Seismic Analysis and Design of Steel Liquid Storage Tanks

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ABSTRACT

Practicing engineers face many issues and challenges on the design and seismic evaluation of liquid storage tanks. These challenges are generally either in the application of the current design codes and standards, or in choosing an appropriate design method. This paper addresses the design issues on the liquid storage tanks especially on the steel tanks, and the application of the ANSI/AWWA D-100 standard on the design of ground steel tanks.

INTRODUCTION

The greater Los Angeles area have experienced lifeline damage due to earthquakes. Collapses of water tanks during the 1933 Long Beach and the 1971 San Fernando earthquakes had serious consequences. Liquid storage tanks are critical lifeline structures that are geographically dispersed over broad areas. These tanks are exposed to a wide range of seismic hazards, community users, and interactions with other sectors of the built environment. Problems associated with the seismic behavior of liquid storage tanks involve the analysis of three systems: the tank, the soil and the liquid, as well as the interaction between them along their boundaries. To achieve accurate results, a 3-D nonlinear finite element analysis of tank system shall be implemented considering (1) the interaction between the tank and the liquid (2) the dynamic soil-structure interaction. Such 3-D nonlinear finite element analysis, including the contained fluid as well as the foundation soil in the system, is complex and extremely time consuming. Figure 1 illustrates the technical complexity on the analysis of such systems, and such approach is generally not practical for engineers to pursue.

