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SHAKING TABLE TESTS ON A LIQUEFIED NATURAL GAS STORAGE TANK MOCK-UP SEISMICALLY PROTECTED WITH ELASTOMERIC ISOLATORS AND STEEL HYSTERETIC TORSIONAL DAMPERS

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SUMMARY

Within the framework of the European Commission-funded REEDS Project [ENEL *et al.*, 1996], a series of shaking table tests were conducted on a Liquefied Natural Gas (LNG) storage tank mock-up to confirm the effectiveness of an isolation system comprising laminated rubber bearings and steel hysteretic torsional dampers. The tests also served to calibrate numerical models.

For purposes of comparison, three different tank structure configurations were tested: 1) fixed-base; 2) seismically isolated with rubber bearings only; and 3) seismically isolated with rubber bearings and steel hysteretic dampers. The third configuration was tested with two different elastic stiffness and yielding force values for dampers, according to the type of installation, comprising either two or four dampers.

The shaking table tests showed the beneficial effects of both types of seismic isolation system in reducing seismic response compared to the tank directly affixed to the shaking table. The tests demonstrated the damper capability to limit total displacement owing to rubber bearings, which is particularly important in the seismic design of an LNG storage tank

INTRODUCTION

The Liquefied Natural Gas industry, slightly more than 30 years old, has recently begun to attract more widespread attention. Its continued growth could be ensured by the coalescence of two important factors. Since Natural Gas is a non-polluting energy source, it can easily conform to tighter environmental regulations. It also benefits from highly efficient technologies, especially for generation of electricity [Cedigaz, 1998]. The potential risk associated with LNG storage tanks is enormous. Danger always originates from a leak: gas vaporises and explosive air-mixtures are produced resulting in explosions and fire, even long distances away. Thus, accidents can also affect other tanks and areas surrounding the terminal. Consequently, any of said deleterious effects produced by accidents must be restricted to the interior of the LNG storage tank [Guillon, 1986].

The use of elastomeric isolators for the seismic protection of LNG storage tanks has already been studied as well as applied to storage tanks [Baumann, Böhler, 1997; Bomhard *et al.*, 1993; Tajirian, 1993]. The effectiveness of elastomeric isolators has also been experimentally verified [Kelly, Chaloub, 1988]. Shaking table tests were conducted on two cylindrical water tanks, fixed and isolated, during this study. Results show a significant reduction in accelerations and dynamic pressures exerted by the fluid within the container. Concurrently, said results shed light on a potential problem. Namely: the low frequency motion that characterises the motion of base isolated structures can be close to the sloshing frequency of the contained liquid and thereby can increase the liquid elevation response. Another problem is the high displacement induced by the use of elastomeric

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isolators. Indeed, a lot of pipes are attached to the roof of tanks and large displacements could induce serious damage or require the installation of special devices (whose cost is quite high).

The objective of the study presented here is to verify whether the addition of dampers to the elastomeric isolators could overcome said problems in the latter, *i.e.* reduce horizontal displacement and free surface liquid elevation while not simultaneously increase too much dynamic pressures (as well as other structural response parameters). The study comprised shaking table tests on a LNG storage tank mock-up seismically isolated using steel hysteretic dampers together with elastomeric isolators. Said tests aimed to demonstrate the effectiveness of such an isolation system as well as to calibrate the numerical models used in simplified and detailed analyses. Only the preliminary results of this study are presented here. A further refinement of the results will be published elsewhere.

PRELIMINARY NUMERICAL PARAMETRIC ANALYSIS

Parametric analyses were conducted on a simplified model of a full-scale tank with and without seismic isolation, as well as with and without steel hysteretic dampers when using seismic isolation. The objective of said analyses was to demonstrate how the structural response depends on different parameters (*i.e.* horizontal stiffness of the elastomeric bearings; elastic stiffness, yield force and maximum displacement of the steel hysteretic dampers) and, consequently, to aid the selection of the optimal values of said parameters in the design. In these analyses, the rubber bearings were modelled as linear springs, whereas a bilinear model was used for the steel hysteretic devices (with post-yielding stiffness assumed to be equal to 3 % of the elastic stiffness). The optimisation objectives were to minimise shear force and overturning moment as well as base displacement.

