Steel Tanks

Seismic Design of Ground Supported Liquid Storage Welded Steel Tanks

By Ashwin Ranga Swamy, P.E.

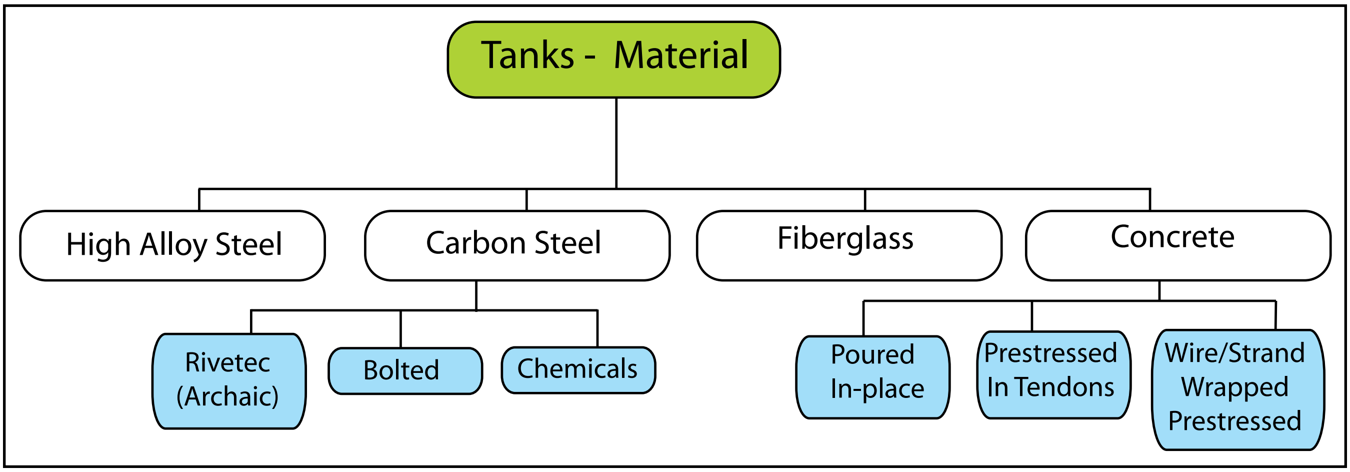

Figure 1a: Classification of tanks based on material

Tanks are non-building structures which are normally value engineered on the basis of return on investment. Tank manufacturers rely on in-house engineers or specialty structural engineers to design them, especially under seismic conditions. The intent of the paper is to provide the specifying engineer with references and background criteria to make an informed decision pertaining to design parameters.

Tanks are of different types based on material of construction (*Figure 1a*), type of storage (*Figure 1b*) and even location (*Figure 1c*). Each of these tanks are based on different codes and design methodologies. This article deals exclusively with on-grade liquid filled, welded steel tanks based on the latest ASCE 7-05, which also refers to AWWA D100 and API 650 codes, as published by the American Water Works Association (AWWA) and American Petroleum Institute (API), respectively.

Liquid storage tanks, which have been in construction over centuries, have become a major topic in today's seismic engineering world. One example of this is the rupture of a 5 million-gallon concrete reservoir in Westminster, California, which caused nearly $27 million in damages, on September 21, 1998. Other water districts have been using this as a case example during the design or retrofit of their reservoirs. Another example is the rupture of many welded steel petroleum tanks in Alaska due to the 1964 earthquake.

The performance of water, petroleum and chemical tanks and reservoirs in an earthquake is critical to society. The water supply is essential for controlling fires that usually occur during an earthquake and which can cause more damage and loss of life than the event itself. Broken petroleum tanks can lead to large uncontrollable fires (*Figure 2*), while chemical spills can result in enormous environmental damage.

