SEISMIC RISK REDUCTION AT PETROCHEMICAL AND LNG FACILITIES: MAIN RESULTS FROM INDEPTH PROJECT

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ABSTRACT :
The INDEPTH Project (INnovative DEvices for seismic protection of PeTrocHemical facilities), partially funded by the European Commission (Contract EVG1-CT-2002-00065) during the 5th Framework Programme, studied, developed and applied innovative seismic isolation and/or dissipation devices to some of the critical structures present at petrochemical and LNG facilities. A cost-benefit analysis was also performed to evaluate the financial impact of the proposed applications. The project met its scope with an integrated approach, combining numerical analysis and experimental validation. Numerical analyses, with different levels of complexity, were performed for the selected structures (LNG tanks, cylindrical storage tanks and spheres) both with and without the seismic protection device. Experimental validation was also performed both on single devices and on scaled, real structures, providing data for calibration of the numerical analyses and codes. This paper focuses on solutions studied, developed and tested for seismic isolation and energy dissipation in the context of LNG and spherical tanks. The isolated solutions have been compared with non-isolated alternatives and with a conventional retrofit in the case of spheres.

KEYWORDS:
Petrochemical, LNG, Refinery, Evaluation, Retrofit, Seismic

1. INTRODUCTION

In the framework of the INDEPTH Project (Development of INnovative DEvices for Seismic Protection of PeTrocHemical Facilities), structures in petrochemical plants with their seismic vulnerability have been studied. The most critical structures have been selected for a complete study. Cylindrical (with different aspect ratios) product storage tanks and spheres, as well as liquefied natural gas (LNG) tanks have been numerically evaluated at fixed and isolated base conditions; for spheres also a retrofit with energy dissipating braces has been studied. Tests have been carried out on prototype devices and on a spherical mock-up on a triaxial shaking table. Results obtained from tests have been used to tune the numerical analyses performed both with complex and simplified models. As final effort, the INDEPTH partners performed a cost analysis relevant to the studied solutions.

In this article, results obtained for spheres and LNG tanks are summarized. For spheres, two solutions are presented: energy - dissipating braces and base isolation devices. Both solutions can be used for retrofitting of existing spheres. Base isolation solutions (three different types of devices have been studied) have also been experimentally tested on a mock-up of a spherical tank, through a six degree of freedom shaking table. For LNG tanks, different sizes of tanks have been considered and a parametrical analysis with different types of isolation devices are shown. For all the cited structures, the cost benefit analysis is reported.

2. DESCRIPTION OF SELECTED STRUCTURES

Walkthroughs were conducted in order to study different layouts of petrochemical plants located in the Southern Europe Mediterranean area (the highest seismic areas) and to choose the most critical structures.

2.1. Spheres

The reference configuration is an actual sphere. This spherical tank was constructed in 1999 and contains refrigerated polypropylene. It was designed to ASME Sect VIII, Div 1 (1995 with 1997 addenda) with additional design requirements from API 620. Seismic design was based on equivalent static methods with a design spectrum with PGA typical of highly seismic areas. It has a capacity of 4200 m^3, a 19.6 m diameter and it is supported on 11 columns with conventional tension-only braces as the lateral force resisting system (Figure 1).

Figure 1 Selected sphere and detail of the tension-only bracing system.

2.2. LNG Tanks

The typical configuration of this type of tank is the full containment one. It is composed of an inner, self-standing steel liner with an outer concrete containment. The inner liner 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. As reference structures, the analyses considered two 60,000 and 100,000 m^3 capacity LNG tanks located in a Spanish LNG site (Figure 2). The main geometrical and physical data components regarding these tanks are given in [Bergamo et al., 2006]. Additionally, a larger generic 160,000 m^3 LNG tank with standard aspect ratio was also considered in the cost benefit final considerations performed for isolated LNG tanks. This configuration is more representative of current LNG tank construction.

Figure 2 100,000 and 60,000 m^3 capacity LNG tanks.

