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BENEFITS OF SEISMIC ISOLATION FOR LNG TANKS

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SUMMARY

The paper discusses the seismic environments in which Liquefied Natural Gas (LNG) tanks need not, may, and must be seismically isolated, as well as the associated costs and benefits when both alternatives are reasonable options. The problems that a gradually increasing seismic demand may cause in an LNG tank are reviewed first: they include greater demands in the inner tank, the possibility of corner uplift and elephant's foot buckling, gross sliding of the inner tank, thickness requirements beyond the weldable limit and global uplift of the inner tank. Some of these problems cause extra costs while others make the construction impossible. The acceleration levels at which these problems are expected to arise are quantified. Although the work also includes conventional and seismically isolated versions of two existing tank configurations (60,000 and 100,000 m^3 capacity) it concentrates on a 160,000 m^3 tank, which is more representative of current tendencies; for the latter, both a surface slab and a pile foundation are considered. The feasibility of conventional and seismically isolated designs is examined as a function of the design acceleration.

Some assumptions are then introduced for the costs of the required features and materials, leading to cost estimates for dealing with the seismic threat for each seismic environment and tank design option. Over the range of accelerations that allow both isolated and non-isolated designs, approximate cost comparisons are established. The study was carried out within the framework of the EC-funded INDEPTH project.

1. INTRODUCTION

Earthquakes impose significant demands on structures in many parts of the world. One way of dealing with them consists on providing seismic isolation for the structure, which may be designed to decrease the stress and other demands on the structure, even if it may entail other less desirable side effects such as increased relative displacements. The present paper attempts to clarify the advantages and disadvantages of this strategy in relation with LNG tanks. The study was carried out within the framework of the EC-funded INDEPTH project as well as the works by Bergamo et al [2006], Castellano et al [2006] and Gregoriou et al [2006].

The more extended type of tank is the full containment one, which is the one considered here. It is composed of an-inner, self-standing steel tank and an outer concrete tank. The inner tank is cylindrical and open at the top; it is made of cryogenic steel (9% Ni) and normally rests on thermal insulation. The outer tank is made of concrete. Typically the cylindrical wall is post-tensioned, both in the vertical and hoop directions, and is generally about 80 cm thick. The base slab and spherical roof dome are made of reinforced concrete. Adequate thermal insulation is provided between the two tanks.

The Repsol LNG plant at Huelva (Spain) had been adopted as the reference facility. This plant has two operating tanks, with storage capacities of 60,000 and 100,000 m^3, respectively, and a third one under construction, capable for 150,000 m^3. Additionally, a larger generic 160,000 m^3 LNG tank with standard aspect ratio was also considered. This configuration is far more representative of current tendencies in LNG tank construction.

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For the purposes of this study, only the properties of the inner tank have an influence on the results. For the 9% Ni steel, the Young's modulus considered is 200 GPa, the Poisson's ratio is 0.3 and the density is 7850 kg/m^3.

2. DESCRIPTION OF THE SEISMIC INPUT

The seismic input has been defined by means of two features: a spectral shape and a reference acceleration used for scaling the previous spectral shape. For the spectral shape, three different ones have been considered, one corresponding to a medium type spectrum and two which are enriched either in the low or in the high frequency range of the spectrum. More specifically, the three spectral shapes adopted are those that the draft of Eurocode 8 [CEN, 1997] recommends for soil types B, C and D and type 1 earthquakes (magnitude M_s>5.5) and S=1. The spectral shape for the vertical motion has been obtained multiplying by 0.7 that of the horizontal motion. The reference acceleration a_g will be taken as a continuously varying parameter, descriptive of the hazard level at the site. For a given spectral shape, this will allow studying the acceleration levels at which the various design solutions are unfeasible, attractive, required, etc.

3. COST ASSUMPTIONS

Increasing levels of seismic demands have of course an influence on the cost of designing, building and operating any of the structures considered. These cost effects are a function of whether the tank is seismically isolated or not, and of some other design aspects. In the present section, an attempt will be made to review the relevant cost items and to provide information suitable for quantifying the incremental costs incurred.

It should be underlined first of all that any reliable information on costs concerning specific construction items is very hard to acquire, specially for the LNG tanks. The reason is that contractors tend to maintain the confidentiality of that type of information. LNG tanks are typically awarded as turnkey projects, and prospective EPC contractors (Engineering, Procurement, and Construction) are loath to disseminate their cost information.