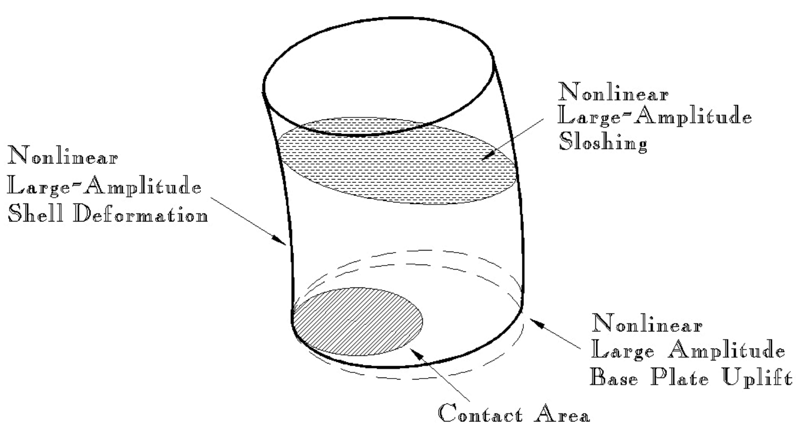


Figure 1. Nonlinear Complex Behavior of Liquid Storage Tanks

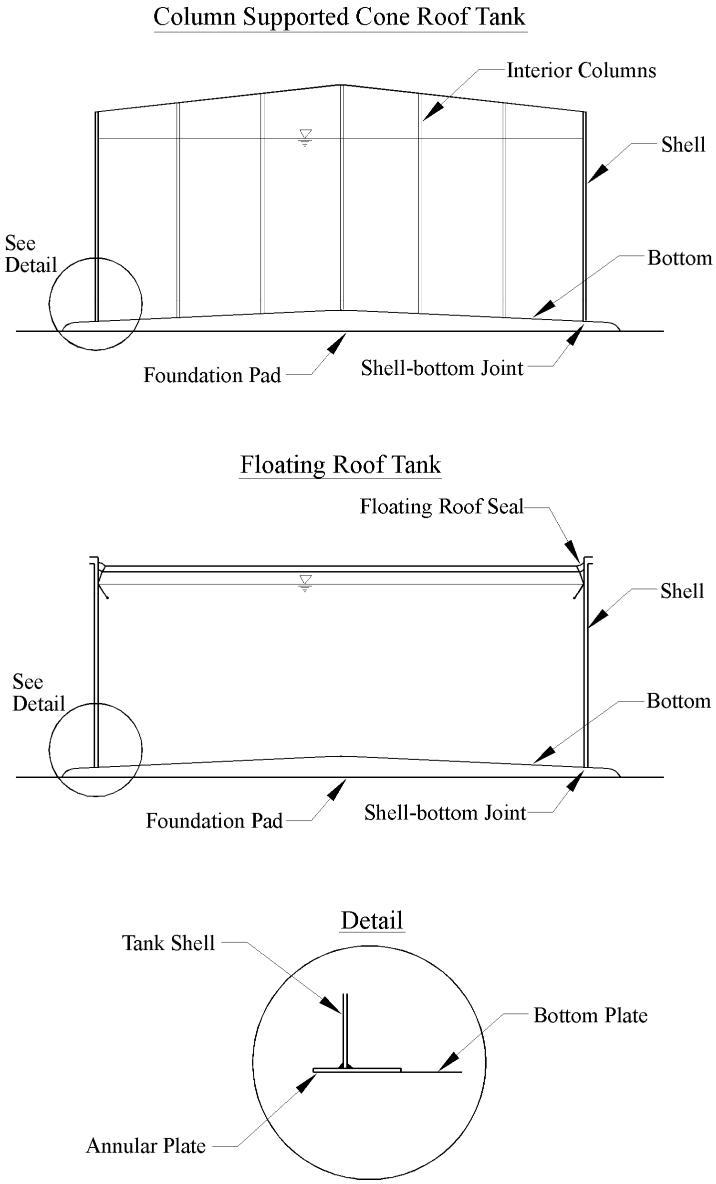


Figure 2. Fixed-roof and Floating-roof Tanks

Currently practicing engineers apply generally two methods for seismic analysis/design of liquid storage tanks. One is the Standard Method, and the other one is the Response Spectrum Method. The Standard Method is used when the site response spectrum is not available and the procedure is included in the ANSI/AWWA D-100 standard. This method is based on the earlier simplified analyses of liquid storage tanks. The Response Spectrum method, on the other hand, shall be used if the site response spectrum is available. The present available codes and standards, such as AWWA D100, API 650 standards, and the New Zealand recommendations, suggest the use of a response spectrum to evaluate the overturning moment exerted on the tank wall. For large or high-importance-factor tanks, it is essential that the site-specific earthquake response spectrum curves be provided.

ANALYSIS AND DESIGN/EVALUATION OF STEEL LIQUID STORAGE TANKS

1. Lateral Earthquake Load

After the horizontal ground acceleration is determined from the response spectrum based on the fundamental natural period of a tank, a lateral push analysis is performed to calculate the overturning moment at various height of tank wall. Pseudo-dynamic load in a parabolic distribution is used to apply on the tank wall for hydrodynamic pressure. This pressure pushes the tank in the lateral direction, and the tank uplifts from its foundation and develops a similar uplifting mechanism to that occurred under earthquake excitation. As shown in Figure 3, a hydrodynamic pressure distribution is assumed on the tank wall as

$$p = p_0 (1 - \frac{y^2}{H^2}) COS\theta$$

where y is the elevation of a point on the shell measured from the base, H is the fluid depth, θ is the angle measured from the axis of excitation and p_o is the pressure amplitude at the tank base at $\theta = 0^o$.