3. STUDIED SOLUTIONS FOR USE OF BASE ISOLATION AND ENERGY DISSIPATION IN TANKS

Both base isolation and energy-dissipating braces have been studied for seismic protection of the sphere. In particular, base isolation has been studied both for new spheres and for retrofit of existing spheres. Use of energy-dissipating braces was studied mainly for retrofit of existing spheres. Design for base isolation foresaw three different types of rubber devices placed under the base frame of the spherical mock-up. The three types of devices were high damping rubber bearings (HDRB), lead-rubber bearings (LRB) and fiber reinforced rubber bearings (FRRB), respectively, with 10 %, 30 % and 10% equivalent viscous damping. Fibre reinforced rubber bearings have been studied in the INDEPTH project as an alternative to HDRB, aimed at reducing costs.

Retrofit of existing spheres was studied utilizing energy-dissipating braces to substitute for the existing braces. In particular, two types of energy-dissipating braces have been studied, using as energy dissipation non-linear fluid viscous dampers or buckling-restrained braces. The fluid viscous dampers (VD) are piston/cylinder devices that use fluid flow through orifices to absorb energy. Orifices are situated in the piston head, which allow the fluid to move back and forth between the two chambers. The force generated by these devices is a function of the piston velocity with a very high efficiency of the hysteretic loop, very high equivalent viscous damping and thus optimal reduction of displacements at the same maximum force [Infanti et al., 2002]. The buckling-restrained braces (BRB) are a particular implementation of steel hysteretic dissipative devices, charged with the task of assuring a reliable absorption of earthquake energy through stable tension-compression yield cycles [Summers et al, 2004]. The restraining system considered in this study is that consisting of encasing a steel core, covered by a slip interface, into an outer steel tube filled with mortar (Figure 3).

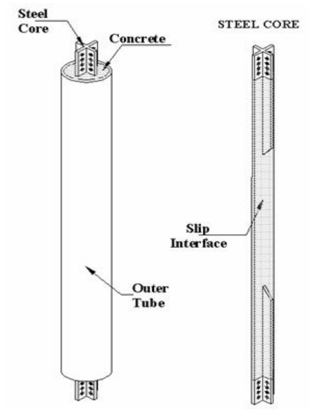

Figure 3 Sketch of a Buckling Restrained Brace.

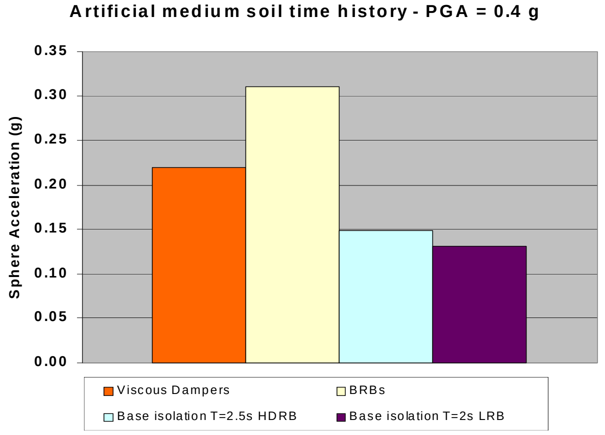

Figure 4 Comparison among accelerations at the sphere centre of gravity

Concerning LNG tanks, three different isolation systems have been considered: high-damping rubber bearings (HDRB), lead rubber bearings (LRB) and low damping rubber bearings coupled with non-linear fluid viscous dampers, i.e., an isolation system with a global visco-elastic behaviour (VE). On the largest tank (160000 m^3), for the cost benefit evaluations, two solutions for the application of these devices have been studied, related to soil conditions. The first solution foresees devices directly placed on the piles, the second utilizing a slab below the outer tank on which devices lay.

4. SELECTED SPECTRA

Most time history analyses and the tests campaigns were performed using as common input an acceleration time history synthesised from the EC-8, 5% damping, Soil C spectrum, with PGA = 0.4 g and duration 40 s [CEN, 2002]. Some analyses were carried out using EC-8 spectra for other soils, and time histories synthesised from said spectra and duration 20 s instead of 40 s.

