparable for several parameters. Most nuclear plant tanks have greater unnormalized and normalized seismic capacity indices. These comparisons show that the experience data are applicable to nuclear plant tanks, and that earthquake performance of nuclear plant tanks should be good.

Thinwalled Stainless Steel Tanks Stainless steel tanks with shell thicknesses of about 0.1 inches are commonly used to store consumable liquids. They were categorized separately from tanks at power plant and industrial facilities because of dissimilarities in tank parameters and construction. Thinwalled stainless steel tanks have suffered shell buckling, leakage, and even rupture or collapse in past earthquakes (Photo 2). Although damage is more common, tank failure with total loss of contents is still relatively infrequent. The instances of tank failure occurred due to a combination of high ground motion (horizontal PGA of about 0.5g), large shell radius to thickness ratio (greater than 1000), and non-ductile anchor failure.

## ANALYTICAL EVALUATIONS OF SELECTED DATA BASE TANKS

While the available earthquake experience data shows that the performance of anchored tanks at power plant and industrial facilities is good, the data base is probably not large enough to conclusively envelope all important tank parameters.

Consequently, analysis methods are needed to verify tank seismic adequacy. Selected data base tanks were evaluated using current analytical methods to provide first estimates on the adequacy of these methods (i.e., determine if a conservative method is conservative) and to identify major considerations for future study.

The following three methods to determine tank buckling capacity were investigated: Conservative design, high confidence of a low probability of failure (HCLPF) capacity, and best estimate. Major differences between these methods are summarized in Table 3. Seismic response analyses followed the recommendations of Refs. 2 and 3. The conservative design method could be used to design a tank to meet current U.S. nuclear plant criteria. The stress analysis provisions of Ref. 4 were used. The HCLPF capacity method followed the recommendations of Ref. 3 for the seismic reevaluation of existing nuclear plant tanks. Conservative seismic capacities were determined using parameters and procedures more liberal than design criteria. Ductile anchor bolt yielding with subsequent shell stress redistribution was permitted. The best estimate method calculated approximate median capacities against initial shell buckling. It followed the HCLPF capacity method, but used estimates of median shell buckling and anchor bolt yield stresses. Slight reduction in effective seismic load due to inelastic energy absorption by yielding anchor bolts was also included when appropriate.

Selected data base tanks which did not buckle were evaluated. Fixed base seismic responses were determined for estimated actual site ground motions, including amplification due to shell flexibility. Ratios of seismic capacity to seismic demand were calculated for these tanks by all three evaluation methods. Results are summarized in Table 4.

The conservative design and HCLPF capacity methods are conservative if capacity to demand ratios are less than unity for tanks that did not buckle. This was found to be the case. Lower bound estimates on the implicit factors of safety for given ground motion, based on the inverses of the capacity to demand ratios, appear to be about 1.5 to 2 for the HCLPF capacity method and about 2.5 for the conservative design method. Tank design or reevaluation by these methods will introduce additional conservatism through the specification of ground motion input that has a low probability of exceedance. Two cases have capacity to demand ratios less than unity for the best estimate method. Although termed best estimate, there may still be conservatism introduced by neglecting potential soil-structure interaction (SSI) effects, and uncertainties in the ground motion and buckling stress estimates.

## CONCLUSIONS

Review of readily available earthquake experience data demonstrates that the performance of anchored tanks from power plant and industrial facilities is good. There have been instances of anchor damage, buckling, and minor leakage. However, anchored tank failure with a gross loss of contents was probable in only a single known instance. The primary cause was failure of a stiff attached pipe that experienced larger seismic displacements after brittle anchor failure. However, the tank wall maintained its integrity.

The experience data base described herein may not be complete, and is probably not large enough to conclusively envelope all important tank parameters. Analysis methods are therefore needed to verify tank seismic adequacy. The conservative design and high confidence of a low probability of failure capacity methods appear to provide levels of conservatism consistent with their intended applications. The best estimate evaluations indicate that more rigorous investigation may be necessary to reduce certain conservatisms and uncertainties.