The most common cause of steel tank ruptures is failure due to longitudinal vertical compression and radial tension that can burst a vertical seam and spill the entire contents. In steel tanks, this takes the form of bulging or an "elephant's foot" at the base before actual rupture as shown in *Figure 3*. Other forms of damage include roof damage due to surface wave sloshing and tearing out of the anchor chairs due to uplift forces. Excessive movement of the tank can break connecting pipes that do not have sufficient flexibility built into them, resulting in loss of liquid contents. Damage also occurs due to inadequate anchorage for uplift forces as shown in *Figure 4*. Finally, failure of the foundation due to liquefaction or lateral movement of the supporting soil can result in loss of support and rupture of the vessel.

Over the last several decades, engineers have been using the standard linear static procedure recommended by the AWWA and API publications. Theoretical solutions were developed for seismic analysis prior to the older AWWA and API codes, but most tanks were designed for static and wind loads with rule-of-thumb safety factors developed by petroleum and water supply companies. The newer codes have replaced the static formula with more complicated equations utilizing the dynamic characteristics of the fluid and the tank.

continued on page 24

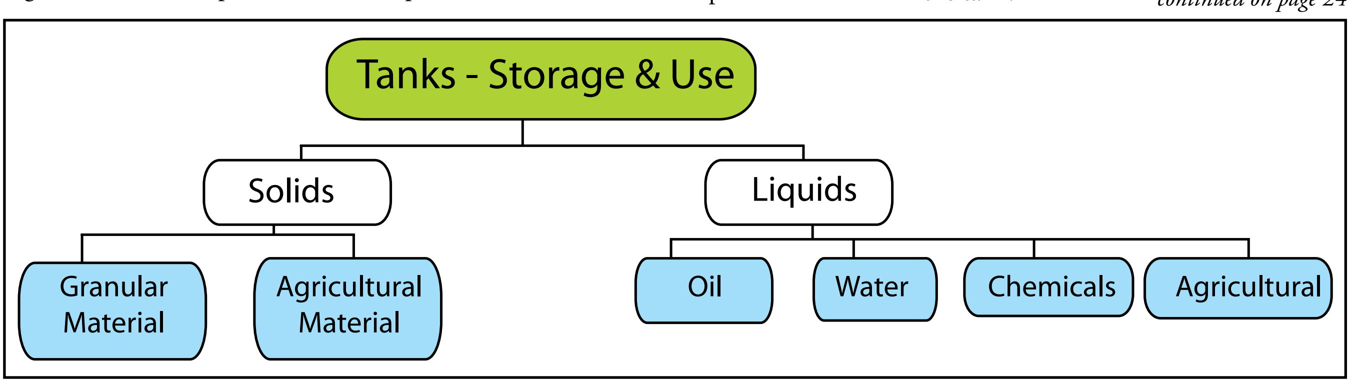

Figure 1b: Classification of tanks based on storage & use

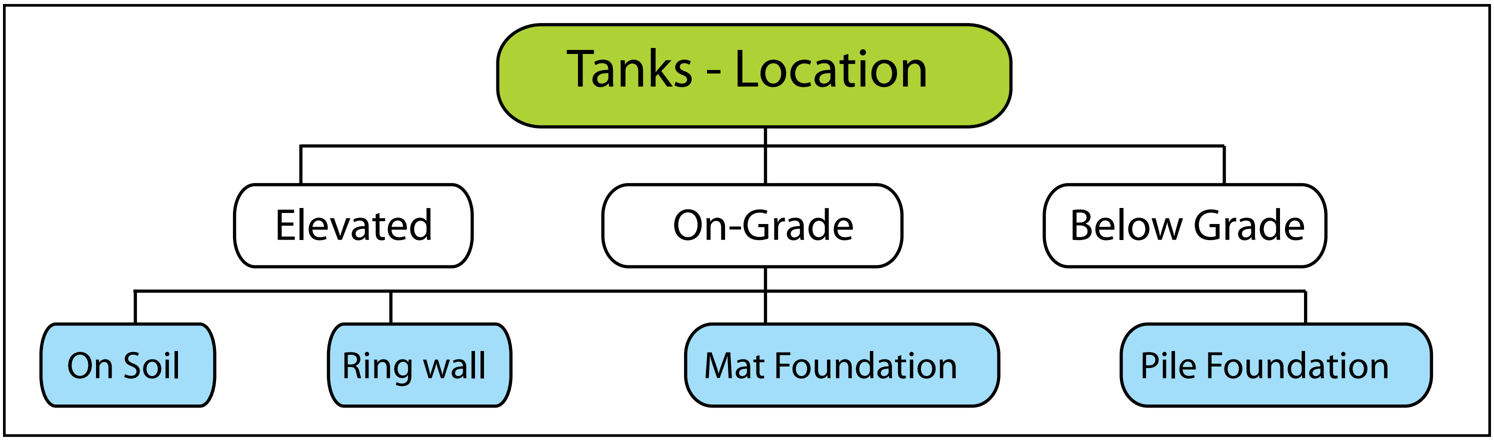

Figure 1c: Classification of tanks based on location

History of Tank's Seismic Design

Analytical studies were undertaken in the late 1940s through the early 1960s by Jacobsen at Stanford and Housner at Cal-Tech. Lydik Jacobsen, under a grant from the U. S. Navy, analyzed the dynamic forces exerted by a fluid on the inside of a cylindrical tank and on the outside of a cylindrical pier. The two cases are similar from a theoretical standpoint. This analysis was then used both for the design of tanks and for submerged piers or caissons in a marine environment.

By analyzing what he called impulsive hydrodynamic forces of fluids, he derived graphs from which values for the "effective" mass of the fluid could be obtained for various height-to-diameter ratios. This "effective" mass then had an appropriate seismic force factor applied to it to obtain the seismic shear. The method was still in use by many engineers well into the 1980s. It is interesting to compare his findings with current practice.