5. PARAMETRIC NUMERICAL ANALYSES

5.1. Sphere

In order to design the base isolation system or the energy-dissipating braces for the sphere, a finite element model was implemented in the ABAQUS code and several parametric numerical analyses were performed to optimize the characteristics of the devices. Non-linear time-history analyses were carried out. The model implemented includes the 11 columns of the tank modelled with linear beam elements. In case of 100% filling, the liquid is modelled as a lumped mass at the centre of gravity (CoG) of the sphere rigidly connected to the sphere, the sphere itself considered a rigid body connected to the top of the columns. In case of partial filling, the impulsive and the convective masses are considered as lumped masses connected to the sphere rigidly for the impulsive mass and with a beam that has the stiffness necessary to obtain the sloshing period for the convective mass. The braces are modelled with non linear springs with no compression stiffness to simulate the limited buckling resistance of the real braces in the step by step analysis. The viscous dampers are modelled with non linear dashpot elements able to reproduce the real force versus velocity relationship. The buckling restrained braces are modelled with elastic-plastic trusses. HDRB (or FRRB) devices have been modeled using a linear dashpot (to introduce the isolator damping of 10 %) in parallel with linear springs (to simulate the isolator stiffness), while LRB isolators have been modeled coupling in parallel a spring with an elastic-plastic beam to reproduce the hysteretic loop of the lead rubber bearings (equivalent viscous damping ratio 30%).

The sphere with base isolation, the varying parameter in the analyses was the effective horizontal stiffness of the isolators, corresponding to the following six period values: 1.5, 2, 2.5, 3, 3.5 and 4 seconds. Within the obtained results, the isolation systems with LRB and isolation period T=2 s, and HDRB with T=2.5 s have been chosen as optimal. These configurations provide almost the same value of acceleration, and consequently, of base shear for the sphere, even though the maximum displacement is much lower for LRB as the associated damping value is higher [Bergamo et al., 2006]. The response parameter chosen for the selection of the design parameters for the dampers was the sphere acceleration at the CoG, because both the base shear force (that must be resisted by the braces) and the overturning moment (causing compression loads in the columns) are directly related to this value.

The best results in terms of reduction in acceleration is offered by the two base isolation solutions (see Figure 4), but the dissipative braces, in particular the viscous dampers, give a response very similar to that of base isolation. This result is of particular interest, because the retrofit of an existing sphere using dissipative braces is much easier to implement than seismic isolation. Other comparison of results amongst the different retrofit strategies studied in the project are reported in [Castellano et al., 2006]. Further numerical analyses on a more detailed model of the sphere were carried out, considering the dampers selected as optimum from the parametric analyses described above. Full results of the project are contained in (Bergamo, et al., 2007).

5.2. LNG Tanks

The simplified FEM model used for the parametric analyses aimed at comparing the different isolation systems is based on beam elements and represents the following quantities in the simplest manner compatible with the physical characteristics of the structures:

- Inner steel tank;
- Outer concrete tank;
- Foundation slab (as lumped mass);
- Dome (as lumped mass);
- Convective and impulsive mass of LNG;
- Soil stiffness and damping.

An element representing the isolation system in the horizontal direction was included in the model instead of soil stiffness and damping. For all the models a direct-integration seismic analysis was carried out using the time-history described earlier. Three different types of isolation systems were studied. Each isolation system model is characterized by different parameters. Results are contained in Bergamo et al. (2007) and Crespo et al. (2006). See Figures 5 and 6 below.

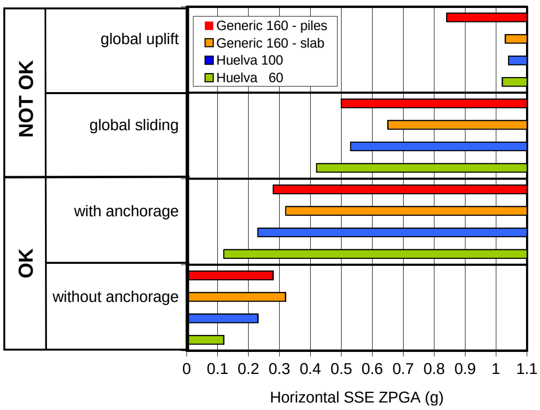

Figure 5 Onset of problems for non-isolated tanks.

