SEISMIC RESPONSE OF FLEXIBLE CYLINDRICAL TANKS

R. W. CLOUGH
Department of Civil Engineering, University of California, Berkeley, California 94720, U.S.A.

D. P. CLOUGH
Norwegian Institute of Technology, Trondheim, Norway

SUMMARY

An experimental study of the seismic behavior of thin shell circular cylindrical liquid storage tanks is described. The investigation was planned to evaluate the adequacy of present methods of tank design, and was conducted using the Earthquake Simulator Facility of the University of California, Berkeley. The model tank considered in this paper was 6 ft high by 12 ft in diameter, and was welded from thin sheet aluminum to simulate a steel tank 36 feet in diameter. During testing the tank had an open top, held 60 inches of water, and was subjected to a time scaled El Centro (1940) earthquake, amplified to a peak acceleration of 0.5 g. Both base free and base fixed conditions were studied.

Results of the experiments demonstrate that fluid pressures included both impulsive and convective components, and that the wave sloshing followed basic theory quite closely. But it also was apparent that the tank flexibility influenced the hydrodynamic pressures, as indicated by pressure amplification in the clamped tank, and by a total change of pressure history in the unclamped case. Significant out of round distortions of the tank were developed, of a three lobe form for the free base case and with four lobes in the fixed base case. Uplift of the tank base was closely related to the out-of-round deformation of the unanchored tank, whereas initial eccentricities apparently caused the section distortions in the anchored system. Stresses in the tank wall do not follow the expected pattern of response to overturning moment; instead they seem to be mainly associated with the section distortions. At present there is no analytical procedure for predicting these distortions.
1. **Introduction**

Typical thin shell cylindrical liquid storage tanks have suffered significant damage in many recent earthquakes [1,2]; hence it is apparent that either the design criteria or the seismic response analysis procedures are in need of review. Most current design techniques involve estimates of dynamic fluid pressures based on assuming a rigid tank wall and single mode of sloshing [3]. Although doubt has been expressed concerning the validity of these assumptions when applied to thin shell metal tanks, experimental data have not been available to evaluate them.

Accordingly, an experimental research program was proposed by a group of organizations under the leadership of Chevron Oil Field Research Company to study the seismic behavior of cylindrical liquid storage tanks, using the earthquake simulator facility of the Earthquake Engineering Research Center (EREC), University of California, Berkeley. The two principal model tanks considered in this study had dimensions (diameter x height) of 12 x 6 ft and 7 1/2 x 15 ft, and were intended to represent relatively broad and relatively tall tanks, respectively.

It was anticipated that the seismic behavior of these two geometries would be significantly different, and preliminary study of the experimental results supports this expectation. However, reduction of the data from the tall tank has not yet been completed, so this paper deals only with the seismic behavior of the model which was 6 ft high and 12 ft in diameter. Included in the paper is a brief description of the earthquake simulator facility, of the test tank and instrumentation, a listing of the test parameters, and a discussion and interpretation of the test results. A complete description of the test program and results obtained from this model is presented in Reference 4.

2. **Earthquake Simulator** [5]

The EERC Earthquake Simulator Facility at the University of California Richmond Field Station was designed by faculty and staff of the Department of Civil Engineering, the hydraulic actuator and control system was supplied by MTS Corporation, and the entire facility including the data acquisition system and the building was funded by the National Science Foundation. It was completed and put into regular test operations in April 1973.

The shaking table is a 20 ft square concrete slab, heavily reinforced and post-tensioned in both directions, and weighing about 90,000 pounds. It is supported by hydraulic actuators in a 1,500,000 lb foundation block. Four actuators drive the table vertically and three drive it in one horizontal component; independent vertical and horizontal motions can be applied simultaneously. A rubberized membrane provides a seal between the edge of the table and the foundation block, and during tests 2 to 4 psi of air pressure is applied under the table to support the dead weight of the table and test system; thus the vertical actuators supply only the vertical accelerations.