"…more sophisticated studies that attempt to predict behavior with varying combinations of shell thickness foundation and soil interaction characteristics…"

After the 1964 Alaska earthquake, a major study was made of tank failures which resulted in the basic methodology, as described above, for the linear static procedure still in use. In the late 60s, analytical studies began to appear in the literature by Veletsos and others who attempted to provide a theoretical framework to account for actual vessel behavior during earthquakes. This has continued to the present date with more sophisticated studies that attempt to predict behavior with varying combinations of shell thickness, foundation and soil interaction characteristics. However, a general procedure has not yet appeared.

Major Prevalent Codes

The most widely adopted code in the United States is the International Building Code (IBC) which, according to their website (**www.iccsafe.org**), is being adopted by 47 states plus Washington, D.C. California, which is currently using the Uniform Building Code (UBC) as the basis for its state code, has adopted the 2006 IBC for its next code and according to the California Building Commission (**www.bsc.ca.gov**) has an effective date of January 1, 2008. The latest 2006 IBC refers to American Society of Civil Engineers' standard ASCE 7-05 for seismic parameters, especially for the tank design in Section 15.7.

The people from UBC would be quite surprised to see the difference, since ASCE 7 has become quite detailed and references other specific codes. This has had a domino effect on the other codes, since they have revamped their codes to be in line with the ASCE 7. The ASCE 7 procedure for tank design applies to general tanks while some specialty tanks are referenced to their appropriate codes.

The design of tanks in the petroleum industry has been referred to the standards published by API, **www.api.org**. API standard API 650 titled *Welded Steel Tanks for Oil Storage*, though published in November 1998 (10th Edition) is into its fourth addendum dated December 2005. Appendix E covers the seismic design which has been totally redone in their new addendum. API 650 pertains to contents stored at atmospheric pressure, while API 620 covers tanks for low pressure (pressures in their gas or vapor spaces not more than 15 psi).