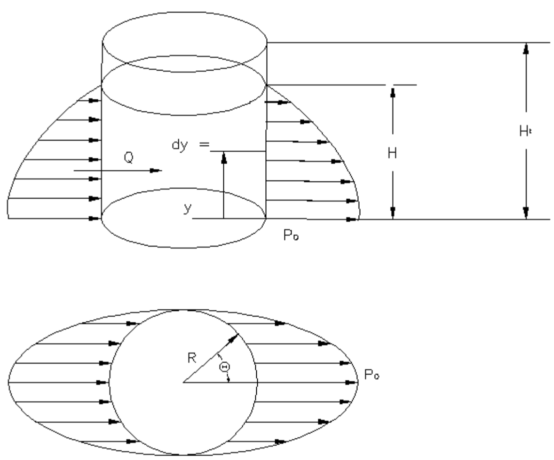


Figure 3. Pseudo-Dynamic Loads Applied on Tank Wall

Based on the hydrodynamic pressure distribution, the overturning moment at any height of tank shell can be derived through integration. Figure 4 shows how the variation of overturning moment along tank wall. The overturning moment about the center of the base is $M = 0.25\ \pi H^2 p_o R$. The base shear of the tank can be determined in a similar way for shear design, and the base shear $Q = 0.67\ \pi H\ p_o\ R$. The response quantities evaluated include the maximum values of the hydrodynamic circumferential, shearing and axial stresses in the tank wall.

To determine the minimum shell thickness required for each ring, it is necessary to evaluate the shell buckling status for the design level of the seismic ground motions. Checking on the buckling of tank wall is very critical because most of the unanchored tanks failed in a buckling mechanism: the elephant foot buckling in broad wide tanks while tall tanks suffered a diamond shaped buckling spreading around the circumference.

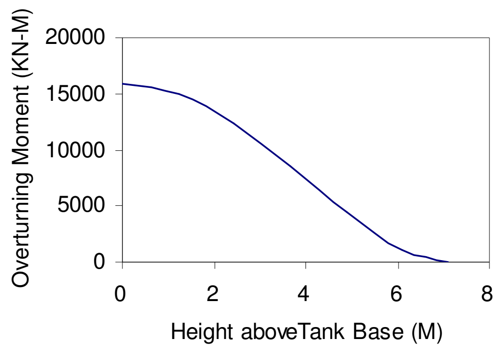


Figure 4. Variation of Overturning Moment along Tank Wall due to Lateral Earthquake Load

2. Effects of Vertical Component of Ground Shaking

The vertical component of the ground acceleration induces a hydrodynamic wall pressure in addition to that induced by the horizontal component. The pressure is uniformly distributed in the circumferential direction and varies in the axial direction as well as with respect to time. If the peak response of the vertical component of an earthquake occurred simultaneously and in the same direction with the peak response of the horizontal component, it may significantly increase the exerted hydrodynamic forces on the tank wall. Therefore vertical acceleration shall be taken into consideration on tank design. Seismic load case must include the horizontal and vertical components of earthquakes, and the load combinations could be (100% Horizontal + 40% Vertical) and (40% Horizontal + 100% Vertical) to be safe.

3. Uplift of Unanchored Tanks

Nonlinear finite element analysis should be performed for unanchored tanks so that uplift displacement can be determined. This is especially critical for the design of tank attachments. Equivalent springs shall be used for formulation of ground flexibility. The response of the unanchored tank was governed primarily by a rocking motion. The contact characteristics of the unanchored tank with its foundation are important factors in evaluating the response of such tanks. The uplift displacement on the tension side is much higher than the penetration displacement on the compression side. Such a behavior is expected due to the tensionless nature of the foundation.

4. Fundamental Frequency/Period of Tank-Liquid System

The fundamental natural periods are determined based on the method that was described in the publication of American Society of Civil Engineers, Guidelines for the Seismic Design of Oil and Gas

Pipeline Systems. In this method, both the Veletsos-Yang and Haroun-Housner procedures are used to consider the effects of damping, roof mass, and vertical component of ground shaking.

5. Wave height/water-surface displacement

After the sloshing wave period is determined, the horizontal seismic wave acceleration Ac can be obtained from the provided response spectrum. The sloshing wave height is calculated based on the horizontal seismic wave acceleration as *7.53 D Ac/18=0.418 D Ac*, where *D* is the diameter of tank. The sloshing wave height needs to be determined for the fixed-roof tanks so that enough freeboard is specified for the design of such tanks.

