SEISMIC RESILIENCE FOR LNG TANKS

Yogesh Meher, Vice President Global Engineering, and Alex Cooperman, Senior Principal Plate Structural Engineer, CB&I, consider effective measures for seismic safety in LNG tank projects.

Seismic resilience of critical infrastructure, such as LNG storage tanks, is essential to the safety and economic well-being of the general population. Seismic design of LNG tanks is very important and often controls the design and configuration of the tank structure, especially in high seismic areas.

Seismic design standards and industry requirements

The LNG industry and tank design standards[1,2,3,4] define general requirements for seismic design of LNG tanks. The current industry practice in both US and European standards is to design LNG tanks for two main seismic levels. At a lower seismic level, defined as operating base or operating level earthquake (OBE or OLE), the LNG tank must remain fully operable, and as a result the structure must remain completely elastic. At a high seismic level, defined as safe shutdown or contingency level earthquake (SSE or CLE), the LNG tank may sustain damage, but no product release can occur. The standards allow some reduction in seismic load due to structure inelastic behaviour and energy absorption via damage without loss of containment or structural integrity.

In addition, US standards recommend consideration of aftershock level earthquake (ALE), assuming all the LNG stored in the primary liquid container is released into the secondary liquid container.[1,3,5,7] The ALE is defined as 50% of SSE.[1,3] European regulations do not require consideration of an ALE case.

NFPA 59A[1] defines OBE as a seismic event associated with a return period of 475 years and SSE as an event associated with a return period of 2475 years. European regulations specify the same return period for OBE and a 4975-year return interval for SSE.[4]

LNG steel tank design procedures for seismic loads are defined in API620 Annex L[5] and EN 1998-4.[6] A portion of liquid mass in the tank will respond to the horizonal component of seismic excitation as a rigid body (impulsive mass) while the other portion of the liquid will respond in a sloshing wave mode (convective mass). The typical tank seismic design model is shown in Figure 1. Concrete tank design recommendations for seismic activity and guidance for seismic modelling are provided by ACI376,which includes finite element analysis.[7]

Both NFPA 59A and EN 1473 provide for a site-specific seismic study to be conducted for all LNG facilities. The study includes both OBE and SSE site-specific seismic spectra based on the specific local geotechnical conditions and proximity to seismic faults. Furthermore, to avoid underestimation of OBE and SSE seismic levels based on site-specific analysis, NFPA 59A applies minimum OBE and SSE seismic levels based on seismic load specified by ASCE/SEI 7-22 for the site geographical location.[8]

Seismic behaviour of LNG tanks

Because impulsive and convective seismic masses do not respond in unison to ground excitation, the effects due to responses of impulsive and convective horizontal seismic components are combined using the square root of the sum of squares (SRSS) method. In addition to horizontal seismic activity, vertical seismic excitation may also significantly affect the tank design. Vertical seismic acceleration increases the effective product specific gravity due to excitation pointed in the upward direction. The same vertical seismic effectively reduces product specific gravity and tank structure weight when pointed in the downward direction. In the latter case, it results in reduction of tank stability due to reduction of the tank structure weight and liquid product weight contribution in both overturning and sliding resistances.

Current US LNG tank standards recommend considering 100% horizontal seismic activity in combination with 40% vertical seismic for stability verification and both 100% horizontal and 40% vertical, and vice versa, for tank component design, including the tank shell, roof, and platforms.

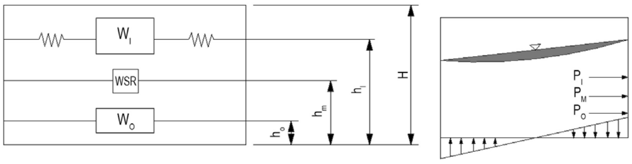

Figure 1. Tank seismic design model. W_l = liquid convective mass; W_o = Liquid impulsive mass, W_{SR} = mass of the tank structure; h_o, h_m and h_l = respective elevation of each mass.

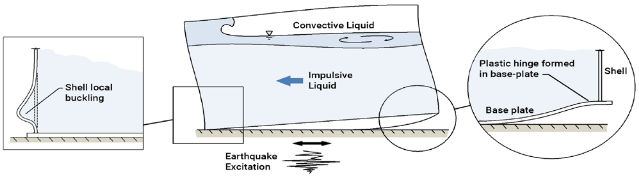

Figure 2. Typical effects on the tank due to seismic.

