SHAKING TABLE TESTS UPON A BASE ISOLATED STEEL LIQUID STORAGE TANK

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ABSTRACT :

The paper deals with the results of shaking table tests upon a steel liquid storage tank with a diameter of 4 m, filled with water up to one meter. This thank is a 1:14 scale model of a real big liquid steel storage tank installed in a petrochemical plant. First, the tank has been tested in the fixed base configuration with floating roof. Subsequently, the same thank has been seismically protected with two type of isolators: high damping rubber bearings and sliding isolators with elasto-plastic dampers. In each configuration the model has been subjected to the same series of tests. The results confirm the effectiveness of both the isolation systems for reducing the pressure on the tank wall and the negligible influence of the floating roof. On the contrary, for the base isolated case a little increasing of the vertical oscillations of the floating roof has been found, partially compensated by a significant increasing of the damping, which reduce the number of the free oscillations in the post-earthquake phase

KEYWORDS:

Steel storage tanks, shaking table test, base isolation, rubber bearings, sliding bearings

1. INTRODUCTION

The seismic safety of an industrial plant can be effectively increased using tools already adopted in civil engineering, even if the protection levels have to be chosen on the basis of the severity of possible accident consequences. This objective can be reached essentially in two ways: 1) increasing either the strength of the support structure of the equipment or the strength of the equipment themselves in case they have structural character, 2) reducing the effects induced by earthquakes. The first strategy is commonly used in the design of structures; the second one, based on a more recent idea, has seen in the last years a significant number of applications, but only in the civil construction field.
Among the techniques employed for reducing the seismic action, the base isolation systems with elastomeric bearings or sliding isolators with elastoplastic devices are mostly used; the first one is usually adopted for the base isolation of buildings, while the second one is frequently employed for the seismic isolation of bridges. On the contrary, similar methods have been used until now for a very limited number of industrial applications; for example, in Europe the isolation technique has been adopted only for few cases; for example the seismic protection of Petrochemical LNG terminal of Revythousa, Greece, and of ammoniac tanks, at Visp, in Switzerland (Tajirian 1998, Marioni 1997).
The Department of Structures of the University of Roma Tre and the Department of Structural and Geotechnical Engineering of the University of Rome "La Sapienza", are involved in a research project, funded by the Italian National Institute for Occupational Safety and Prevention, whose aim is the study of the applicability of the base isolation technique in petrochemical plants exposed to seismic risk. Among industrial components, the big steel tanks for the storage of petroleum and its derivatives have been taken into account, for their high seismic vulnerability and suitability for the application of base isolation technique.

In fact, in the recent past (e.g. Itzmit earthquake in 1999, in Turkey) most of this kind of tanks have been destroyed, especially as consequence of fires caused by earthquakes.
In this paper, the effectiveness of the base isolation on steel storage tanks has been investigated first through numerical models and then checked by shaking table tests upon a reduced scale (1:14) physical model of a real steel tank (diameter 55m, height 15.6 m), typically used in petrochemical plants. In the experimental campaign the floating roof has been taken into account. It is often present in this kind of tanks and its influence is generally neglected in the numerical models.
The tests have been carried out using the six d.o.f. 4 x 4 m shaking table installed in the laboratory of ENEA (Italian National Agency for New Technologies, Energy and the Environment) Research Centre “La Casaccia” at Rome. The tests have been performed on the physical model both in fixed and isolated base configurations; in particular two alternative base isolation systems have been used: high damping rubber bearings devices and PTFE-steel sliding isolation devices with c-shaped elasto-plastic dampers.
In the following, after a brief summary of the dynamic behaviour of tanks, with and without base isolation systems, the main results of the experimental tests are shown and discussed. Other results can be found in (Giannini and Paolacci, 2007)

2. DYNAMICS OF LIQUID STORAGE TANKS

2.1 Fixed base tanks

The dynamics of cylindrical tanks subjected to a base motion has been extensively studied by several authors. Starting from the earliest work of Housner (1963), the hydrodynamic pressure induced by the liquid on the tank wall due to the base motion has been determined, taking into account the deformability of the tank wall; see for example (Fisher 1979, Haroun & Housner 1981, Velestos & Tang 1987).
In brief, the liquid mass can be imagined subdivided in two parts: an impulsive component, which follows the base motion and the deformability of the tank wall, and a convective component, whose oscillations cause superficial wave of different frequency with a very low percentage of mass (≈4%) relative to the higher modes; moreover, while in the slender tanks the most part of the liquid moves rigidly with the tank, in the broad tanks most of mass oscillates in the convective modes.