The modelled LNG storage tank is a full containment, double wall type, net capacity =125,000 cubic meters. The tank system consists of a free-standing, 9% Nickel steel, open top inner tank containing the LNG, and a concrete tank encasing and protecting the inner tank from external hazards. The tank has the following characteristics: diameter of the inner tank: 79.5 m; height of the inner tank: 27.80 m, design LNG level: 27.30 m; maximum LNG operating level: 26.50 m; total weight when full about 100,000 tons.

The results of the parametric analyses show that an optimal LNG tank response can be achieved by means of a combination of rubber bearings with a total stiffness in the range of 300-600 MN/m and dampers having a total elastic stiffness in the range of 2000-3000 MN/m, and a total yielding force between 40 to 80 MN. The maximum design displacement was 0.16 m for said optimal isolation system.

The structural response does not essentially change by varying the elastic stiffness of dampers within a 1000 - 3000 MN/m range. Even with steel hysteretic dampers having elastic stiffness lower than 1000 MN/m, the shear force and overturning moment on the tank do not vary a lot, although there is an increase in base displacement.

EXPERIMENTAL SET-UP

The tank taken as model for the mock-up to be used for the shaking table tests is the LNG Tank on which preliminary parametric numerical analyses were performed (see § 2). In order to simplify the tests as well as the understanding of the behaviour, only the inner tank shell was modelled in the mock-up. The concrete wall, roof, suspended deck and foam glass were not directly included; they were only taken into account by additional masses in order to respect the global load exerted on the aseismic devices.

The mock-up three independent scale factors were 1/20 for length, 1 for acceleration, and $2.128*(1/20)^3$ for mass (due to presence of water instead of LNG). The Froude similitude was respected. The scale factors for the other quantities can be derived by dimensional analysis. Specifically, the scale factor values for frequency, time, force, and stiffness are 4.472, 0.2236, 2.66×10^{-4}, and 5.3266×10^{-3} respectively. The mock-up was thus 3.975 m in diameter and 1.425 m in height (see Figure 1). The design liquid level was 1.365 m. The total mass was about 30000 kg, almost 60 % of which represents the liquid. A frame of HEB 200 type beams supported the mock-up and served to connect it to the shaking table or to the isolation system.

A six degrees of freedom 4 m × 4 m shaking table was used.

The tank mock-up was tested in four different configurations: with its base directly connected to the shaking table (“Fixed”), isolated through 4 rubber bearings only (“RB”), isolated through 4 hysteretic torsional dampers and rubber bearings (“RB+4D”), isolated through 2 hysteretic torsional dampers and rubber bearings (“RB+2D”).

In each configuration, the mock-up was first subjected to random tests to measure the natural frequencies and corresponding mode shapes. The seismic tests were conducted thereafter. Three different horizontal accelerograms were applied in one direction to the shaking table, at different intensities (mainly –6 dB and 0 dB). The same comprised two synthetic acceleration time histories (generated by the Euro-Code 8 Spectra type B and C for soft and medium soil, respectively, with a peak ground acceleration of 0.30 g) and one ground motion acceleration time history recorded in the North-South direction at Tolmezzo (Italy) in 1976 (named in the following EC8-B, EC8-C, and Tolmezzo, respectively).

The tests used a liquid level of 1 m, *i.e.* almost 30 % lower than the design level. The empty tank mock-up was also tested in the isolation configuration comprising rubber bearings and 4 dampers, with all 3 earthquakes applied at 0 dB intensity.

Eight accelerometers were used to measure accelerations, respectively, on the shaking table, at base of the tank and along the tank wall. Four displacement transducers were installed on the base beams to measure horizontal displacements (two in the direction of excitation, and two perpendicularly). A load cell was used for each damper to measure force. Six pressure transducers were used to measure the dynamic pressure along the mock-up wall. Eight displacement transducers along four vertical lines were used to measure horizontal mock-up wall displacement, *i.e.* its ovalisation. The tank wall strain field was measured through six strain gauges at the points where maximum deformations were expected. The free surface water elevation was measured by two displacement transducers connected to a pair of buoy systems.

ISOLATION SYSTEM

As previously asserted, the isolation system comprised both laminated low damping rubber bearings and steel hysteretic dampers. The scaled design displacement was 8 mm, for the configurations comprising rubber bearings and dampers.

