Hazard and Safety Investigations for LNG Tanks
Part 1 : Earthquakes

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The authors address the external hazards to aboveground full containment LNG storage tanks. Part 1 in this issue deals with seismic design, and it is concluded that a base isolation system allows a significant reduction of the earthquake forces on the tank, and provides a reliable safety factor against earthqauake damage. Part 2 will deal with accidental events, blast and impact.

Our industrialized world is characterized by an increasing energy demand. As a result more and even larger LNG storage tanks are needed. If these are to be built in locations endangered by natural catastrophes or near densely populated areas, engineers must avoid disasters and limit the consequences of every conceivable scenario.

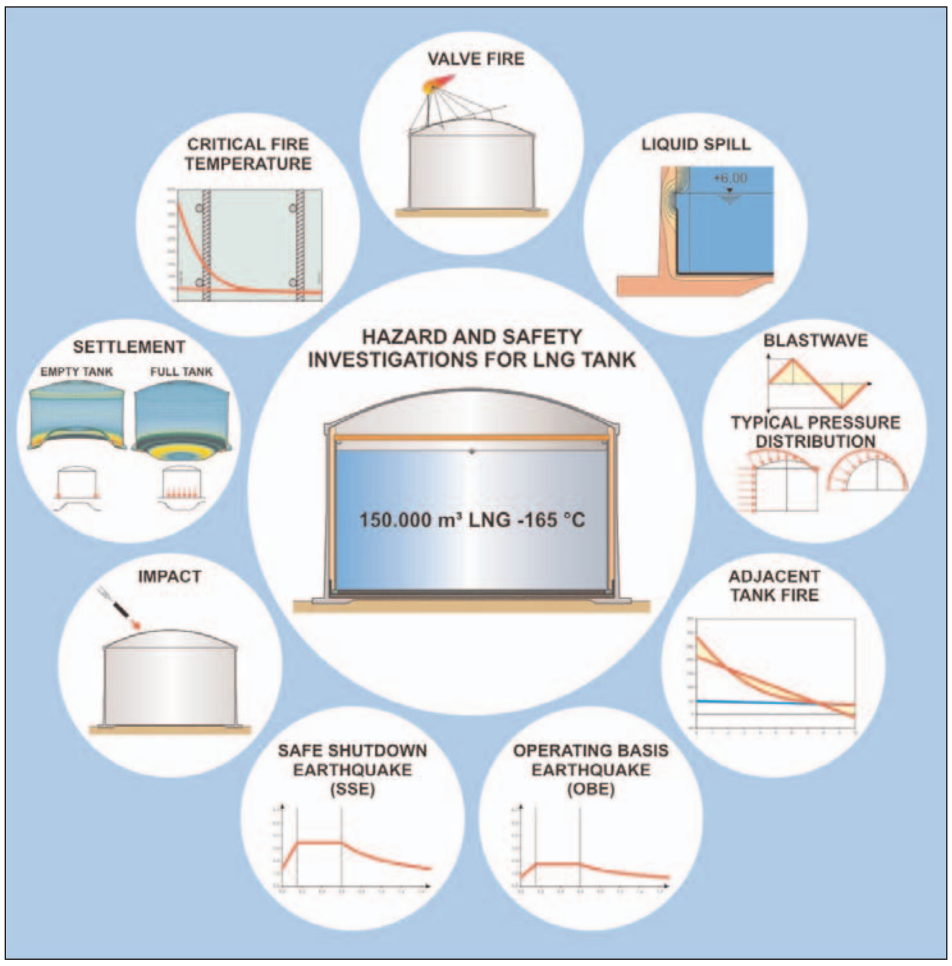


Figure 1: Load cases for LNG-tank design

Nowadays typical LNG terminals have aboveground storage tanks with capacities ranging from 160,000 m³ to 180,000 m³; capacities of 200,000 m³ are under planning. In the case of a containment failure, the economic damage would be substantial and the danger to life, property and environment correspondingly great. Consequently, storage tanks for liquefied gases at low temperature require most advanced design and construction techniques to ensure that the potential risk involved is reduced to a minimum. The state of the art calls for a full containment system with a prestressed concrete outer tank [1].

The tank design shall consider operation load cases such as internal pressure up to 290 mbar, limitation of settlements, hydro test with a minimum of 125 % of the filling load as well as seismic loading (OBE - Operating Basis Earthquake Scenario). The concrete outer tank shall also resist emergency load cases such as fire, impact, blast wave, seismic load (SSE - Safe Shutdown Earthquake Scenario) and liquid spill due to failure of the inner tank (see Figure 1). An economic design of the reinforced and prestressed concrete structure for these load cases is only possible if non-linear material behaviour is considered.