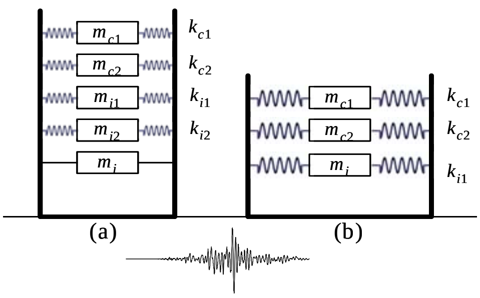

Figure 2 Equivalent spring-mass model:
(a) general, (b) broad tanks

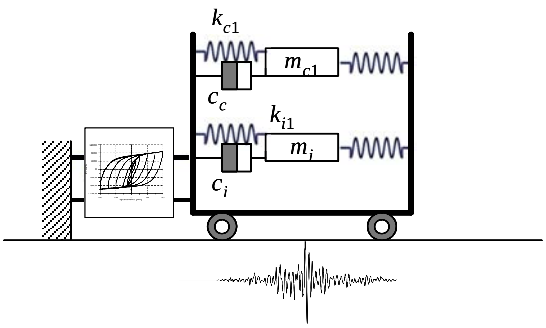

Figure 2. Dynamic model of a base isolated broad tank.

Under the hypothesis of rigid tank, the impulsive and convective part of hydrodynamic pressure can be easily evaluated. On the contrary, the part, which depends on the deformability of the tank wall, can be determined solving a fluid-structure interaction problem, whose solution depends on the geometrical and mechanical characteristics of the tank: radius R, liquid level H, thickness s, liquid density ρ and elastic modulus of steel E. The problem can be uncoupled in infinite vibration modes, but only few of them have a significant mass. Thus, the impulsive mass is distributed among the first vibration modes of the wall.
On the basis of the above observations it can be drawn that the study of the hydrodynamic pressure in tanks subjected to a seismic base motion can be easily performed using the simple model shown in Figure 1, in which the liquid mass is lumped and subdivided in three components: rigid, impulsive and convective masses named m_i , m_{ik} (mass of *k-th* mode of the wall vibrations), m_{ck} (mass of *k-th* convective mode). The impulsive and convective masses are connected to the tank wall by springs of stiffness k_{ik} and k_{ck}. The total pressure is given by

adding the effects of the mass m_i subjected to the base motion acceleration, of the masses m_{ik} subjected to the acceleration of the wall relative to the bottom of the thank, and of the masses m_{ck} subjected to the absolute acceleration.
In case of broad tanks the model of Figure 1(a) can be updated by the simplest model shown in Figure 1(b). In fact, the contribution of the higher order vibration modes is negligible and the entire impulsive mass is practically equal to the mass of the first vibration mode; moreover, because the distributions of the impulsive pressure, with and without wall deformability, are almost coincident, the effects of the impulsive action are simply taken into account by the response in terms of absolute acceleration of a simple oscillator of mass m_i and stiffness k_i. Neglecting the higher convective modes effect, the model becomes a simple two degrees of freedom model. The frequencies of the convective and impulsive modes are generally very different (tenths of a second against tens of seconds). This justifies the usual choice of neglecting the interaction between these two phenomena.

2.2 Base isolated tanks

The idea of seismic protection of tanks through base isolation technique is not new. Starting to '90 many works on this subject have been done (Wang et al. 2001, Shrimali & Jangid 2002). Unfortunately, few practical applications has been realized (Tajirian 1998) and a limited number of experimental activity has been performed (Bergamo et al. 2007).
On the basis of the observations of the previous section a dynamic model of a base isolated tank can be easily built. For example a simple model of base isolated broad thanks is shown in Figure 2.
The vibration period of the impulsive component of pressure generally falls in the maximum amplification field of the response spectrum, whereas the convective period T_c is usually very high and thus associated with a low amplification factor. This implies a high effectiveness of the base isolation system, which can reduce highly the base shear due to the impulsive pressure component. Neglecting the influence of the wall deformation, the period of the isolated structure is approximately given by:

$$T_{iso} \approx 2\pi \sqrt{\frac{m_i + M_s + M_b}{k_{iso}}} \tag{1}$$

in which m_i is the impulsive part of the liquid mass, M_s and M_b are respectively wall and base tank masses, and k_{iso} is the elastic stiffness of the isolators.
For broad tanks m_i is a relatively small part of the total mass and this allows a significant reduction of the devices dimensions. Moreover, in case of big tanks, for which $T_c >> T_{iso}$, the first period of the convective motion is not practically modified, with the consequence that the base isolation does not have any important mitigation effects on the sloshing pressures. This is not an important limitation, because the pressure generated by the convective motion, is very small because of its very long period in comparison with the impulsive component of pressure. The negative effect of the sloshing is related only to the superficial motion, because either the height of the wave can exceed the upper limit, causing overtopping phenomenon, or the floating roof motion could cause a breaking of the gaskets and the leakage of dangerous vapours of inflammable substances. Unfortunately, the base isolation does not modify this phenomenon.

3. SHAKING TABLE TESTS

3.1 Description of the physical model

The full scale structure is a big steel liquid storage tank typically installed in petrochemical plants. The dimensional characteristics of the tank are the following: radius R=27.5m, height H_s=15.60 m, liquid level H=13.7 m, liquid density ρ=900 kg/m^3, and wall thickness variable from 17 to 33 mm. The scale model has radius R=2 m, height H_s=1.45 m and wall thickness s=1 mm (Fig. 3). Thus, the scale ratio is about 13.7. Because the period of the sloshing mode is a function of the square root of the dimensions (Eurocode8, 2003), the time scale of the convective motion is 3.7. In order to obtain the same scale ratio for the impulsive frequencies it would be necessary to reduce the thickness of 140 times with respect to the real one. This is obviously impossible and only one time scale can be respected. In particular, the convective motion scale has been adopted during the test (Giannini and Paolacci, 2007).

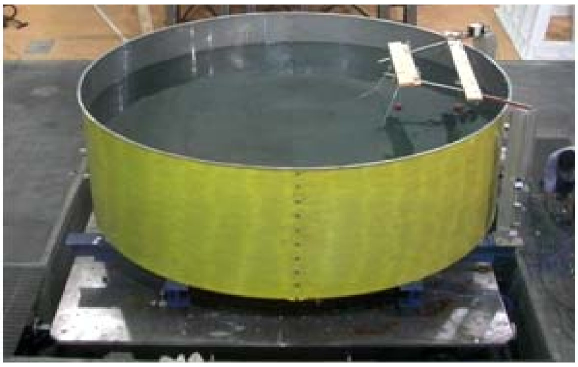
Figure 3. The tank without floating-roof.

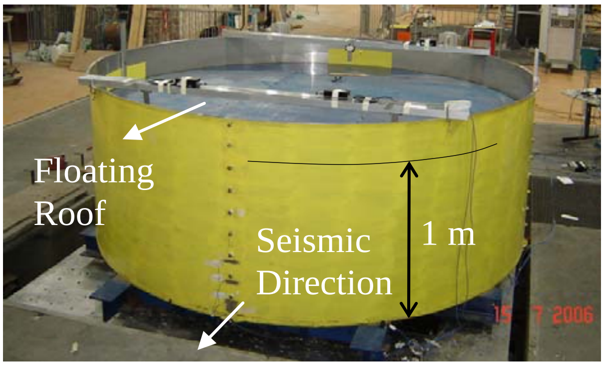

Figure 4. Floating roof installed on the mock-up

The floating roof of the full scale tank is realized through a truss structure, which sustains steel plates. In order to maintain the mass ratio, the floating roof of the mock-up has been realized with a wood structure (Figure 4). The gasket, which in the full scale tank is composed by a more complex mechanism, has been here realized with a rubber tube applied along the circumference of the roof.

3.2 Design of base isolation systems

For the seismic protection of the tank two isolation systems has been used: high damping rubber bearings (HDRB) and PTFE-steel isolation devices with metallic c-shaped dampers (MD). Both the base isolation systems have been designed by choosing a properly isolation period (T_{iso}) and then evaluating the stiffness k_{iso} using the equation (1). For the high damping rubber bearings the damping ratio ξ has been assumed equal to 10% whereas the yielding force of the metallic dampers has been designed using the method proposed by Ciampi et al. (2003).