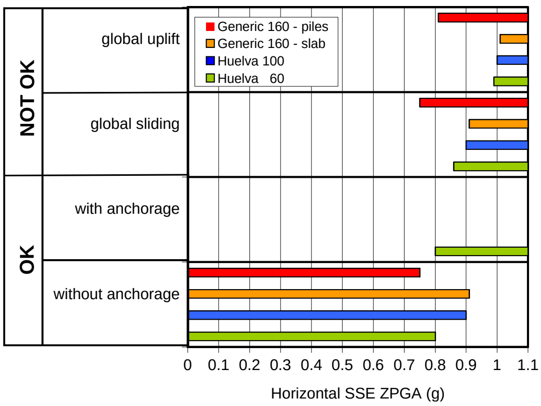

Figure 6 Onset of problems for isolated tanks.

6. SHAKING TABLE TESTS

Shaking table tests were carried out on a mock-up of a sphere. The mock-up was designed to reproduce the same fundamental frequency of the actual sphere. The scaling down of the dimensions (i.e., the construction of a real physical model) would have been difficult (especially for columns and thickness of the sphere). The design of the mock-up aimed to reproduce the dynamic characteristics, rather than the stresses, of the real sphere. Real acceleration time-histories, without scaling, have been used both for the mock-up design and for the tests.

The mock-up was designed to be as large as possible within the limits of the shaking table, for seismic input up to PGA=0.4 g. The test sphere is supported by four columns bolted at both ends. The isolation system for the mock-up reproduces the two isolation configurations selected as reference cases in the parametric analyses of the full scale sphere, i.e. HDRB with T=2.5 s and LRB with T=2 s. The isolated spherical mock-up was mounted on CESI shaking table with two pipe flexible joints manufactured by IWKA connecting the mock-up to the shaking table [Bergamo, Gatti, 2005]. The latter were included to verify whether properly designed joints can withstand the high displacements of an isolated sphere. Further results in terms of peak values of most important response parameters are given in [Bergamo et al. 2007].

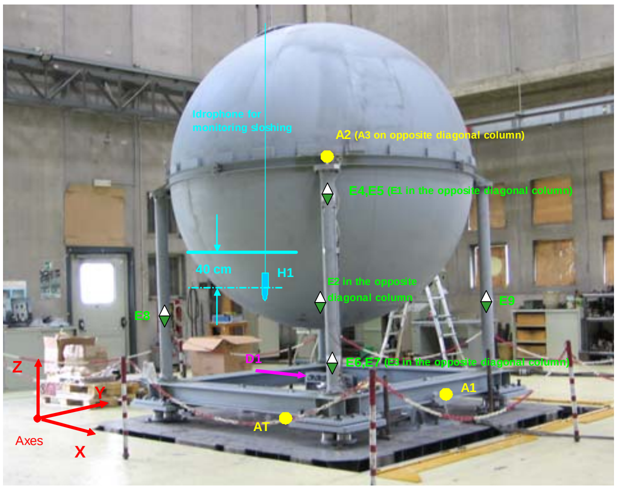

Figure 7 Sphere mock-up on CESI shaking table during test campaign.

7. COST – BENEFIT EVALUATIONS

7.1. Retrofit of Sphere

Both conventional retrofit and retrofit with energy-dissipating braces was performed. For the conventional retrofit, two different damage levels can be assumed: minimal damage with response modification factor, R, approximately equal to 1.5 and code-based design with R approximately equal to 4.0 (damage permitted). For the retrofit with energy-dissipating braces, the devices were optimized for each PGA level, and accordingly, it is postulated that there would be minimal, if any, damage in the structure.

Retrofit options include replacing the existing braces with conventional steel pipe braces or energy absorbing dissipative braces. For the energy absorbing braces, both the design and cost estimate for buckling restrained braces and non-linear viscous dampers are presented. Due to the significant high cost to retrofit existing steel columns and foundations, retrofit options are generally only considered up to the governing capacities of the columns and piles. In this regard, braces that absorb energy and exhibit higher damping, such as those utilizing BRBs and VDs, can offer considerable advantage over conventional 'all-steel' braces. One final comment is that, although not considered explicitly in the cost-benefit analysis below, it is also possible to retrofit with isolators, as already said. However, this will involve additional operational downtime for the sphere while each column is sequentially cut, the sphere jacked up, the isolators inserted and the column connected back in place. The cost of such operational issues needs to be considered on a case-by-case basis.

The cost comparison for the different retrofit options for the existing sphere considered in the INDEPTH Project is presented in Figure 8. In the analysis, peak ground acceleration ranges from 0.2 to 0.6 g.