Table 1 - Applicable Experience Data Base Tanks

| Earthquake | Facility | PGA (g)(1) | Component | EQ (2) Effects |
|---|---|---|---|---|
| San Fernando, 1971 | Glendale Power Plant | 0.28 | Distilled Wtr Tank #1A | 1 |
| San Fernando, 1971 | Glendale Power Plant | 0.28 | Distilled Wtr Tank #1B | 1 |
| San Fernando, 1971 | Glendale Power Plant | 0.28 | Distilled Wtr Tank #2 | 1 |
| San Fernando, 1971 | Glendale Power Plant | 0.28 | Fuel Oil Day Tank #1 | 1 |
| San Fernando, 1971 | Jensen Filt Plant | 0.50 | Washwater Tank | 2,3 |
| San Fernando, 1971 | Pasadena Power Plnt B1 | 0.20 | Distilled Water Tank | 1 |
| San Fernando, 1971 | Pasadena Power Plnt B2 | 0.20 | Distilled Water Tank | 1 |
| San Fernando, 1971 | Pasadena Power Plnt B3 | 0.20 | Distilled Water Tank | 1 |
| Managua, 1972 | Asososca Lake | 0.50 | Surge Tank | 2 |
| Ferndale, 1975 | Humboldt Bay Pwr Plt 3 | 0.30 | Condensate Strg Tank | 1 |
| Miyagi-ken-oki, 1978 | Sendai Refinery | 0.40 | Fire Water Strg Tank | 2,4 |
| Humboldt Cty, 1980 | Humboldt Bay Pwr Plt 3 | 0.25 | Condensate Strg Tank | 1 |
| Greenville, 1980 | Sandia National Lab | 0.25 | Fuel Oil Strg Tank | 2,3 |
| Coalinga, 1983 | Coalinga Wtr Flt Plnt | 0.60 | Wash Water Tank | 2,4 |
| Coalinga, 1983 | Kettleman Gas Comp Stn | 0.20 | Lube Oil Fuel Tank #2 | 1 |
| Coalinga, 1983 | Kettleman Gas Comp Stn | 0.20 | Lube Oil Fuel Tank #3 | 1 |
| Coalinga, 1983 | Kettleman Gas Comp Stn | 0.20 | Lube Oil Fuel Tank #6 | 1 |
| Coalinga, 1983 | Pleasant Valley P-Stn | 0.56 | Surge Tank | 2 |
| Coalinga, 1983 | San Luis Canal P-Stn | 0.35 | Surge Tank | 2,5 |
| Coalinga, 1983 | Union Oil Butane Plnt | 0.60 | Diesel Fuel Oil Tank | 1 |
| Coalinga, 1983 | Union Oil Butane Plnt | 0.60 | Diesel Fuel Oil Tank | 1 |
| Chile, 1985 | Las Ventanas Pwr Plnt | 0.25 |  | 1 |
| Chile, 1985 | Las Ventanas Pwr Plnt | 0.25 |  | 1 |
| Chile, 1985 | Las Ventanas Pwr Plnt | 0.25 |  | 1 |
| Chile, 1985 | Las Ventanas Pwr Plnt | 0.25 | Oil Storage Day Tank | 1 |
| Chile, 1985 | Las Ventanas Pwr Plnt | 0.25 | Oil Storage Day Tank | 1 |
| Adak, 1986 | Fuel Pier Yard | 0.20 | Small Craft Refuel Tank | 1 |
| Adak, 1986 | Power Plant #3 | 0.20 | Tank #4 | 1 |
| Adak, 1986 | Power Plant #3 | 0.20 | Tank #5 | 1 |
| New Zealand, 1987 | Caxton Paper Mill | 0.40 | Chip Storage Silo | 1 |
| New Zealand, 1987 | Caxton Paper Mill | 0.40 | Hydrogen Peroxide Tank | 1 |
| New Zealand, 1987 | Caxton Paper Mill | 0.40 | Secondary Bleach Tower | 1 |
| New Zealand, 1987 | New Zealand Distillery | 0.50 | Bulk Storage Tank | 1 |
| New Zealand, 1987 | New Zealand Distillery | 0.50 | Bulk Storage Tank | 1 |
| New Zealand, 1987 | New Zealand Distillery | 0.50 | Bulk Storage Tank | 1 |
| New Zealand, 1987 | New Zealand Distillery | 0.50 | Bulk Storage Tank | 1 |
| New Zealand, 1987 | New Zealand Distillery | 0.50 | Receiver Tank | 1 |
| New Zealand, 1987 | Whakatane Board Mills | 0.30 | Pulp Tank | 1 |
| New Zealand, 1987 | Whakatane Board Mills | 0.30 | Pulp Tank | 1 |
| New Zealand, 1987 | Whakatane Board Mills | 0.30 | Pulp Tank | 1 |
| Whittier, 1987 | Pasadena Power Plnt B1 | 0.17 | Distilled Water Tank | 1 |
| Whittier, 1987 | Pasadena Power Plnt B2 | 0.17 | Distilled Water Tank | 1 |
| Whittier, 1987 | Pasadena Power Plnt B3 | 0.17 | Distilled Water Tank | 1 |