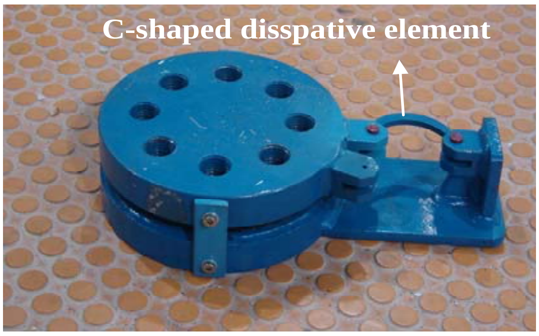

Figure 5. Sliding bearing with dissipative damper.


Figure 5. High Damping Rubber Bearing

Table 1. Isolation devices characteristics.

	HDRB	MD
Isolation period in real scale (sec)	2.8	1.6
Initial stiffness(kN/m)	900	1617
Yielding strength (kN)	3.00	7.880
hardening ratio	0.40	0.05
Fiction coefficient	--	2-3%

The prototypes of the isolator devices, properly realized for the experimental activity by the Company Alga Spa (Milan), are shown in Figure 5 and 6. The isolators have been characterized by cyclic imposed displacement tests carried out in the experimental laboratory of the University of Roma Tre. The main characteristics of the

devices are summarized in Table 1.
In order to check the effectiveness of the control systems, for each isolator typology four devices have been used, which have been placed at the cross of the bottom metallic beams.

3.3 Test set-up

A series of dynamic tests have been carried out on the tank using the shaking table installed at the Research Center of ENEA "La Casaccia" (Rome). The mock-up has been tested in four different configurations: 1) fixed base without floating roof (FB) 2) fixed base with floating roof (FBR) 3) isolated base with HDRB and floating roof (IBR) 4) isolated base with elasto-plastic devices and floating roof (IBM).
Six different base motion histories have been used in each configuration (four natural and two synthetic accelerograms, generated by Simqke (Vanmarcke & Gasparini 1976), according to the Italian code spectra), scaled to different intensity levels. For all accelerograms the time scale has been changed according to the above indications. The natural accelerograms have been selected from the PEER database, between time histories recorded for soil B or C and generated by seismic events with magnitude lower than 8 and epicenter distance lower than 50 km. Another more selective criterion, here adopted, consists of a selection of signals filtered using a high-pass filter with cut-off frequency greater than 0.1 Hz; in fact, as already seen, this is almost the frequency of the sloshing motion of the full scale tank. The records used during the tests are reported in Table 2. The tank has been also tested using white-noise and harmonic signals with variable frequency (sine-sweep) for the identification of its dynamic characteristics.

Table 2. Characteristics of the natural records used during the experimental tests

Accelerogram	M	Distance (km)	PGA (g)	Duration (s)
Irpinia, 11/23/80,Sturno, 270	6.5	32	0.313	40.00
Duzce 11/12/99, Duzce, 180	7.2	8.2	0.482	25.88
Kocaeli 08/17/99, Arcelik,090	7.4	17.0	0.149	28.00
Chi-Chi 09/20/99, TCU120, w	7.3	8.1	0.268	90

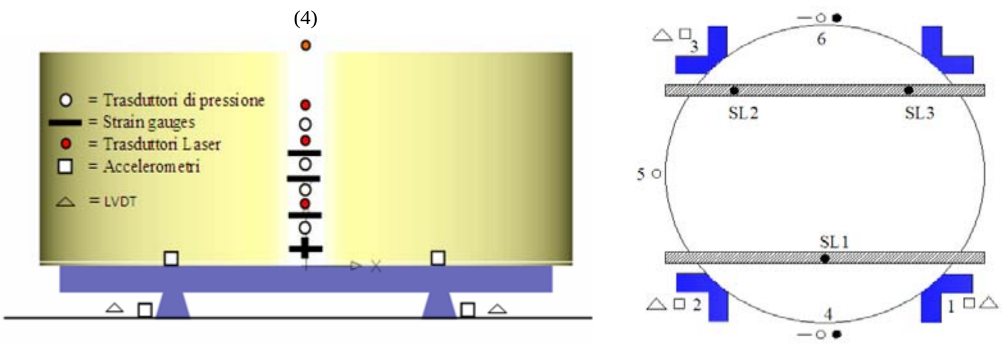

Figure 7 – Experimental Set- up

The response signals were measured using numerous sensors: pressure transducers, strain-gauges and laser transducers placed on the tank wall. Laser transducers have also been used for the sloshing motion of the liquid or floating roof, whereas the motion of the table has been monitored by several accelerometers. In the isolated base configurations the motion of the structure with respect to the base has been measured by wire LVDT sensors. The arrangement of the sensors has changed between the several series of tests. In Figure 7 a sketch of the main sensors used in the isolated base configuration is shown.