High seismic load may affect the design of LNG tank as follows (Figure 2):

- Result in increase of the tank shell plate thickness due to hydrodynamic liquid pressure and vertical excitation.
- Affect overturning stability of the tank.
- Affect sliding stability of the tank.
- Result in increase in the tank height to accommodate seismic sloshing wave height.

The impulsive tank mass has a period of vibration in the range of 0.2 – 0.5 seconds, which typically puts the impulsive mass acceleration at the peak of the response spectra. The convective period is dependent on the tank diameter and typically ranges between approximately five seconds for a small tank to 12 seconds for a large tank. Therefore, the seismic accelerations associated with the convective period are much smaller than those associated with the impulsive period.

Mitigating seismic loads

The most economical solution to handling high seismic exctiation depends on several factors, including the magnitude of seismic activity, real estate availability, and soil type. Re-proportioning of the LNG tank, such as making the tank shorter in height and larger in diameter, changes the percentage of the liquid mass associated with both impulsive and convective components by decreasing the mass of the horizontal impulsive component and increasing the mass of the horizontal convective component. However, because the convective component is associated with much lower seismic acceleration, the overall response is reduced, sometimes significantly. A simple re-proportioning of the tank can help make the tank stable and reduce the base shear to help mitigate any sliding issues. If the real estate is available, then re-proportioning the tank may be the simplest and most economical solution to handle high seismic levels up to a certain limit.

Another effective option to reduce the tank seismic response is accounting for soil-structure interaction (SSI). Due to soils flexibility, SSI allows increasing:

- The effective period of the tank impulsive mass.
- The system damping due to additional soil damping.

Due to increases in the effective period and damping ratio, the effective acceleration applied to the impulsive mass, which typically is a controlling acceleration, may be reduced significantly.

While consideration of SSI may be very effective to reduce seismic loads applied to the tank, it should be noted that SSI is effective only for soft soils. The industry standards also limit the maximum increase in the damping ratio due to SSI.
API620 Annex L limits the maximum damping ratio due to SSI to 10% for OBE and 20% for SSE.

In very high seismic locations, tank re-proportioning and SSI may not be able to provide the required reduction in seismic load, in which case the only remaining option is to add base isolation to the tank system. Seismic isolation is the most effective option to reduce seismic loads and handle very high seismic activity. The cost of seismic isolation should be accounted for the overall tank system cost.

Seismic isolation devices

Seismic isolation devices allow a very significant reduction in the horizontal impulsive seismic acceleration due to a large increase in both the effective period of vibration and the effective damping. The isolators allow an increase in the effective impulsive period from a typical 0.2 – 0.5 seconds to 3 – 5 seconds following the vibration period of the isolation device. Seismic isolators are also very efficient in seismic energy absorption, resulting in an effective damping ratio of more than 30%. A typical energy dissipation curve for this seismic device is shown in Figure 3. Both the increase in the impulsive period and the effective damping dramatically reduce the seismic acceleration applied to the horizontal impulsive seismic mass, reducing hydrodynamic pressure, overturning moment, and base shear. However, isolation devices have little effect on seismic wave height, as a typical convective period for a midsize or a large tank is much longer than the period provided by isolators, and the liquid convective mass damping ratio stays at 0.5%.

Both lead-rubber and friction pendulum seismic isolators shown in Figure 4 are efficient seismic isolation devices and allowed by the existing standards. High damping rubber isolators are not recommended by ACI376 due to inconsistencies in performance.

The period shift in a lead-rubber isolator is achieved due to flexibility of the rubber, while yielding of the lead core allows for high damping performance.

A friction pendulum isolator provides a large increase in both effective period and damping via curvature of the components and friction on the sliding surfaces. Various types of friction pendulum isolators are schematically shown in Figure 5. Double and triple pendulum isolators accommodate the same level of seismic excitation as a single pendulum with significantly less displacement. Furthermore, a triple pendulum system allows a very soft start, eliminating an initial spike in acceleration due to static friction being higher than dynamic friction. This is achieved by using a sliding coating material with much lower friction coefficient for the inner sliders than that used for the outer sliders.