Innovative steel hysteretic torsional devices were used as dampers. The characteristics of said dampers are described in detail in [Dusi et al., 2000]. In comparison with more traditional dampers based on bending of steel elements, these torsion-based steel dampers are endowed with much longer fatigue life as well as higher energy dissipation efficiency.

Both the rubber bearing and damper mechanical characteristics were experimentally verified.

The hysteresis loops of one damper, measured during an imposed-displacement test at ± 10 mm amplitude, are shown in Figure 2. The elastic stiffness resulting from the first cycle of this test was 2.3 kN/mm; the yielding and the maximum force resulting from the fifth cycle (usually taken as reference cycle) were 4.34 kN and 5.26 kN, respectively. Consequently, total damper elastic stiffness was 4.6 kN/mm when two dampers were used, and 9.2 kN/mm when four dampers were used (corresponding to 865 and 1730 MN/m for the full-scale tank, see § 2). The total yielding force was 8.68 and 17.36 kN when using, respectively, two or four dampers (corresponding to 33 and 65 MN for the full scale tank, see § 2).

The average stiffness values measured on one rubber bearing were as follows: 439 N/mm (shear stiffness at 8 mm displacement, corresponding to about 17 % shear strain) and 157.6 kN/mm (vertical stiffness). The total horizontal stiffness of the rubber bearings thus results of 1756 N/mm (corresponding to 330 MN for the full-scale tank, see § 2).

EXPERIMENTAL RESULTS

A total of 25 seismic tests were conducted in the different configurations previously described. Only preliminary results are presented here, pending final data processing.

A significant improvement in all the main response parameters was observed in all isolation configurations as compared to the fixed base configuration. For example, accelerations can even be reduced by 80-90 %, and dynamic pressures by 80 %.

The test results confirm that the presence of dampers can yield a drastic reduction in base displacements in comparison to an isolation system without dampers, as shown in Figure 3. Peak base displacement is reduced about 50 %.

Figure 4 shows the peak absolute values for the dynamic pressures measured on the tank walls during the tests using the EC8-C ground motion at 0 dB, in all four different configurations. Minimum dynamic pressures are achieved with the linear isolation system. However, it is evident that the proper selection of dampers characteristics can yield a reduction from 40 to 70 % (as with the tank with 2 dampers added to the rubber bearings) or even higher, compared to the fixed base configuration. In effect, such tests do not fully show the damper benefits because the mass used was lower than the design value. Figure 5 shows the displacement time history measured on one of the two dampers in the test EC8-C at 0 dB. From Figure 5 one can see that the peak displacement is lower than one half of the design value in all the earthquake-induced cycles but one. That is why the dampers' energy dissipation was not so high in these tests.

The more powerful the earthquake, the more effective the dampers (see Figure 6). For example, at –6dB, when 4 dampers are used in addition to rubber bearings, the tank base peak displacement was 25% lower than when the isolation system comprised only rubber bearings. Conversely, at 0 dB, said displacement reduction reached 45 %. At 0 dB, dampers are thus about 40% more effective than at –6 dB.

Figure 7 also shows how the effectiveness of the dampers increases with earthquake intensity. The peak accelerations measured at different levels are compared for the tank isolated with rubber bearings and 4 dampers subjected to the EC8-C ground motion at 0 (PGA = 0.26 g) and + 6 dB (PGA = 0.55 g), as well as for the tank in the fixed base configuration subjected to the same ground motion at 0 dB. Doubling the PGA, the peak accelerations along the tank wall remain approximately the same in the tank isolated with the dampers. The maximum acceleration (Level 4, *i.e.* at a height of 945 mm with respect to the tank base) reached in the isolated tank during the test at PGA=0.55 g is 40 % lower than the peak acceleration reached at the same level in the fixed base tank during the test at PGA=0.29 g.

The experimental results were compared to the results of finite element analyses on the mock-up, performed with the software COSMOS/M, revision 2. Said comparison permitted the calibration of the model. Modal analyses as well as time history dynamic analyses were conducted. The calibrated model satisfactorily reproduced the dynamic response of the structure in terms of peak values and frequency.