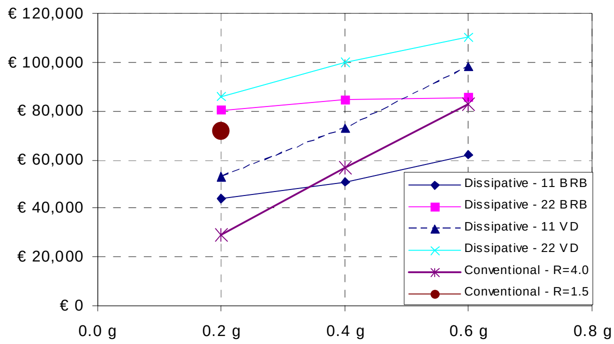

Figure 8 Cost comparison among the proposed retrofit solutions.

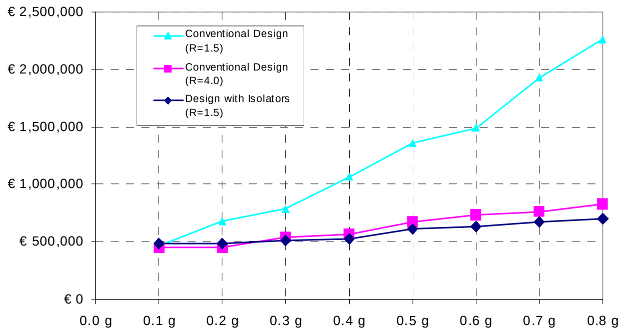

Figure 9 Cost comparison for new sphere with and without base isolation.

Both horizontal seismic loads and vertical seismic loads were considered in the analyses. It should be noted that the 'tension-only' bracing members are generally not suitable for high seismic demand (due to lack of ductility). The cost estimate was prepared in order to compare conventional retrofit and retrofit with energy-dissipating braces. The cost of energy-dissipating braces varies with size, i.e., increases with increasing PGA due to increasing displacement and load demands. For PGA values greater than 0.2 g, piping re-route plus flexible connections for a 16 inch (406.4 mm) liquid outlet line at base of sphere is recommended. For the retrofit using dissipative braces, the cost of buckling restrained braces is somewhat less than that of viscous dampers. Also, the cost for the 11-brace configuration is less than that for the 22-brace configuration. However, the 11-brace configuration is not generally recommended due to potential torsional response in the system and increased column bending effects. Furthermore, there is a distinct lack of redundancy in the 11-brace system compared to the 22-brace system. For the retrofit using conventional braces with minimal damage of R=1.5, the braces can only be upgraded to a PGA of approximately 0.3 g. Beyond this level, the piles and columns would need to be strengthened at considerably greater expense. Hence, if minimal damage is needed beyond the 0.3 g PGA level, the only retrofit option is replacing the existing braces with dissipative braces. However, if normal damage can be tolerated (using R=4.0 in a conventional code-based design), the least expensive 22-brace retrofit option is replacing the existing braces with conventional steel pipe braces. Note, however, that at approximately 0.6 g PGA, the 22 BRB option and the conventional (R = 4.0) pipe braces have a similar retrofit cost. This implies that better performance (i.e., minimal damage) can be obtained using the 22 BRBs for the same cost as conventional pipe braces that have in their design basis an implicitly higher level of expected damage.

7.2 Design of a New Sphere

For design of a new sphere, it is usually conservatively assumed that the sphere is fully filled. Both conventional design and design with base isolators can be performed and compared. For the conventional design, two different damage levels can be assumed: minimal damage with response modification factor, R, approximately equal to 1.5 and code-based design with R approximately equal to 4.0 (damage permitted). For the design with base isolators, minimal damage with R approximately equal to 1.5 can be selected. In the INDEPTH project, peak ground accelerations from 0.1 to 0.8 g have been considered. In the design, 11 columns and 22 braces are assumed.

The support structure cost comparison for the new sphere design with and without base isolators is presented in Figure 9. Further details on cost assumptions are given in [Bergamo et al, 2006]. It can be seen that the sphere with base isolators has apparent cost advantage over conventional designs when the PGA exceeds approximately 0.25 g and the cost for the conventional design with minimal damage is significantly higher than the design with base isolators. It is important to note that the costs provided are not the total construction cost. Rather, they are representative of relative support structure costs.