Because of the relevance to the overall safety and economics of tank design, this article presents more detailed information concerning earthquake design. In a subsequent issue of the *LNG Journal*, the accidental events, blast and impact will be dealt with.

Seismic Design

Design Method: Large-scale storage tanks have a fundamental natural period of about 2 to 3 Hz, depending on their shape and geometry, and are more or less within the range of maximum excitation of typical severe earthquakes. They will in fact be subjected to much stronger accelerations than the ground beneath them. According to Eurocode 8 [2], for example, the peak amplification factor is approximately 3.5. Earthquakes are thus a determining factor with regard to the availability and integrity of LNG tanks in areas of seismic activity. In this regard, additional measures are necessary in order to avoid damage.

Fundamental to the above has been the assumption that the motions experienced by the structure are the same as the free-field motion at ground level. This is the case for structures founded on rock or other rigid foundation material [3]. For structures on softer soils, the foundation motion may be significantly different from the free-field ground motion due to the damping of the soil. This interaction between the structure, its foundation and the supporting soil medium is a natural form of energy dissipation. If the tanks are founded on rock or if the tanks are exposed to severe earthquake excitations where the natural damping of the foundation is inadequate, effective means of influencing the vibration behaviour must be implemented.

In the case of conventional structures and buildings, plastic deformation capabilities are utilized to the full in order to reduce the earthquake effects by means of the damping and ductility associated with their deformation properties. In the case of storage containments, the requirement of tightness and the containment function do not allow for inelastic design spectra (reduction factors). For example, according to Eurocode 8, the analysis has to assume linear elastic behaviour, allowing only for localized non-linear phenomena without affecting the global response [4].

Structures that have only minimal capacity to absorb energy by plastification, such as LNG storage tanks, require to be protected from damage, especially as they involve a high danger potential. This can be achieved by a base isolation system.

For an earthquake design, all structures have to be treated in the same way. First, the failure modes and the corresponding design criteria must be identified. Typically for an LNG containment, this is the uplifting of the inner tank and subsequent buckling of the tank wall and its sliding potential due to horizontal excitation. Second, a suitable design model has to be created for the analysis.

For the investigation of the above risks, the idealization of the tank structure using a tuning fork model is best suited; see Figures 2 and 3. From a design philosophy point view, a crucial question is to what extent the reliability and accuracy of an analysis can be improved by a more discrete idealization. For practical design and for the study of the relevant parameters it seems more effi-

Figure 2: Tuning Fork Model of Non-isolated Tank

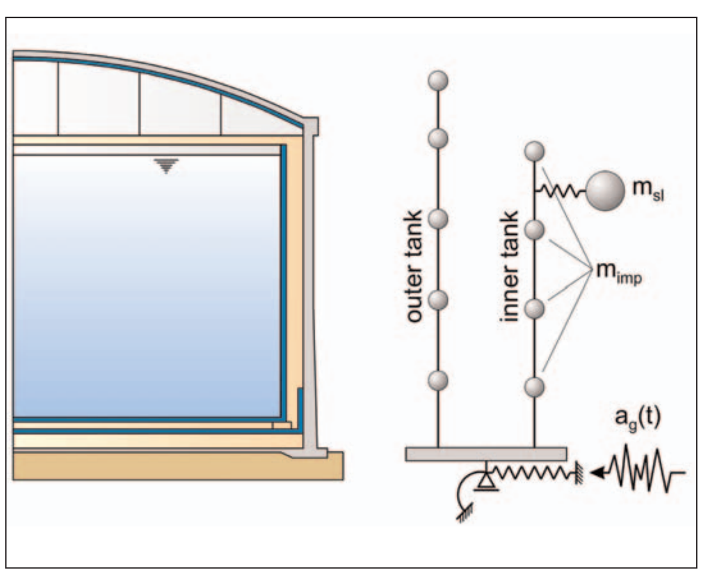
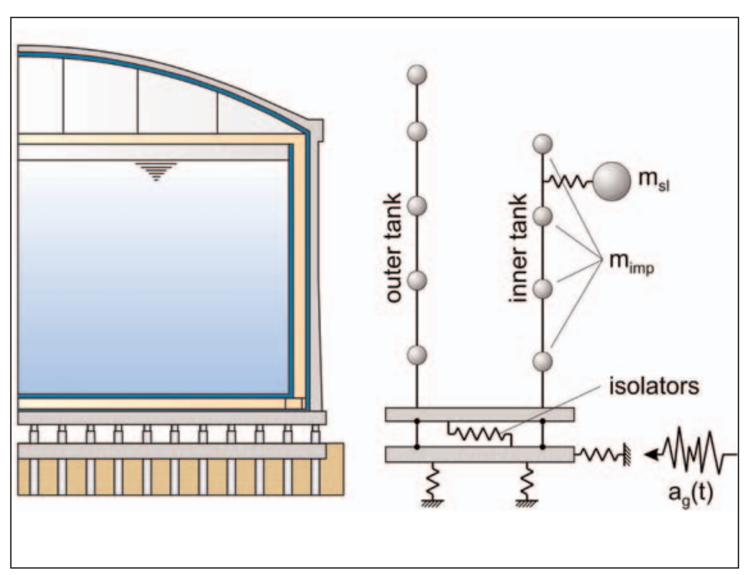