6. Hoop Stress in Tank Wall

The hydrodynamic hoop stress shall be combined with the hydrostatic stress in determining the total hoop stress based on the approach shown below--square root of sum of squares . The calculated stress in the tank wall shall not exceed the allowable design stress. The allowable stress must be reduced by the applicable joint efficiency, then increased by one-third for seismic allowable stress.

$$\sigma_s = \frac{\sqrt{N_i^{\,2} + N_c^{\,2} + (N_h a_v)^2}}{t}$$

Where:

σ_s = hydrodynamic hoop stress

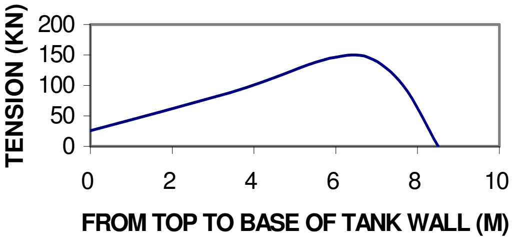
N_i = impulsive hoop force

N_c = convective hoop force

N_h = hydrostatic force

t = thickness of the shell ring under consideration

In order to make the design process more efficient, a program was developed based on the AWWA D-100 standards, with my research work incorporated in it. The program is both for design of new tanks and for seismic evaluation of existing tanks.



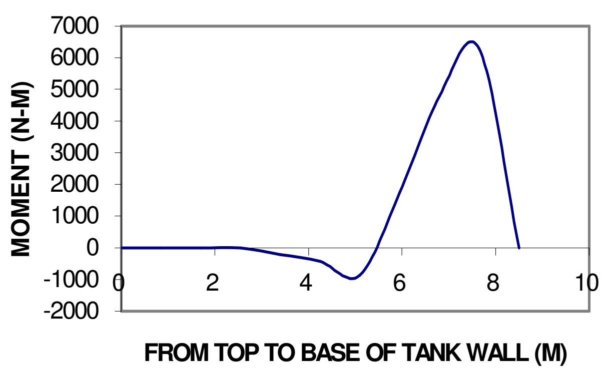


Figure 5. Variation of Ring Tension and

Bending Moment of Tank Wall

7. Program development to facilitate tank design

A program was developed for both tank design and seismic evaluation of existing tanks. Both the AWWA D-100 Standard Method and the Response Spectrum Method are included in the program. It is used to determine the wave height, overturning moment, anchorage requirement, and shell buckling status especially near the bottom of unanchored tanks during earthquakes. For the Response Spectrum approach, the means of calculating the fundamental horizontal period, vertical period and the liquid sloshing period are built in the program.

CONCLUSIONS

A lateral push analysis shall be implemented with a pseudo-dynamic hydrodynamic pressure. The response quantities include the maximum values of the hydrodynamic circumferential, shearing and axial stresses in the tank wall, as well as the buckling status of tank shell at any height. Such approach has advantage over the Standard Method in the AWWA D-100 standard. The hoop tension force, overturning moment and shear force at any height of the shell can be determined through analysis, thus it is more systematic and consistent on the design. In addition, sloshing wave height needs to be determined for the fixed-roof tanks so that enough freeboard is specified for the design of such tanks. Furthermore, both horizontal and vertical components of ground motions shall be considered for the seismic design of new tanks or evaluation of existing tanks.

For large or high-importance-factor tanks, it is essential that the site-specific earthquake response spectrum curves be provided. Thus the earthquake horizontal acceleration, the vertical acceleration, and the horizontal seismic wave acceleration can be determined more accurately based on the fundamental periods of the tank system. Furthermore, a 3-D nonlinear finite element analysis is recommended for the tank system including the contained fluid and the foundation soil, when the resources are possible. By doing this type of analysis, the fluid-structure interaction and the soil-structure interaction can be considered in the nonlinear analysis. Therefore the results are accurate enough to assure an ultimate design of critical lifeline structures-- liquid storage tanks.

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