3.1 Isolation devices

For an isolation system consisting of elastomeric isolators, the estimated costs are shown in Table 1 for different tank capacities and calculated displacements. The isolation design is taken to be governed by the AASHTO Guidelines. It should be noticed that costs may be strongly affected by the code used: for example a design following the Italian seismic code will result in higher costs, while the Japanese code will probably result in lower ones.

Table 1 Cost of isolation for various LNG tank configurations and three displacement levels

Tank capacity (m^3)	Calculated displacement (m)	Cost of isolation (M€)
60,000	0.2	0.48
	0.4	0.96
	0.6	1.72
100,000	0.2	0.80
	0.4	1.62
	0.6	2.63
160,000 (slab)	0.2	1.15
	0.4	2.52
	0.6	4.46
160,000 (piles)	0.2	1.15
	0.4	2.52
	0.6	4.86

3.2 Flexible connections

The relative movement between the various structures and the ground allowed by the seismic isolation requires providing the piping with connections that maintain their function in spite of those relative movements. For a typical LNG tank the cost of the flexible connections has been estimated as 0.3 M€.

3.3 Concrete

Unit costs for different types of concrete structures are needed. The following unit costs have been considered:

- concrete on the ground: 300 euros/m^3
- elevated concrete which requires formwork and structural supports: 450 kg/m^3

If the local geotechnical conditions are such that the tank requires a pile foundation, the placement of seismic isolators does not entail the need for any additional concrete: one device would be placed in each pile, more or less directly under the base slab of the tank. However, if the tank only needed a surface slab for foundation, though, the placement of isolation devices requires constructing a double mat and concrete pedestals located between the two slabs. The devices would be placed in the upper part of the pedestals. It has been assumed that, except for its periphery, a shallow slab is only 0.7 m thick, while in the case of a double slab a thickness of 1 m is required for both slabs; pedestals are constructed every 12 m^2 of slab and they are assumed to be 2 m high and 1 m in diameter.

3.4 Steel

As the seismic demand increases, the walls of the steel tank may need to be thicker and there is also the possibility that steel anchors are needed. The required steel thickness is a function of the expected pressures in the liquid, which are of course affected by the earthquake. The steel needed for both, container and anchors, is cryogenic, adequate for withstanding the low temperature at which the LNG is stored (-166 ºC approximately).A unit cost of €5/kg has been used here.

Anchorage is not required with the usual aspect ratios of tanks until the PGA reaches about 0.3g. When required, the minimum cost of anchorage has been taken as 0.35 M€, increasing with the amount of steel required by the anchor system.

3.5 Heating system

The contents of the tank are stored at -166ºC. Thus, when the base slab is placed directly on the ground, it becomes necessary to heat the slab in order to keep the ground from freezing underneath. If the base slab is elevated and air circulates freely below, then heating is no longer necessary. This arrangement, however, is only possible when there is a double slab or, in the case of pile foundations, if the piles are extended some 2 m above the ground surface before building the slab.

The total cost of the heating system may be on the region of 1 M€, already installed in the tank. However the energy costs during the life of the tank are much harder to include because, over long time periods, their effect may be greatly distorted by unsupported assumptions about the likely future evolution of inflation rates, interest rates and electricity costs. For the present study, the energy savings have been taken to be equivalent to the upfront saving of 10 years of energy consumption, with a unit cost of 0.1 €/kWh. The energy savings for a 160,000 m^3 tank can then be estimated at 1 M€.

4. DESCRIPTION OF THE SEISMIC INPUT

LNG tanks are considered to be high responsibility structures due to the chemical energy that they store. As a consequence, their design requirements [API, 1998; BSI, 1993; CEN, 1997; NFPA, 2001] are fairly stringent. As an example, they take into account an Operating Basis Earthquake (OBE) with a return period of 475 years and a Safe Shutdown Earthquake (SSE) with a return period on the region of 5 to 10 thousand years, depending on the specific standard being used. They also include many other requirements and postulated accidents.

The design must finally satisfy all of the requirements imposed. However, seismic considerations govern only certain specific aspects of the design, their implications obviously growing as the design motions increase. But for many of the tanks' characteristics, the design is largely unaffected by the seismic specifications.