The table may be controlled to provide any desired seismic inputs in the two components, using magnetic tape records of the displacement histories. Usually these are derived by double integration of accelerograms recorded during an actual earthquake. The maximum displacements of the table are 15.5 in. and 12.5 in. in the horizontal and vertical directions, respectively; corresponding peak accelerations are 2/3g and 4/9g when testing a maximum payload of 100,000 lb.

The facility includes a 128 channel digital data acquisition system. During normal operation each transducer signal is sampled at rate of about 50 readings per second and
recorded in digital form on a magnetic disc. After completion of an earthquake test, the
data are transferred from disc to magnetic tape for subsequent processing and plotting.

3. Test Structure and Instrumentation

The 12 ft x 6 ft tank, shown on the shaking table in Fig. 1, was welded from sheets of
aluminum 3 ft high and 0.080 and 0.050 in. thick. It was intended to simulate a 36 ft diameter
steel prototype, the modulus of elasticity ratio providing for similitude of gravity and
seismic stresses, using a time scale of $\sqrt{3}$. A 9 in. wide annulus of 0.80 in. aluminum sheet
was welded to the base of the tank wall and bolted to the 1/8 in. steel plate which formed
the central portion of the tank bottom.

The tank was attached to the shaking table by four bolts located at a 3 ft. radius about
the center of the bottom plate. In addition, anchoring devices were provided which could
clamp the edge of the base plate rigidly to the table. Thus two different tank systems were
studied: (1) with the tank wall free to uplift, and (2) with the base of the tank wall fully
clamped.

Instrumentation was installed to measure the acceleration and displacement of the shak-
ing table as well as the most significant features of the tank response. Four pressure trans-
ducers were located in the south tank wall on the excitation axis at 2, 18, 35, and 53 in.
above the base. Six wave height gages were positioned at equal intervals along the excita-
tion axis. Direct current differential transformers (DCTT's) were used to measure radial and
tangential displacements at sections 36 and 74 inches above the base, radial components being
measured at 45° increments around the circumference and tangential components at 90° inter-
vals. In addition, vertical displacements of the tank base were measured at the north and
south edge; thus a total of 26 displacement gages were used. Twenty strain rosettes were
applied to the inner and outer tank wall surfaces at 10 gage stations. Seven of these were
located on a section 2 in. above the base at angles (from North) of -30°, 0°, 30°, 60°, 150°,
and 180°. The other three were located on a vertical line at 0°, with heights of 1/2, 1/8,
and 1/4 in. above the base.

4. Test Parameters

The principal test parameters of this investigation were as follows:

- Base Constraint: Fixed or free
- Water Depth: 35, 48, 60 in.
- Roof Type: Open, fixed conical, floating
- Earthquake Intensity: El Centro (1/8g, 1/16g, 1/2g), Picoima (1/2g), Parkfield (1/2g)

All earthquake inputs were speeded up by a factor of 1.73 to maintain similitude.

Due to space limitations only the "standard" case will be discussed here: El Centro
earthquake (N-S component) with 0.5g peak acceleration, 60 in. water depth, and open top.
The only parametric variation considered is the base condition: fixed or free.

5. Test Results & Discussion

5.1 Time-History: A vast amount of data was obtained in each earthquake simulator test,
because the earthquake excitation had a duration of approximately 20 seconds, 50 readings per
second were obtained in each channel, and a total of 98 significant channels were recorded.
Thus each test case provided about 98,000 items of response information. Such large quanti-
ties of information can be evaluated only in graphical form, and three different types of
plots were constructed to assist in the interpretation.
The data obtained from each individual gage can be studied most conveniently in the form of a time-history plot, and certain features of the response behavior are evident in parallel plots of records made by several different gages. Fig. 2 is an example of this type of plot, showing in the successive graphs the history of acceleration, pressure at the tank base, wave height at the side of the tank and uplift of the tank base. Of significance in these plots is the close correlation shown between (a) table acceleration and (b) liquid pressure. Evidently the base acceleration induces impulsive pressures rather directly; however, careful examination of the pressure record reveals both high frequency and long period effects superimposed on the acceleration response. These are due to vibratory response of the tank wall and the first mode liquid sloshing, respectively. The latter effect is clearly shown by comparison of curves (b) liquid pressure and (c) wave height. The other significant feature of Fig. 2 is shown in plot (d) uplift, which demonstrates that the uplift is in response to the base accelerations but primarily at times when the sloshing favors uplift. Although Fig. 2 illustrates the behavior of the tank when free to uplift, the pressure and wave response was observed to be very similar for the fixed base condition.