The main difference was that the measured signals (in particular, at the points located on the shell), in addition to the main frequencies, had some higher frequency content than the calculated time histories. Furthermore, some measured displacements were lower than the ones calculated. Such differences could be explained by the geometric defaults present in the actual mock-up, as well as the tension in the shell not taken into account in the model. At any rate, the calculated peak values were always higher than the measured values.

Figure 8 shows a comparison between experimental and numerical results for the base displacement time histories in the tank isolated with rubber bearings subjected to the EC8-B accelerogram.

CONCLUSIONS

Test results have confirmed that the use of steel hysteretic dampers drastically decreases the large displacements reached by the tank isolated with rubber bearings only. Consequently, the safety of the piping system connected to the tank could be significantly increased and/or the cost of the piping connection joints substantially reduced.

It is worth noting that the damping capabilities of the devices were not fully exploited by the tests discussed herein because the liquid mass did not reach the design value. Tests have clearly shown that the effectiveness of dampers in reducing the structural response (displacements, pressures, accelerations, etc.) increases with increasing earthquake intensity. Consequently, the effectiveness of the dampers should be significantly higher under design loading conditions.

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Figure 1: The LNG storage tank mock-up on the shaking table.

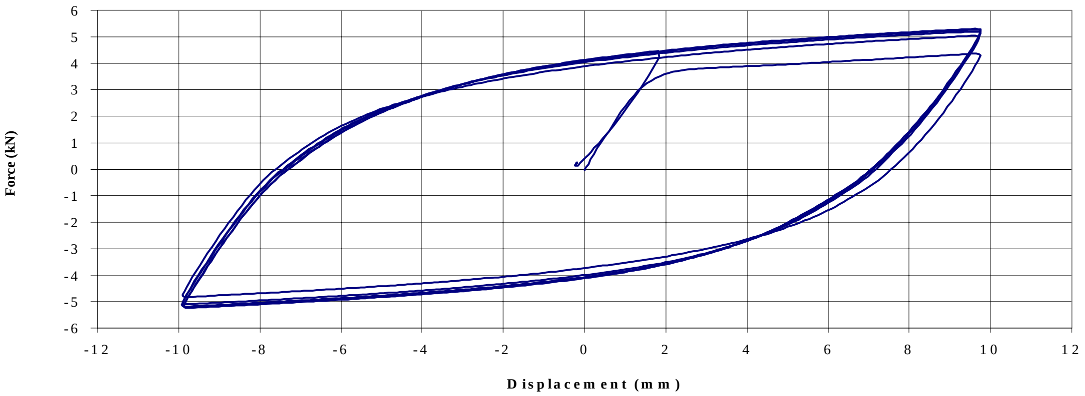

Figure 2: Hysteresis loops measured on a steel hysteretic damper equal to the ones used for shaking table tests (cycles 1-5).