Figure 3: Tuning Fork Model of Isolated Tank



cient in most cases to apply simplified models which are related to the individual design tasks rather than increasing the number of elements in a finite element analysis. Such a procedure allows the opportunity to study the essential engineering questions in a clear and comprehensive manner.

Non-isolated Structure: The dynamic study of a tank system must comprise all relevant parameters. The effect of earthquake excitations on a non-isolated tank system can be illustrated by the example of the inner steel tank of a full containment LNG tank. The effect of the LNG liquid is described by the impulsive liquid mass m_{imp} rigidly connected to the inner tank and the sloshing mass m_{sl}, which, however, has only a minor influence on the dynamic behaviour of the inner tank due to its low period.

If the horizontal inertial force created by the accelerated masses m_{imp} and the resulting overturning moment exceeds a certain value, then the steel tank lifts up resulting in plastic deformation of the bottom corner [5]. The deformation of a non-anchored tank due to the uplift increases rapidly and simultaneously the vertical stresses on the opposite side. The wall may buckle (elephant footing). The vertical stress, which may cause buckling, is a critical design criterion. Due to the uplifting earthquake, excitations with a Peak Ground Acceleration of approximately 0.3 g may cause considerable damage to an unanchored inner tank.

The uplifting may be avoided by anchoring of the inner tank wall into the bottom slab of the concrete outer tank. The anchors, however, penetrate the bottom insulation, the secondary tank bottom and the vapour barrier. Furthermore the welding for fixing the anchor straps on the inner tank shell causes additional stresses in a heavily loaded area. Because of these potential weak points in the design, particularly in the case of earthquake induced loads, anchors are frequently not permitted by plant owners.

Base-isolated Structure: In order to design the tank structure for high earthquake accelerations, the arrangement of a base isolation system is the most efficient way to avoid the risk of buckling of the inner tank shell and fulfil the tightness requirements of the outer tank. The main concept in base isolation is to reduce the fundamental frequency of structural vibration to a value lower than the predominant energy-containing frequencies of the earthquake ground motion.

The isolation system requires an additional foundation slab and pedestals on which the isolators can be located. The bearings allow large horizontal displacements, which are necessary to increase the period T, and they are stiff in the vertical direction. The analysis model of the tank system is extended by the isolators, represented by an additional horizontal spring, and is shown in Figure 3.

The earthquake energy is essentially dissipated by the large deformation of the isolators. The displacement of the steel tank is comparatively small and the overturning moment is reduced and does not cause uplifting of the steel tank.

The advantages of a base isolation system can be appreciated, when the accelerations for non-isolated and isolated tanks are compared, see Figure 4, which shows a typical spectrum for a loose to medium cohesionless soil, a type frequently encountered in locations geographically and logistically suitable for the location of LNG terminals.

The deformations of an inner tank supported by isolators are in the elastic range and the inner tank is stressed far below the buckling limit. Without base isolation the deformations of the steel tank increases up to the plastic range, causing uplifting and probably buckling.

Isolators

The modern base-isolated structures are supported by horizontally flexible but vertically rigid bearings interposed between the base of the structure and its foundation. Typically two types of isolators are applied in the LNG tank design in seismic hazardous areas: High Damping Rubber Bearings (HDRB) and spheric sliding isolators like Friction Pendulum Bearings (FPB).