An increase in the input motions leads to larger seismically generated stresses, liquid pressures, forces and displacements. In principle, this type of consequences can be handled by simply increasing material quantities. The seismic effects on quantities and costs are therefore gradual, growing with the size of the design motions. However, there are thresholds beyond which, the strengthening process cannot be pursued continuously; at those points, either a new feature must be incorporated or, perhaps, the design is simply not possible any longer.

The outer tank undergoes few, if any, impositions from earthquake considerations. This is because, being the outer protective skin, it must sustain also all other threats from the outside and some from the inside. This includes low probability winds, impacts from flying missiles, overpressures from a hydrocarbon cloud deflagration, etc. The two more demanding ones, though, are the major leak (when the liquid gas is postulated to cross freely the inner tank and contact the outer tank, bypassing the thermal insulation) and the external fire (in which the tank is subjected to high thermal fluxes for certain periods of time). As a consequence, except for perhaps having to add a small amount of reinforcement in the dome, the design of the outer tank is barely affected by the specified seismic motions.

On the other hand, the inner tank is simply designed for containing the liquid gas, already protected from most external events by the outer tank. It is therefore much more sensitive to the earthquake effects, since they are practically the only ones (beyond operating conditions) for which the outer tank provides little protection. One of the consequences of the earthquake is sloshing, the generation of standing waves in the free surface of the liquid. The predicted wave height must be incorporated as additional freeboard of the inner tank in order to prevent spills. This therefore entails increased height requirements of both inner and outer tanks, with considerable financial consequences. However, typical sloshing periods are very high (about 10 s); the periods of non-isolated and isolated tanks differ substantially (about 0.5 s and 2 s respectively), but they are so far removed from the sloshing period that the sloshing amplitude is generally not affected by seismic isolation. In short, sloshing implies an increase in costs but, being similar for both isolated and non-isolated tanks, it does not lead to a differential advantage.

Apart from sloshing, which involves the so-called convective liquid mass, the movements of the rest of the liquid mass, the impulsive mass, entail pressure variations in the liquid. The same occurs with the vertical ground movements, which also excite the liquid mass. All the imply departures from the preexisting hydrostatic pressures. Also, rocking excitation may lead to excessive compression of the tank wall (producing the elephant’s foot buckling) and/or lift-off at the opposite corner of the tank.

Another undesirable response of the inner tank would be gross sliding. The horizontal demands, coupled with a dynamically decreased vertical weight, may lead to gross sliding of the inner tank. There is little that the designer can do to avoid this problem if it does tend to occur.

Finally, if the vertical accelerations were sufficiently high, the upward vertical forces might exceed the static weight, whereupon the inner tank and the liquid would lift off globally. Again, no practical solution exists for this problem.

For the purpose of the present study, the following problems and solutions, if they exist, are considered:

- Increased liquid pressures and increased compression of the wall: solved by increased steel thickness or stiffening.
- Corner uplift: solved by providing sufficient anchor straps.
- Gross sliding of the tank: fatal, no solution.
- Required thickness of inner tank exceeds about 50 mm: fatal, no longer weldable.
- Global uplift of the tank: fatal, no solution.

The first two items above are not fatal, they simply require additional expenditure. The last three, however, have no known solution in current practice; hence, when those thresholds are reached, the tank can no longer be designed while keeping the conditions that lead to the violations mentioned.

The listing provided above will allow comparing how the additional costs evolve with increasing seismic demands in the various hypotheses, particularly with/without seismic isolation and in sites where a pile foundation is/is not required. It will also allow determining when a given design concept is no longer feasible.

5. CALCULATION OF SEISMIC RESPONSE

The calculations performed involve the response of an isolated tank and that of a non-isolated tank for progressively increasing levels of the response spectrum presented earlier. The non-isolated tank is assumed to rest directly on reasonably competent ground; otherwise it would not have been able to fulfill the requirements that BSI (1993) imposes on differential settlements. Specifically, a soil with an effective shear modulus of 250 MPa and a density of 2000 kg/m^3 is assumed with a shear wave velocity of 350 m/s. The isolated tank is assumed to be supported on devices that are vertically rigid and take the first horizontal period of the tank to 2.5 s with 15% damping. For both tanks, the following tasks are carried out:

– Determination of the liquid masses (impulsive and convective), mobilised in relation with the horizontal response of the tank, on the assumption of a full inner tank.
– Determination of the liquid masses (responding rigidly and in the first breathing mode), mobilised in relation with the vertical response of the tank, on the assumption of a full inner tank.
– Determination of the lower natural frequencies of the inner tank, for both horizontal and vertical excitation.
– Use of the response spectrum method, with suitable combinations of the horizontal and vertical components, in order to determine the need for increasing material quantities, as well as the points beyond which the design is no longer possible.