Similarly, tanks used for water storage have been per the AWWA, **www.awwa.org**. The ANSI/AWWA D-100 titled *Welded Carbon Steel Tanks for Water Storage* recently released its updated edition of 2005 (effective date of May 2006) with updated seismic design parameters contained in Chapter 13. AWWA also published standards for concrete reservoirs, AWWA D110 and AWWA D115 which parallels ACI 350.3.

Basis of Lateral Tank Analysis

According to the API 650, Appendix E, "Ground-supported, flat bottom tanks, storing liquids shall be designed to resist the seismic forces calculated by considering the effective mass and dynamic pressures in determining the equivalent lateral forces and lateral force distribution."

Cylindrical tanks containing liquids, with flexible bottoms resting directly on the ground or base mat, constitute a unique category for structural design. This is because

Figure 2: Tank farm fire at Valdez, Alaska after 1964 earthquake which burned for two weeks. (Courtesy of National Geophysical Data Center)

the entire weight of the tank contents contributes to the lateral seismic force, while only a small percentage of that weight helps to resist overturning.

Further complicating the analysis is the fact that the lateral force consists of two components: impulsive forces and convective forces. The first is the type of force that structural engineers are familiar with, which relates to the inertia of a portion of the liquid along the walls and the bottom which moves in unison with the tank as a rigidly attached mass. The second (convective) force is caused by the movement of the remaining fluid inside the tank, which is the subject of fluid dynamics analysis.

The relative importance of these two forces depends on the physical configuration of the tank. Because the lateral component of the seismic forces is primary, the larger width-to-height ratios allow the convective forces to come more into play. Whereas, when the height is more than the width (H/D > 1) the impulsive forces are predominant. *Figure 5*, from AWWA D100 (AWWA Figure A.5), shows the relative importance of the two forces for varying D/H.

The natural period for these two components is also quite different. When a dynamic response spectrum is used in the analysis, the period for the impulsive force is typically a fraction of a second while the convective period is several seconds long. The way that these different components are handled varies with the analysis methodology that is used.

The defining consideration in the analysis of the tank is whether the overturning moment is large enough to result in significant uplift of one side of the tank wall. If this were allowed to occur, the longitudinal compression and tangential tension on the other side would become excessive and cause buckling and probable rupture.

Uplift of the tank shell is resisted by the weight of the shell and supported roof plus a band of liquid adjacent to it. The width of this band of liquid depends on the stiffness (or thickness) of the part of the bottom plate inside the shell, which is called the annular ring. The designer can thicken this ring but there are limitations; it cannot be thicker than the shell. If this is not sufficient, additional restraint in the form of anchors must be provided.

Figure 3: "Elephant Foot" caused by the movement of water in a large steel storage tank during San Fernando, California, Earthquake February 1971. (Courtesy of USGS Photographic library)

There is an intermediate zone in which some uplift will occur, but anchors are not required by AWWA D100 or API 650. It has been found in the past that the uplift was too small to create failure of these tanks. The design zone for a tank is determined from the overturning ratio (J) obtained from the following equation:

$$J := \frac{M_r}{D^2 \cdot [w_t \cdot (1 - 0.4 \cdot A_v) + w_L]}$$

continued on next page

Figure 4: Buckled water tank lifted off base by Landers Earthquake. (Courtesy of Lindie Brewer, U.S. Geological Survey)

Similar equations are used in ASCE 7, which is mirrored in AWWA and API codes. In the equation, w_t is the weight of the tank shell and portion of the roof reacting on the shell, w_L is the maximum resisting weight of tank contents to avoid shell overturning and A_v is a new addition which is the vertical design acceleration used in AWWA and API.

The API and AWWA codes are based primarily on past experiences of failure of large storage vessels. The seminal work was published by Wozniak and Mitchell in 1978. Mr. Wozniak had been with Chicago Bridge and Iron Company, a major tank fabricator, and Mr. Mitchell, a member of SEAOC, with Standard Oil Company of California. They had access to a large database, including the effects of the great Alaska earthquake of 1964, and were able to take the theoretical data that was available and put it into a set of equations that can be used by practicing engineers.