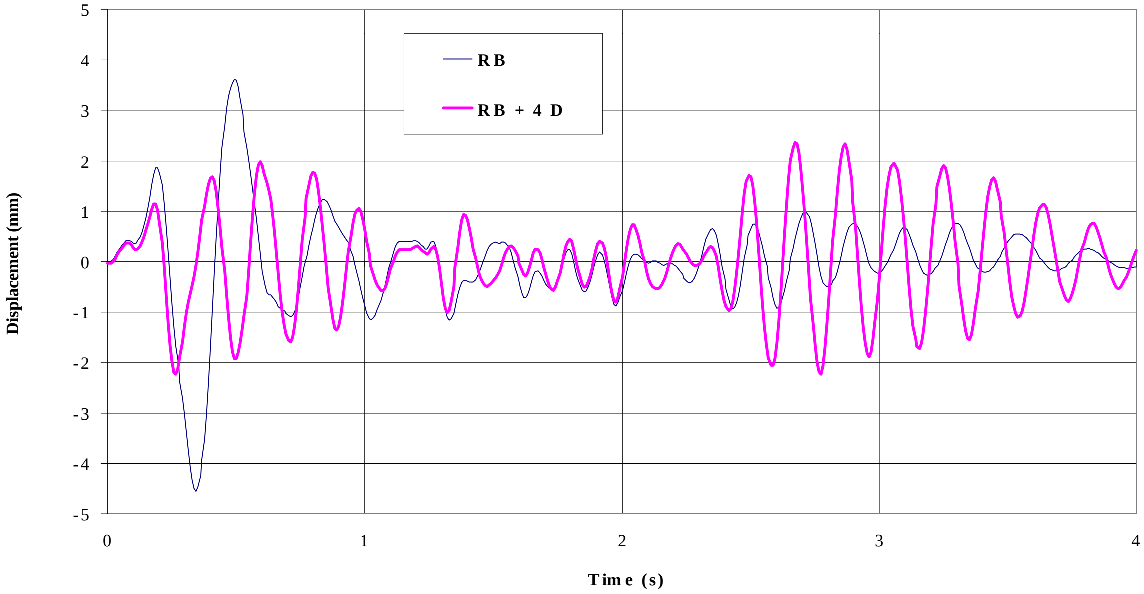

Figure 3: Time histories of the base displacement (tests EC8-B, 0 dB)

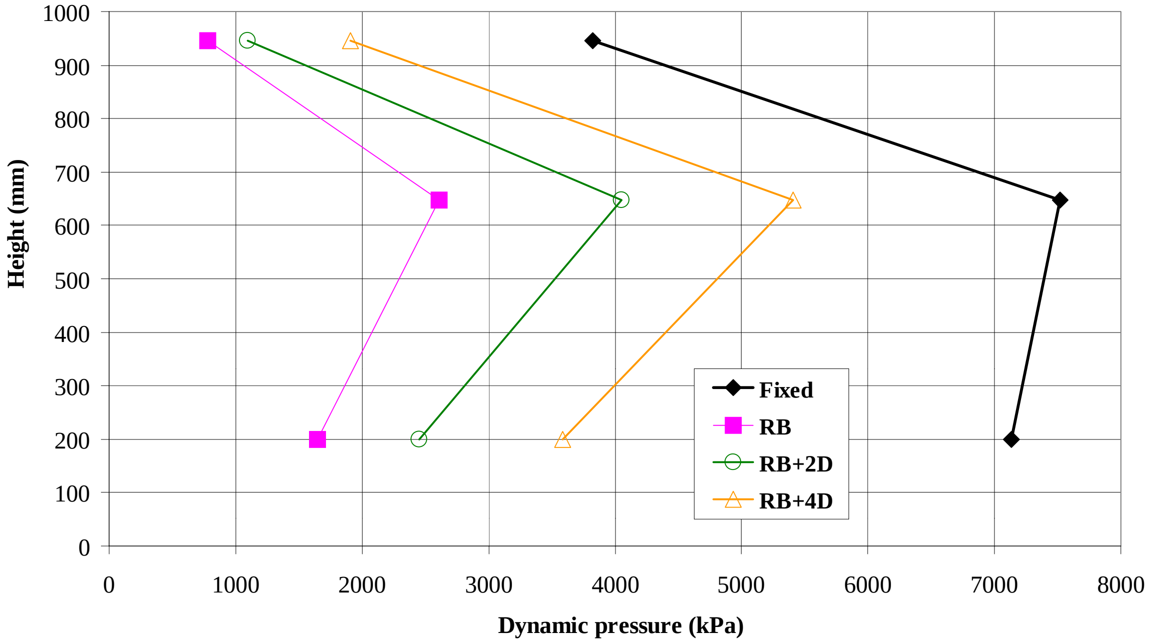

Figure 4: Distribution of peak values of dynamic pressures along the mock-up wall (tests EC8-C, 0 dB).