The basic components of the laminated HDRB are thin steel and rubber plates built in alternate layers. These bearings are similar to bridge bearings; however, new rubber compounds were developed in order to increase the damping properties. The HDRB system is mainly characterized by two parameters: the natural frequency and the damping constant. A central lead core can be used to provide energy dissipation. A two second time period is recommended for this type of bearing.

The FPB consist of two high-grade stainless steel plates with upper and lower concave surfaces. An articulated slider moves along the concave surface, when activated by an earthquake. The sliding surface is coated with a high-strength self-lubricating bearing liner. The lateral movements are restricted by a circular retainer.

The Friction Pendulum steel seismic isolators use geometry and gravity to achieve the desired seismic isolation results. The supported structure responds to earthquake motions with small amplitude pendulum motions. The bearings `isolate´ the structure by taking advantage of this pendulum effect to lengthen the natural period of the structure. The dynamic friction force generated provides the required damping to absorb the energy of the earthquake. The period and the damping are characteristics of the bearings that can be defined independently. Dynamic periods from 2 to 5 seconds can be achieved.

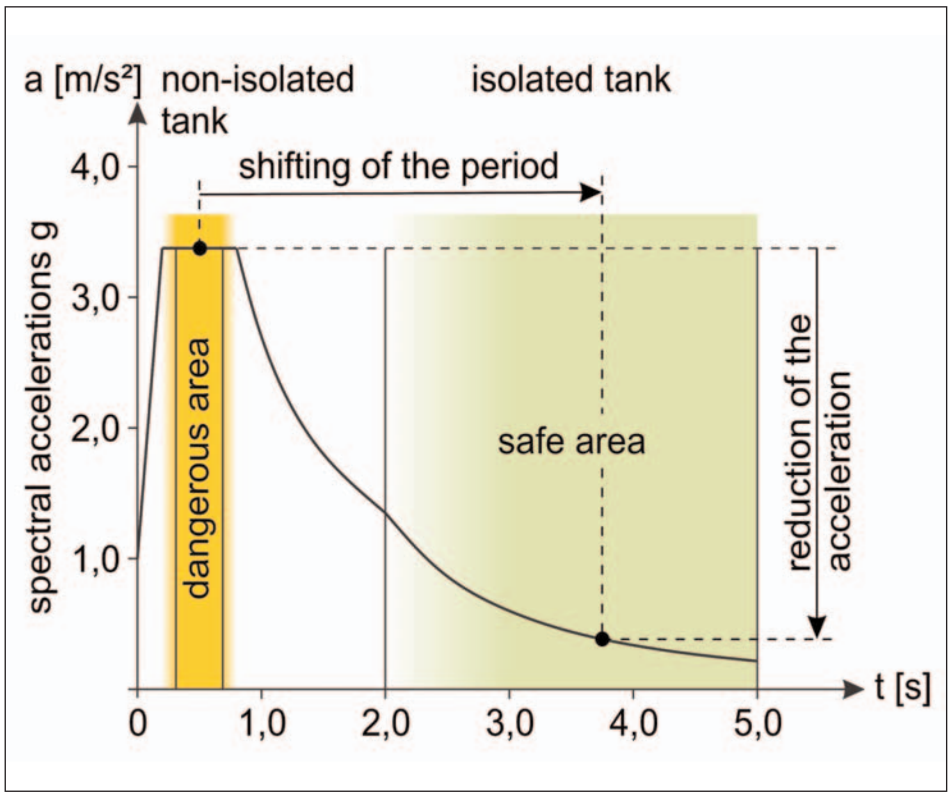


Figure 4: Spectrum (EC8, soil type D) with shifting of the period

Conclusion

The relation between acceleration and period is illustrated in Figure 4. The amplification factor, which is the enhancement of the structural excitation in relation to the earthquake acceleration, is in the range of 3 to 3.5 for a non-isolated full containment tank. The implementation of a base isolation system allows a significant reduction of the earthquake forces on the tank by approximately 80%.

The fundamental natural period is shifted to about 2 seconds using High Damping Rubber Bearings and up to 5 seconds using spheric sliding isolator type bearings. This shifting of the period results in a reliable safety factor against uplifting and prevents damage of the inner tank due to buckling.

The refinement of dynamic analysis techniques allows a precise assessment of the risk resulting from earthquake loading at any given location. Simplified analysis methods developed by the authors allow reliable technical feasibility study at an early stage in project development when a full dynamic analysis may not be justified. ■

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