This appears to have been the basis of both the API 650 Appendix E and the seismic provisions of AWWA D100 in the past.

Significant Code Changes in API & AWWA

Several major changes have been made to the seismic design sections of both AWWA D-100 and API 650. Both are now derived from ASCE 7 and are based on the Maximum Considered Earthquake (MCE). MCE motion is defined as an event with a 2 percent probability of exceedance over 50 years (mean return period of 2475 years).

The zones defined in earlier codes have been replaced with contour maps. These maps are hard to read and interpret, but the mapped acceleration parameters (spectral response acceleration at 1-sec period S1 and 0.2 sec period of Ss) can be easily obtained using latitude and longitude of the project site using the CDROM available from ICCSAFE titled Code Central. These values are also on the United States Geological Survey (USGS) website.

Site specific procedure guidelines are provided in both the AWWA and API. It is required if the tank is located on Site Class F type soil. However, API 650 suggests to consider this approach under a few other conditions as well.

AWWA and API still cater to the needs of projects outside the scope of the ASCE 7 by including provisions under such conditions. AWWA has an appendix chapter mainly for such jurisdictions where ASCE 7 has not yet been enforced.

Impulsive and convective motions are two terms which were dormant in the old codes and have a prominent presence in the newer version. Calculating the impulsive period is a daunting procedure for many engineers due to references to many research papers which, by their nature, may require very sophisticated evaluation. API and AWWA have simplified this approach and ASCE 7 provides some guidance by including reference documents which are shown in a flowchart in *Figure 6*.

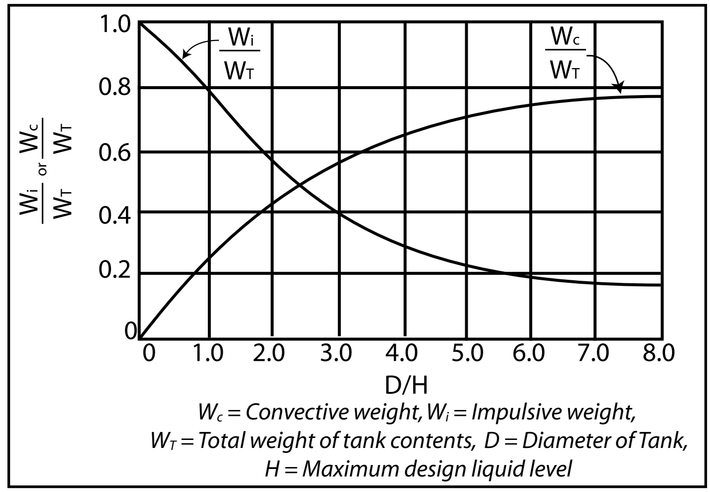

Figure 5: Effective impulsive and convective weights with varying D/H. (Reprinted with permission from ANSI/AWWA Standard D100-05: Welded Carbon Steel Tanks for Water Storage. Copyright © 2006,American Water Works Association.)

A part of the liquid that moves in a long sloshing mode is termed the convective motion and determines the freeboard requirements at the top of the tank. Sloshing of the liquid causes leakage and damage to the roof members, and hence requirements to avoid such damage have been included in the codes.