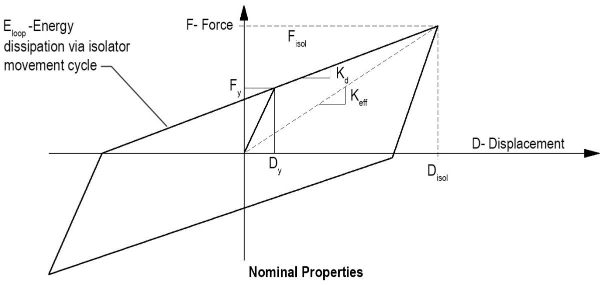

Figure 3. Isolator movement (energy dissipation) loop. K_d = isolator post-yield stiffness; K_{eff} = isolator effective stiffness; F_{isol} = maximum force; D_{isol} = maximum displacement.

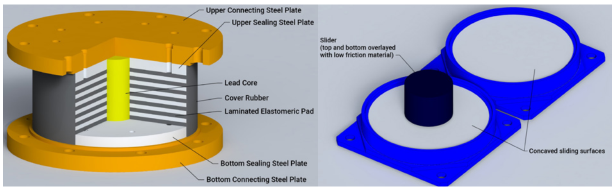

Figure 4. Seismic isolators – lead-rubber isolator (left) and friction pendulum isolator (right).

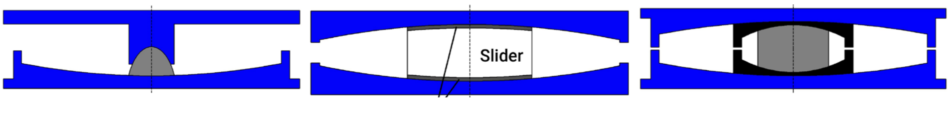

Figure 5. Various friction pendulum isolator types: single pendulum (left), double pendulum (middle), triple pendulum (right).

While seismic isolation helps in significantly reducing horizontal impulsive acceleration, it comes at the expense of high displacement. All connections and attachments external to the tank, such as piping or connections to a free-standing access system, must be designed to have sufficient flexibility to accommodate the isolated tank displacement, which in high seismic regions may be as high as 1000 mm. Because the behaviour of seismic isolation devices is highly non-linear, standards including ACI376 recommend that the seismic isolation system be designed using non-linear response-history design procedure. Guidance for the design of the seismic isolation systems is provided in Chapter 17 of ASCE/SEI 7-22.

CB&I has vast experience in designing and constructing seismically isolated storage tanks for refrigerated liquefied gases, including LNG. Seismically isolated LNG storage tanks have been constructed by CB&I in Turkey, Peru, Chile, the Philippines, and the West Coast of the US.

Conclusion

In conclusion, the seismic loading on an LNG tank has a direct impact on the dimensions of the LNG tank (proportioning diameter and height), liquid sloshing height, and need for anchorage. In locations with very high seismic activity, it can be beneficial to add base isolation to the tank system in the form of lead-rubber or friction pendulum isolators. Use of seismic isolation often results in an economical tank design with a reduced footprint, while providing the most reliable mechanism for accommodating the large seismic displacements that occur during an earthquake. The implementation of a base isolation system allows a significant reduction (as much as 80%) of the earthquake forces on the tank. The company's project delivery model ensures high-quality and cost-effective solutions for projects. Many customers draw on the company's deep knowledge and extensive LNG experience early in a project's development, allowing CB&I to provide input, recommendations, and project-specific solutions that enhance the long-term value of the facility. Its integrated EPC resources enable CB&I to self-perform all aspects of the project, from conceptual design to tank commissioning. **LNG**

Notes

The standards referred to throughout the article are:

1. NFPA 59A-2023 Standard for Production, Storage, and Handling of Liquefied Natural Gas (LNG).
2. EN 1473:2021 Installation and equipment for liquefied natural gas – Design of onshore installations.
3. API 625 Tank Systems for Refrigerated Liquefied Gas Storage, 1st ed., including addendum 4.
4. EN14620-1:2024 Design and manufacture of site built, vertical, cylindrical, flat-bottomed tank systems for the storage of refrigerated, liquefied gases with operating temperatures between 0˚C and -196˚C – Part 1: General.
5. API620 Design and Construction of Large, Welded, Low-pressure Storage Tanks, 12th ed., including addendum 3.
6. EN 1998-4:2006 Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines.
7. ACI 376-2023 Refrigerated Liquefied Gas Containment for Concrete Structures.
8. ASCE/SEI 7-2022 Minimum Design Loads and Associated Criteria for Buildings and Other Structures.