The calculations follow the methodology proposed by the ASCE-Standard 4-98 [ASCE, 2000] and the Guidelines for the Seismic Design of Oil and Gas Pipeline Systems [ASCE, 1984]. For the vertical excitation this methodology is supplemented with that proposed by Veletsos and Tang [1986, 1990]. The calculations of the tank response under vertical excitation are rarely very important in case of non-isolated tanks, but may become decisive when using isolation. Although the horizontal forces are considerably reduced by the isolation, the vertical ones remain essentially unaffected and the relative importance of the latter may therefore become much larger.

The dynamic analysis must incorporate the effects of the liquid mass during the seismic excitation, including both the horizontal and vertical components of the response. For the horizontal excitation the inertial contribution of the liquid mass can be divided into two different components: the portion of the liquid that moves in unison with the tank as a rigidly attached mass, called the impulsive mass, and the rest of the mass that moves independently, experiencing sloshing and rocking oscillations; this second portion is called convective mass. The magnitudes of these contributions have been estimated using Veletsos [ASCE, 1984] methodology. For the vertical calculations a similar approach is followed. Again two masses are evaluated: a rigid mass that follows the motion of the tank's base and a vibrating mass. The period of vibration of the latter is the one corresponding to the first breathing mode of the tank. In this case the rigid mass turns out to be about 42% of the total mass, while the rest of the liquid mass vibrates in the first breathing mode.

An important component of the cost may arise from the need for additional cryogenic steel for the inner tank. The thickness at the various elevations must suffice for dealing with the following three demands:

– Hydrostatic conditions
– OBE conditions
– SSE conditions

It is seldom obvious which of the latter two cases is more limiting, even though the SSE is clearly greater than the OBE, because standards use different evaluation rules and different values of the allowable steel stresses for OBE and SSE conditions. In the calculation of the inner tank, both the horizontal and vertical excitations have to be considered and adequately combined. The rule adopted for combining both actions is 100% in any one direction with 30% in the other.

The calculations of corner uplift follow the methodology described in API 620 [API, 1998].

Figure 1 presents the SSE accelerations triggering each of the problems mentioned in section 4 for the non-isolated case and for each of the four tank configurations considered and spectrum SC. Figure 2 shows the corresponding accelerations for the isolated cases.

The following milestones are of particular significance for the 100,000 and 160,000 m^3 tanks:

– For a non-isolated tank when the peak ground acceleration (PGA) reaches:
    – 0.25g-0.30g: there is corner uplift unless anchorage is provided
    – 0.40g-0.50g: the inner tank starts to slide during the earthquake
    – around 1.00g: there is global uplift of the inner tank