Displacement histories of the tank response are much more meaningful when expressed in terms of components of Fourier expansions rather than by individual gage readings. For this reason, 8 Fourier components of radial displacement and 4 components of tangential displacement were evaluated from the 12 BCDT measurements at both midheight and the top of the tank; 6 of the radial displacement components are pictured in Fig. 3. Time histories of the amplitudes of the Fourier components clearly show the influence of different response frequencies, as is apparent in Fig. 4. Graphs a and b, showing the three lobe and four lobe radial displacements for the free base case, have distinctly lower frequencies than the corresponding fixed base results shown in graphs c and d; moreover it should be noted that the free base amplitudes are about two orders of magnitude larger than the fixed base motions.

5.2 Cross-section Deformations: The Fourier component representation of the tank deformations also provides an effective basis for plotting the distorted shapes at any selected instant of time. Distortion sequences during intervals of intense response are shown in Fig. 5a for the tank with base free, and in Fig. 5b for the fixed base case. The time interval between successive views is about 0.06 seconds (3 reading intervals) and the sequence is left to right, top line first. Fig. 5a clearly shows the three lobe deformation pattern which develops with the occurrence of base uplift, the top rim of the tank deflecting inward as the base uplifts. The four lobe shape shown in Fig. 5b demonstrates that the tank behavior is entirely different when the base is fixed; also, it should be noted that the top rim deflection is only one-fifteenth as great here as in the free base case. In addition, the data show that the top rim deflections are nearly twice the midheight deflections when the base is free, while the reverse is true when the base is fixed.

5.3 Isometric Plots: In order to characterize the complex structural response mechanism indicated by the various transducer readings, a three-dimensional isometric plot format was developed. This consists of time history plots of a selected group of transducer readings, with time indicated in one coordinate direction. In addition, the various plots are arranged with respect to each other in accordance with the relative spatial positions of the transducers on the tank. This makes possible the construction of plots in the plane perpendicular to the time axis which indicate the spatial distribution of the response quantity at successive instants of time.
The example isometric plot shown in Fig. 6 depicts the distribution of membrane hoop stresses at the section 2 in. above the base during the interval of maximum uplift for the base free case. Also shown are the uplift displacement measured at the north and south edges of the tank, and the table acceleration. The correlation of hoop stresses and uplift is obvious; as the tank uplifts on one side, the base of the tank on that side is subjected to compressive hoop stresses produced by the catenary tension in the bottom plate. The hoop stress on the side of the tank still in contact with the table is negligible. In addition, the figure shows good correlation between the uplift sequences and the peaks of table acceleration.

Similar isometric plots for the fixed base case show that the stress distribution is much more complex when the deformations are not dominated by uplift. It is of interest that the axial stress distribution around the base bears no relationship to the linearly varying strain assumption of elementary beam theory.

6. Correlation with Design Assumptions

6.1 Fluid Response: Current thin shell liquid storage tank designs generally are based on hydrodynamic pressures predicted by Houssner's approximate analysis, which assumes that the liquid in the tank may be divided into one part which moves directly with the tank and a second part which moves relative to the tank at the first sloshing mode frequency. Pressures induced by these two masses of water are designated impulsive and convective, respectively; and because the tank is presumed rigid, the impulsive pressure is in direct response to the base acceleration. The sloshing liquid, on the other hand, responds to the base acceleration as a single degree of freedom system, amplified or attenuated as indicated by the response spectrum of the input motions.