Notes:

1. Values shown are estimated average horizontal PGAs.
2. 1 = No damage, 2 = Anchor damage, 3 = Shell buckling 4 = Minor leakage at valve or pipe coupling, 5 = Probable total loss of contents

Table 2 - Data Base Tank Parameters

| Parameter | Summary |
|---|---|
| Peak ground acceleration | Ranges from 0.15g to about 0.6g |
| Soil conditions | Mostly alluviums and sands |
| Foundation type | Base mats and ring walls * |
| Tank vintage | Most built before 1970 * |
| Volume capacity | Most data less than 200,000 gallons |
| Tank material | * |
| Shell height | Most data between 10 feet and 50 feet |
| Shell diameter | Most data between 10 feet and 30 feet |
| Base course shell thickness | Most data between 3/16 in. and 3/8 in. |
| Shell height to diameter ratio | Most data between 1.0 and 2.5 |
| Shell radius to thickness ratio | Most data between 200 and 500 |
| Anchor type | Various, mostly anchor bolts |
| Anchor material | * |
| Ratio of total anchor to tank cross-sectional area | Most data between 0.02 and 0.08 |
| Anchor to tank attachment | Various, mostly chairs or lugs |
| Seismic capacity index | Most values between 0.2 and 1.0 |
| Normalized seismic capacity index | Most values between 0.5 and 2.0 |

* Limited precise data available

Table 3 - Comparison of Analysis Methods

| Item | Conservative Design | HCLPF Capacity | Best Estimate |
|---|---|---|---|
| Impulsive mode damping | 4% | 5% | 5% |
| Allowable anchor bolt force | Code allowable factored by 1.6 | Code allowable factored by 1.7 | Median yield stress on nominal area |
| Shell buckling stress | API 650 Code allowable | Conservative allowable | Median estimate |
| Bottom plate resistance | Not included | Included | Included |
| Stress distribution | Elementary beam theory | Anchor bolt yield and stress redistribution | Anchor bolt yield and stress redistribution |
| Inelastic energy absorption stress correction factor | 1.0 | 1.0 | 0.9 |

Table 4 - Summary of Analytical Results

| Tank | Impulsive Freq. (Hz) | Cons. Design | HCLPF Capacity | Best Estimate |
|---|---|---|---|---|
| Coalinga Water Filtration Plant Wash Water Tank | 6.1 | 0.41 | 0.50 | 0.81 |
| Pasadena Power Plant Unit B2, Dist. Water Tank | 12 | 0.89 | 2.3 | 3.2 |
| Pasadena Power Plant Unit B3, Dist. Water Tank | 7.5 | 0.88 | 1.35 | 1.7 |
| San Martin Winery<br>4'-3" 0 x 20'-0" H<br>Wine Storage Tank | 7.1 | 0.41 | 0.69 | 1.0 |
| Sendai Refinery Firewater Tank (1) | 5.5 | 0.21 | 0.53 | 0.73 |

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1. Capacity to demand ratios are very approximate due to lack of detailed data.

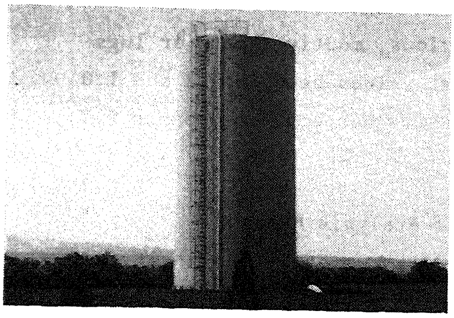

Photo 1: Coalinga Water Filtration Plant

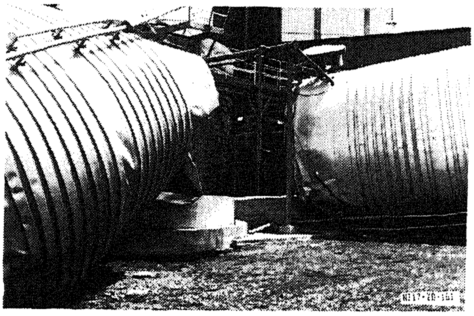

Photo 2: New Zealand Distillery

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