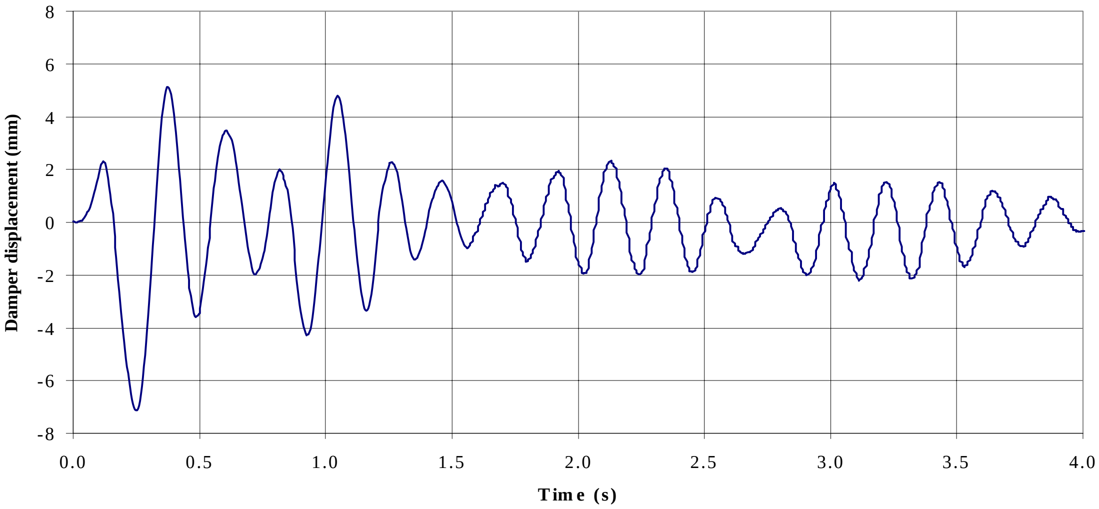

Figure 5: Time history of the displacement of a damper (test EC8-C, 0 dB; configuration RB + 2 D).

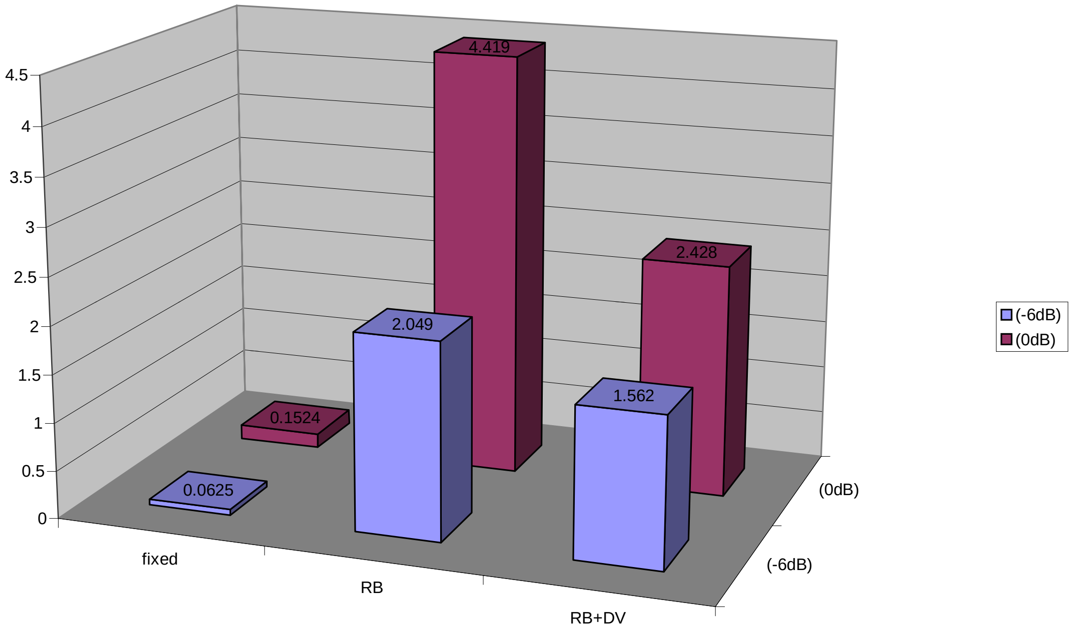

Figure 6: Peak values of base displacements; comparison of different configurations (tests EC8-B, -6 dB and 0 dB; unit is mm).