7.3 LNG Tanks

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 results are combined and compared in Figure 10 for the 160,000 m^3 tank with a slab foundation and in Figure 11 for the pile foundation.

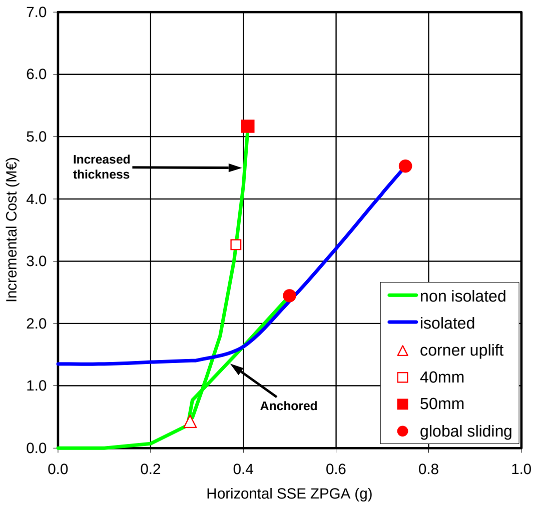

Figure 10 Cost evolution with seismic demand. Slab Foundation.

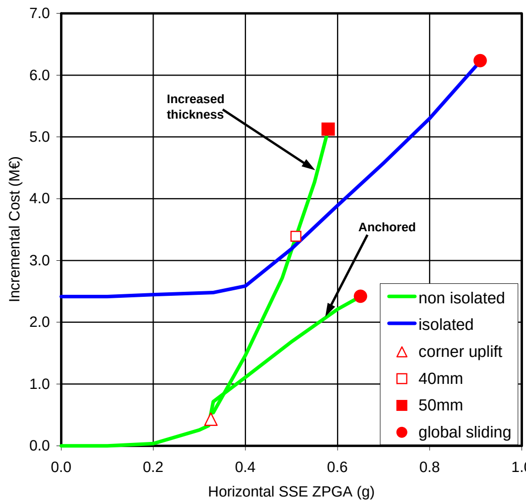

Figure 11 Cost evolution with seismic demand. Pile Foundation.

8. CONCLUSIONS

8.1. Sphere

Amongst the innovative retrofit configurations considered, base isolation was confirmed in theory to be the most effective, in terms of reduction of acceleration at the centre of gravity of the sphere (and thus, reduction of base shear and overturning moment). However, although base isolation can be easily implemented in new spheres, it is much more difficult to implement than energy-dissipating braces for retrofit of existing spheres. The substitution of existing tension-only braces with energy-dissipating braces has been shown to be almost as effective as base isolation, and much more effective than a conventional retrofit, in particular when using nonlinear fluid viscous dampers. In effects, the comparison between the conventional retrofit with steel braces and the innovative retrofit with dissipative braces shows that:

- When the design PGA is below about 0.25-0.3 g, the retrofit using conventional steel braces results in minimal damage (response reduction factor R=1.5).
- When the design PGA is in the range ofhigher than 0.25-0.3 g to about 0.55-0.6 g, using conventional retrofit the piles and columns would need to be strengthened at considerably greater expense. Conversely, replacing the existing braces with dissipative braces can result in minimal or no damage up to the maximum PGA considered, i.e., 0.6 g.

The cost comparison between conventional and seismically isolated design of a new sphere showed that for design PGA values higher than about 0.25 g, seismic isolation permits the sphere to remain relatively undamaged at lower costs than for conventional design.

8.2. LNG Tanks

Based on the work conducted, some conclusions can be proposed concerning tanks with normal aspect ratios:

- When the design peak ground accelerations are below about 0.25-0.30 g, a non-isolated tank is perfectly adequate and is cheaper than an isolated tank.
- When the design peak ground accelerations are in the range of 0.25-0.30 g to about 0.50-0.65 g, 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 0.4 g for the isolated 160,000 m3 tank on piles.
- If the design peak ground acceleration exceeds about 0.50 g, 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 0.50-0.65 g to 0.90 g, only seismically isolated tanks can be proposed.
- When the design peak ground acceleration exceeds 0.90 g 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 1.0 g in the non-isolated and in the isolated case.

9. ACKNOWLEDGEMENTS

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