The validity of the latter aspect of the Houssner model may be assessed by comparing the observed amplitude of sloshing with that predicted using the response spectrum of the shaking table motion. For the standard test case, the observed and predicted peak slosh heights were 13.7 and 15.3 inches, respectively, demonstrating adequate agreement. When the response behavior of this test structure is studied in detail, however, it is evident that the impulsive component dominates the pressure response rather than the slosh mechanism. Correlations of the observed dynamic pressures with analytical results calculated with the Houssner model are shown in Fig. 7. The correlation obtained near the base in the fixed base case, shown in Fig. 7c, is seen to be quite satisfactory, which demonstrates that the rigid tank assumption is valid near the clamped base. Pressures observed at mid-height for the fixed base case, shown in Fig. 7d, are similar to the analytical prediction, but are amplified by a factor of nearly two due to the flexibility of the tank wall. The results for the free base case, shown in Figs. 7a and 7b, demonstrate major deviations of the actual tank behavior from the assumed response mechanisms, due to the influence of uplifting.

6.2 Stress Response: More important than the analytical predictions of hydrodynamic pressure are stress estimates derived from the calculated pressures. In typical design procedures, the stress analysis is based primarily on the overturning moment induced by the dynamic pressures. For fixed base tanks, the stresses are calculated by beam theory, treating the tank as a cantilever column; for unanchored tanks where uplift may occur, equilibrium is established by the weight of the liquid acting on the uplifted tank base. In both cases, the assumed distribution of axial stress around the base of the tank wall has a very simple form. However, the axial stresses determined experimentally in the present study, which have been
presented in isometric plots similar to Fig. 6, exhibit highly localized concentrations apparently associated with the patterns of out-of-round distortions. Thus it is clear that the usual design procedures do not take account of the principal mechanism inducing axial stresses in the test tank.

7. Conclusions

One of the principal conclusions to be drawn from this investigation is that experimental studies such as this have great value in structural mechanics. The tests reported herein have demonstrated for the first time the actual seismic behavior of a thin shell circular cylindrical tank. These results show that the fluid-structure interaction produces significant cross-section distortion of the tank, even though the primary seismic loads tend to induce only translation of the circular section.

The source of out-of-round distortion is clear for the free base case because uplift obviously destroys the axial symmetry by reducing the effective stiffness in the uplifted region. This nonlinear response mechanism is potentially amenable to step-by-step analysis, but no such studies have yet been attempted.

In the fixed base case, the cause of section distortions is less evident, but probably it is associated with initial imperfections in the tank geometry. For example, the four lobe Fourier component, which is strongly represented in the dynamic response for this case, may be associated with the vertical weld lines in the tank which are located at 30° intervals. Linear analysis of the influence of such imperfections seems feasible, but it has not yet been done; moreover, it will be difficult to measure the imperfections in the fluid filled tank.

Hydrodynamic pressures predicted by elementary rigid tank theory show good agreement with experiment only when the tank wall displacements are small. Some modification of the theory is needed to account for tank deformations. Perhaps cantilever column deflections excluding section distortion, as proposed by Veletsos [6] may provide some improvement, but it appears from these results that section distortion is a significant factor both in the hydrodynamic pressures and in the stress response. Thus it may be concluded that further study of the response mechanisms associated with out-of-round distortions for both fixed and free base conditions is essential in order to make improvements in the seismic design procedures of liquid storage tanks.

REFERENCES


Fig. 1  6 ft x 12 ft Model Tank during Shaking Table Test.

Fig. 3  Fourier Components of Radial Displacements
Fig. 2  Earthquake Input and Tank Response – Free Base Case.

a. Table Acceleration

b. Hydrodynamic Pressure at Mid-Height

c. Wave Height at Tank Wall

d. Uplift of Tank Base on Excitation Axis
Fig. 4  Response Amplitude of Selected Fourier Components

a. Base Free - Cos 30 Component

b. Base Free - Cos 40 Component

c. Base Fixed - Cos 30 Component

d. Base Fixed - Cos 40 Component
Fig. 5 Top Rim Deformation History

a. Base Free

b. Base Fixed
Fig. 7 Correlation of Hydrodynamic Pressure-Observation vs. Theory

a. Base Free - 2 in. Height

b. Base Free - 35 in. Height

c. Base Fixed - 2 in. Height

d. Base Fixed - 35 in. Height