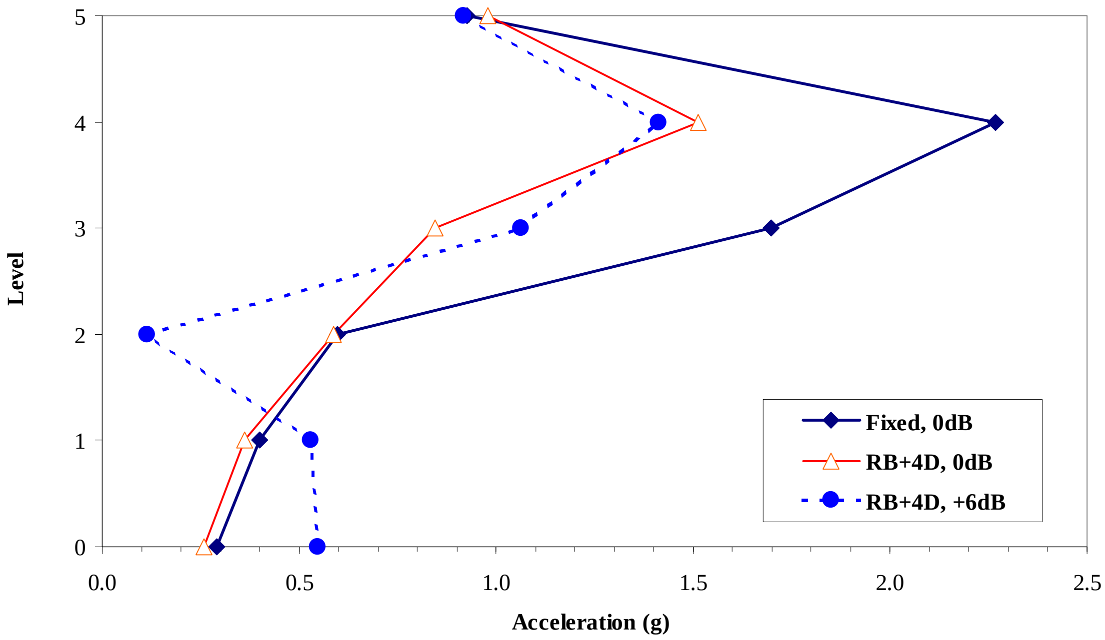

Figure 7: Peak values of accelerations measured at different levels (EC8-C). Level 0: shake table; level 1: tank base; level 2: height 635 mm; level 3: height 660 mm; level 4: height 945 mm; level 5: height 1315 mm.

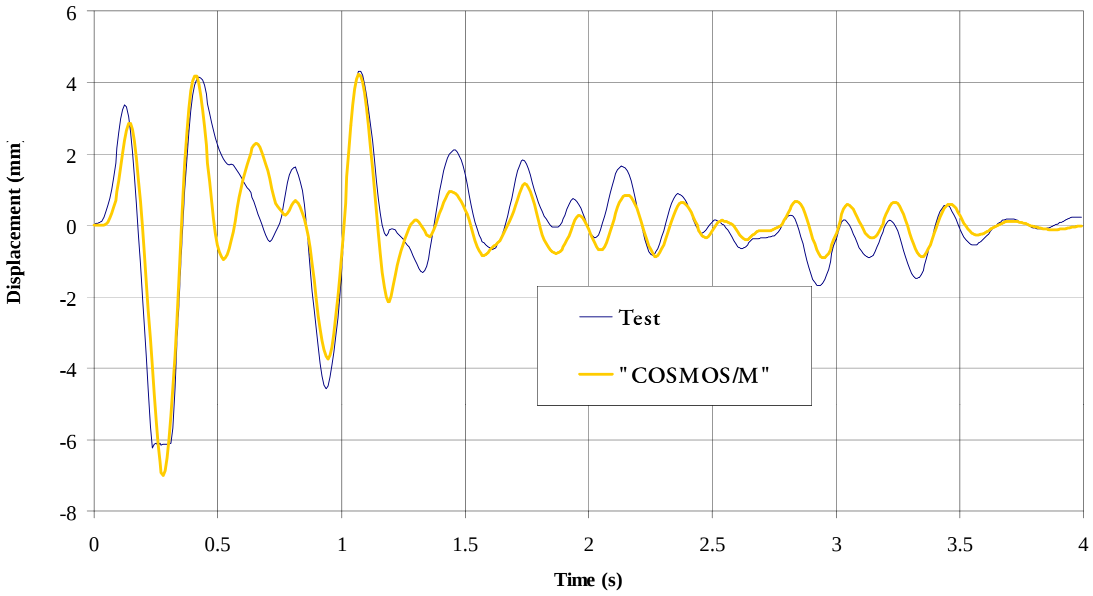

Figure 8: Time histories of base displacement; comparison of numerical and experimental results.