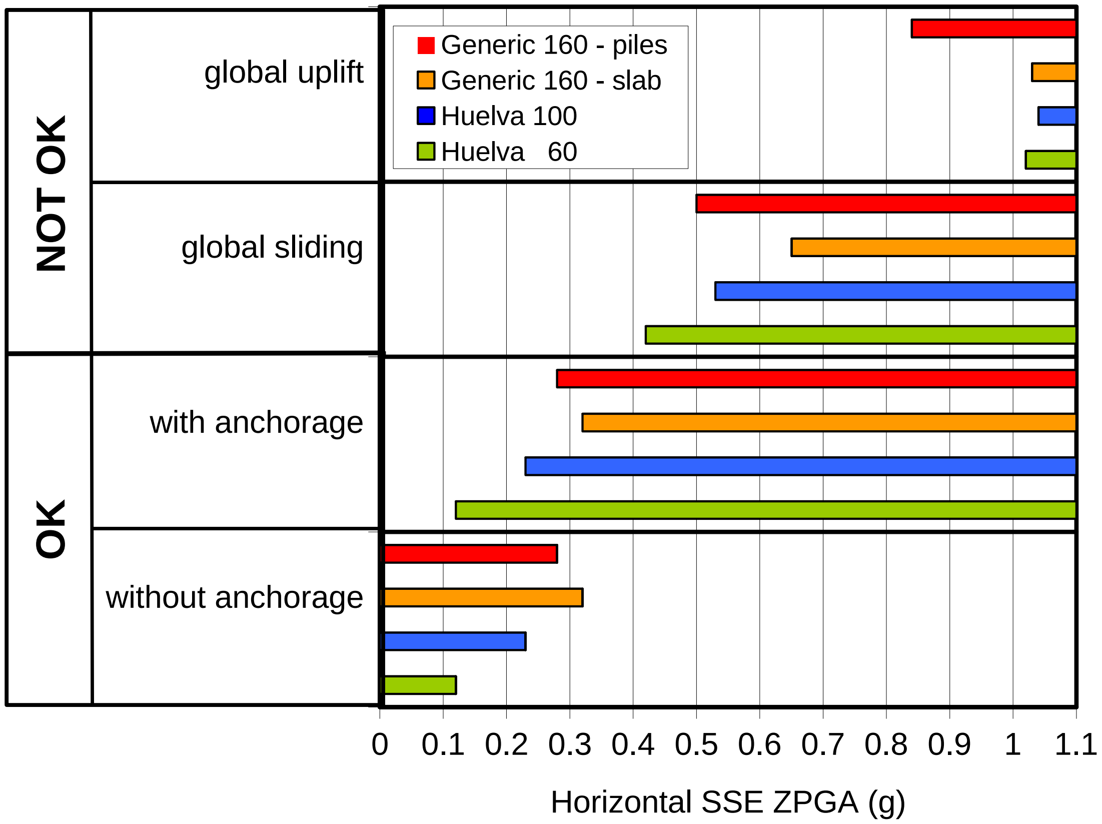

Figure 1 Onset of problems for non-isolated tanks. Spectrum SC

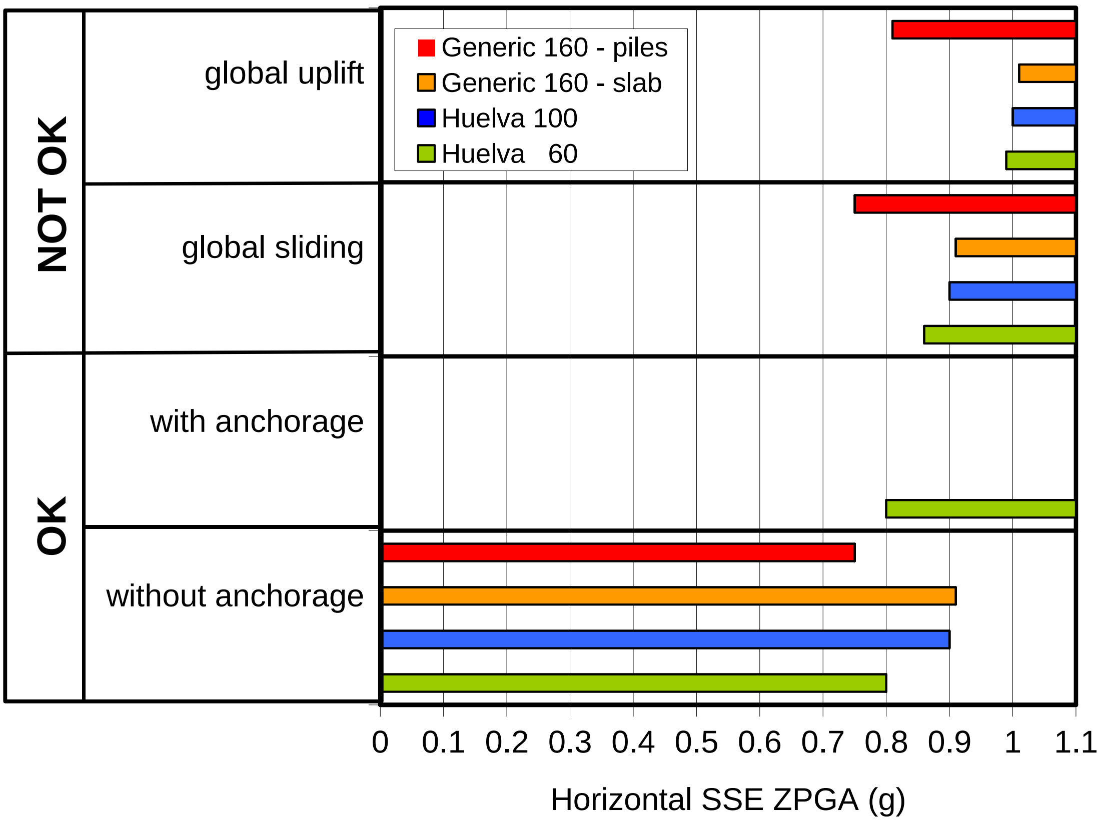

Figure 2 Onset of problems for isolated tanks. Spectrum SC

- For an isolated tank when the peak ground acceleration (PGA) reaches:
    - 0.80g-0.90g: the inner tank starts to slide during the earthquake
    - around 1.00g: there is global uplift of the inner tank

The presence of isolation does not introduce any difference in the tank response to the vertical excitation. The little difference in the accelerations that produce global uplift, which are slightly higher for the non-isolated case (see Figures 1 and 2), is due to the thinner shell thickness required in the isolated case.

As a function of the peak ground acceleration, the following occurs:

- Up to 0.25g-0.30g: isolated and non-isolated tanks are possible without anchorage
- From 0.25g-0.30g to 0.40g-0.50g: the isolated tank is still possible without anchorage, but the non-isolated tank requires anchorage.
- From 0.40g-0.50g to 0.80g-0.90g: only the isolated tank is possible which can still be unanchored.
- From about 0.90g onwards: the tanks cannot be built with the current standards and methodology; even an isolated tank will undergo gross sliding during the earthquake.

For the 60,000 m^3 tank the thresholds are somewhat lower, mainly due to the different aspect ratio of the reference tank, quite uncommon nowadays.

6. DIFFERENTIAL COSTS

By combining the structural and cost information, it becomes possible to compare the different situations and design strategies. Three cases are considered:

- a conventional design, without seismic isolation, whether supported on a surface slab or on piles