Engineers and designers familiar with the API and AWWA were accustoned to seeing

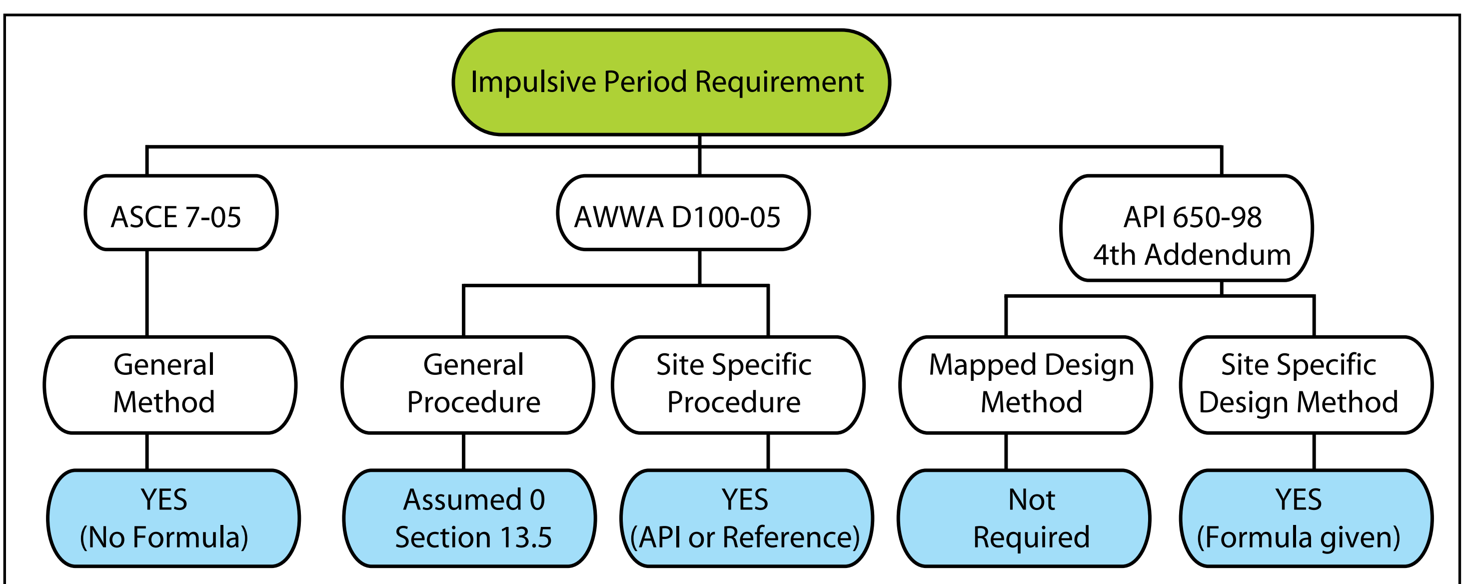

Figure 6: Impulsive period calculation requirement in the different codes

graphs for calculating the effective weights. However, as computers evolved, these graphs were cumbersome. It was a challenge to input these values automatically into an Excel or MathCAD template. The author while developing his MathCAD template had researched into the background of the graphs and obtained the formulae used to create the graph. This made the seismic design of the tank using MathCAD quite simple. These formulae were developed by Wozniak and Mitchell in 1978. For ease with hand calculations, graphs were created. The formulae you will find in the current version of the API and AWWA are the same formula developed by Wozniak and Mitchell, and the author is glad that the template does not need to be revised.

Allowable stress design (ASD) method is still being utilized in both the codes. R values have been enhanced in the current version, with specific value for impulsive and convective forces. The new codes also differentiate the overturning moment at the top of a regular ring wall foundation, and top of foundation for tanks supported on mat or pile-cap foundations.

Path Forward

Research is on-going for the use of newer technologies relative to tank design. Non-linear analysis, performance based design and the use of energy-dissipating base anchors are being considered. The design of ground supported flat bottom tanks, which mostly evolved in the United States after the 1964 Alaska earthquake, has been significantly modified. However, the basic design still remains the same with most of the emphasis resting on the Engineer's sound judgment.▪

Ashwin Ranga Swamy, P.E. is a Lead Engineer at the structural department of Jacobs Facilities, Inc. in Los Angeles, California. He has over 14 years of structural engineering experience in new and existing buildings and non-building structures. He is an active member in several professional organizations, including SEASOC. He can be reached at ***AswinPE@hotmail.com.***