- a seismically isolated tank, which already required a pile foundation in any case and has an isolating device per pile
- a seismically isolated tank, which did not require a pile foundation for other reasons and therefore had to be provided with a double slab and pedestals for placing the devices.

The costs being considered are costs incurred as a consequence of the seismic demands and only if such costs vary between the three cases considered. For example, if a larger earthquake implies greater sloshing heights and therefore an increased height of the inner and outer tanks, the costs of this increase would be taken into account only if they differed between the three cases studied; since they do not, they are not included. This means that the curves depicting the cost evolution with increased seismic demands are only significant in what concerns the differences between the curves, not their absolute values, since there are some other costs which would be common to all the curves and are therefore not included.

To clarify matters, the costs accounted for in each one of the three cases considered are:

- non-isolated tank
    - increased thickness of inner tank
    - anchorage of inner tank
- isolated tank with piles
    - isolation system
    - flexible pipe connections
    - increased thickness of inner tank
    - anchorage of inner tank
- isolated tank on surface slab
    - dual slab and pedestals
    - savings in heating system and energy
    - isolation system
    - flexible pipe connections
    - increased thickness of inner tank
    - anchorage of inner tank

The results are combined and compared in Figure 3 for the 160,000 m^3 tank, spectrum SC and the slab foundation and in Figure 4 for the pile foundation.

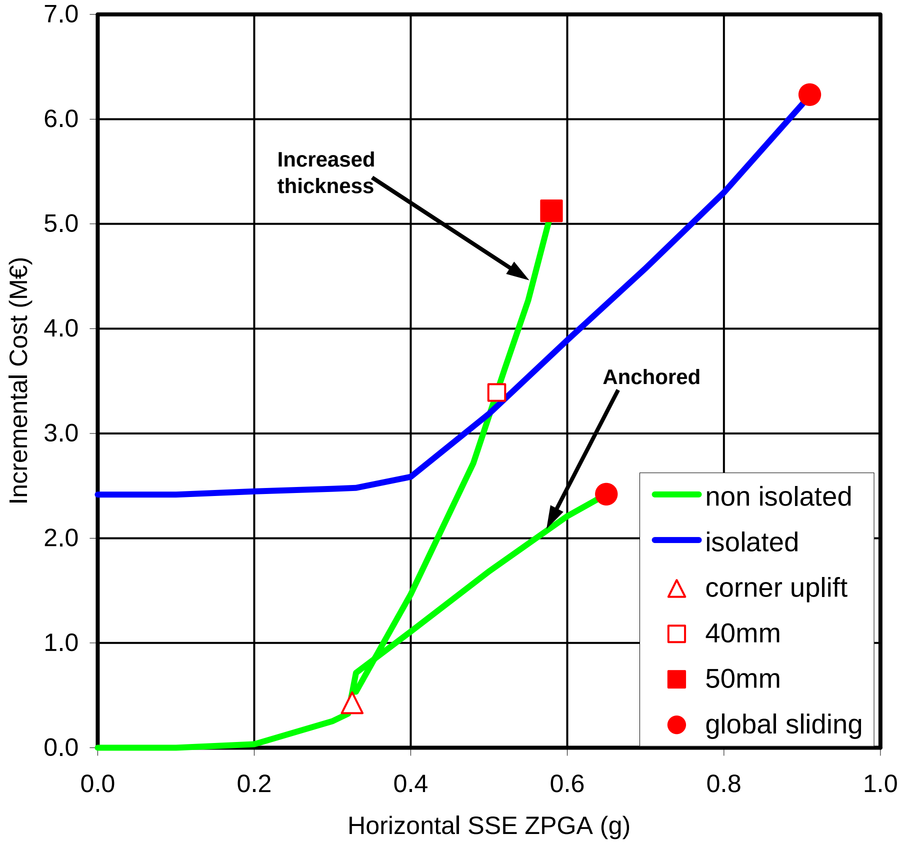

Figure 3 Cost evolution with seismic demand. Slab Foundation

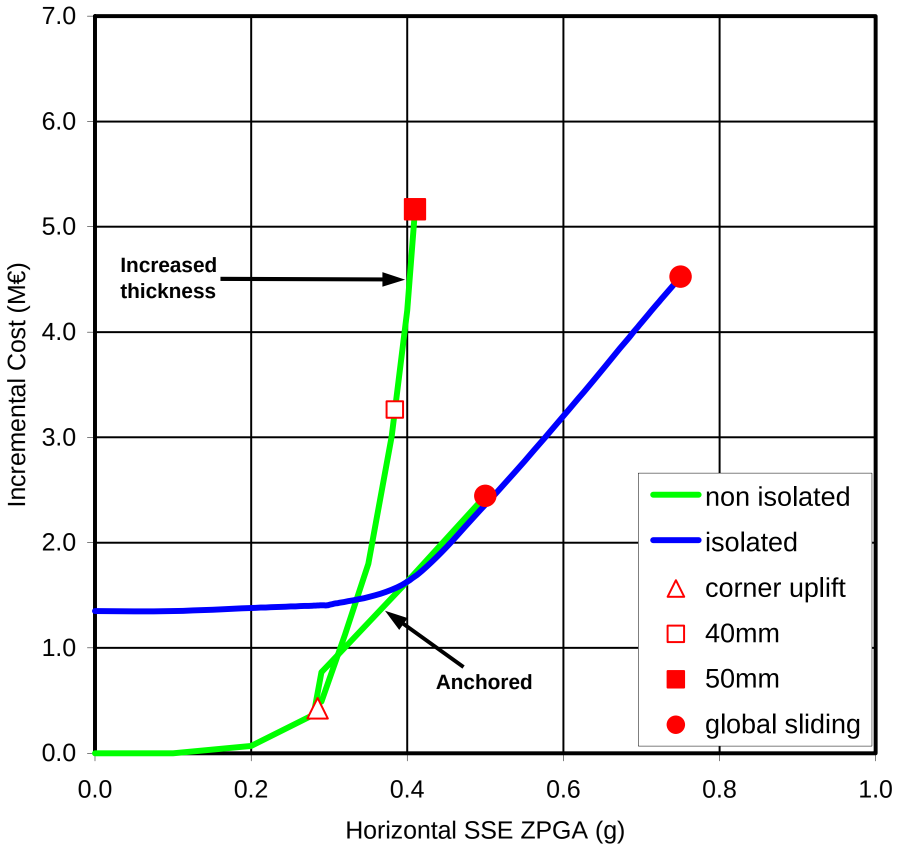

Figure 4 Cost evolution with seismic demand. Pile Foundation

The curves reflect the progressive increases in material quantities being imposed by the larger seismic demands.

In the non-isolated case there is a point (red triangle in the graphs) beyond which something must be done to avoid damage by corner uplift.

A possible solution is to anchor the tank: the discrete jump in one of the “non isolated” curves is associated with the introduction of this anchorage. The other “non isolated” branch represents the case where the problem is tackled by increasing the thickness of the inner tank. The cost of increasing the thickness is higher than that of providing anchorage.

For the pile foundation case, between about 0.25g and 0.50g, at least in principle, a non-isolated tank is possible, providing it is adequately anchored. However, this statement needs some clarification for two reasons:

- Anchorage introduces other “costs” of difficult quantification, beyond the cost of the steel. Technically, it creates undesirable stress concentrations at points of the inner tank, as well as thermal bridges across the thermal insulation under the bottom. Practically, it implies considerable complications and delays in the construction schedule because the anchor straps must be left embedded and protruding when pouring the slab concrete, on which the perimetral beam, thermal insulation and eventually the inner tank will be placed.
- Even though anchorage is a relatively frequent practice, there are serious questions as to its reliability during an earthquake. Anchor straps need to be flexible in bending when radial displacements of the inner tank take place; but they are therefore considerably stiffer for movements in the circumferential direction. For straps being deformed in this direction, it is difficult to ensure that they respond in an adequate fashion (for example, without suffering a relatively brittle fracture at weld locations).

As a consequence of these considerations, although it is difficult to offer a precise quantification, an isolated tank may be preferable to a non-isolated tank at least in the upper part of the 0.25g-0.50g range of peak ground accelerations.

For a tank on a pile foundation the cost of the anchored tank equals that of a tank with isolation at accelerations greater than or equal 0.4g. However, for tanks on a slab foundation, the incremental cost of the isolated tank always exceeds that of the anchored one for the same range of accelerations. The reasons for this are:

- The isolation of a tank on a slab foundation requires building an additional slab and pedestals. These extra costs are only partially compensated by the energy savings.
- The inner tank is somewhat more expensive with a pile foundation, because of its stiffer response.

For a tank on piles, the solution of increasing the inner tank thickness is practically always more expensive than that of isolating the tank. For a tank founded on a slab, this is the case only beyond 0.5g an acceleration at which the thickness required at the base of the inner tank is about 40 mm.

Similar calculations have been performed for other combinations of tank configurations and seismic input, although results are not presented here. Similar conclusions concerning acceleration thresholds and differential costs can be obtained from them.

7. CONCLUDING REMARKS

Based on the work conducted, some conclusions can be proposed concerning tanks with normal aspect ratios (i.e. H/R = 1):

- When the design peak ground accelerations are below about 0.25g-0.30g, a non-isolated tank is perfectly adequate and some two million euros cheaper than an isolated tank.
- When the design peak ground accelerations are in the range of 0.25g-0.30g to about 0.50g-0.65g, a non-isolated tank is still possible but it needs to be anchored, which introduces some uncertainties and involves additional costs of difficult quantification. Even neglecting the latter, the cost difference between the non-isolated and the isolated tank decreases with increasing seismic demands it even disappears beyond 0.4g for the isolated 160,000 m^3 tank on piles.

– If the design peak ground acceleration exceeds about 0.50g, a non-isolated design is no longer feasible since it becomes impossible to ensure that the inner tank does not undergo gross sliding during the earthquake. Thus, in the range of 0.50g-0.65g to 0.90g, only seismically isolated tanks can be proposed.
– When the design peak ground acceleration exceeds 0.90g even an isolated tank is not feasible due to the inevitability of sliding.
– Irrespective of other circumstances, global uplift of the inner tank (the tank loses any contact with the base) is predicted when the design peak ground acceleration attains about 1.0g in the non-isolated and in the isolated case.

One final comment may be offered, related to the fact that all the calculations have been made using the response spectrum method. This is a rather conservative procedure, otherwise very well established in the industry and which poses few uncertainties. The calculations could have been carried out using direct integration of synthetic accelerograms and, in practically all cases, the results would have been less demanding. However, the industrial acceptance of a methodology that departs from the more established procedures, together with the uncertainties arising from the sensitivity of the results to the specific accelerograms implemented, are complex questions that could give rise to considerable problems.

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