4. ANALYSIS OF RESULTS

4.1 Identification of dynamic characteristics

Before evaluating the seismic effects, the main dynamic characteristics of the tank (frequencies and damping) have been identified. The frequencies of the systems have been determined by means of the transfer functions between the input (base acceleration) and output signals (e.g. liquid pressure). The damping ratio has been

evaluated using the logarithmic decrement method applied to free vibrations time histories. For each vibration mode, the signal has been filtered using a pass-band filter around its frequency.
In Figures 8 the transfer function between the input acceleration and one of the sensors pressure (near the tank bottom) is shown, for FRB configuration. In this case the frequency is almost coincident with the theoretical value. Moreover, it is clearly evident a resonant frequency near 17 Hz. This value, which could be corresponds to the frequency of the impulsive motion due to the flexibility of the wall, is significantly different from the frequency value of the first mode predicted by a F.E. model, equal to 21 Hz (Giannini and Paolacci 2007). This difference could be explained with a non-linear behaviour of the tank, which has not been taken into account in the F.E. model. The reason of the non linearity has still not been clarified, but is probably due to geometrical nature, because the tensions are very distant from the yielding values of the steel stress.

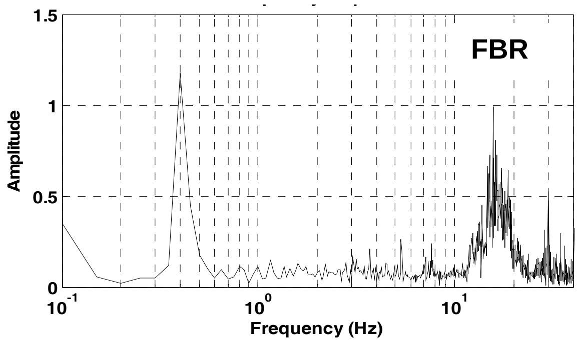

Figure 8. Transfer function of the wall pressure (Config: FBR, Input: White noise)

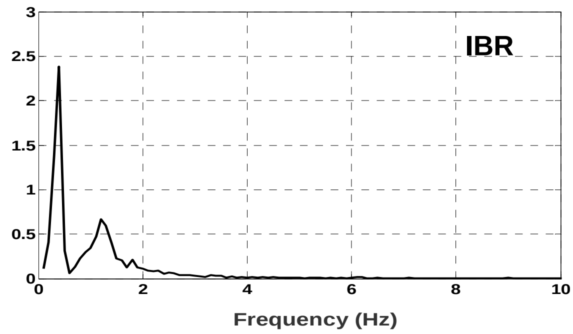

Figure 9. Transfer function of the base displacement of tank (Config: IBR, Input: ARC090-0.35g)

The damping of the sloshing motion has been measured on the basis of the amplitude decrement of free vibrations. In case of free liquid surface the damping is very low and is not in practice measurable; using the floating roof a 1% of damping has been identified. This value, greater than 0.5%, usually adopted in numerical model, is probably due to the interaction between the liquid surface and the floating roof and the friction between rubber gasket and tank wall.
In Figure 9 is illustrated the module of the base displacement transfer function for IBM case and Koaceli accelerogram (PGA=0.35g). The graph shows again a sloshing frequency placed at 0.40 Hz and more clearly the isolation frequency equal to 1.22 Hz, in good agreement with the design indications. It is clear that the base isolation does not have any influence on the frequency motion of the floating roof. On the contrary, a large influence of the isolation systems on the vibration damping of the floating roof motion has been observed. The results have shown a considerable increasing of the sloshing damping, variable in the range 2.5-3.0% for both IBR and IBM isolation cases. This increment was predicted by numerical models, even if a lower value was expected.

4.2 Response of the base isolated tank

The evaluation of seismic effects on the tank wall has been done in terms of maximum base shear induced by the dynamic pressure and relative impulsive and convective components. These forces have been evaluated interpolating the experimental values of pressures with the relative theoretical functions and then integrating along the wall surface. The separation of the sloshing and impulsive components was obtained using high-pass and low-pass filters, with a cut-off frequency of 1 Hz. Instead, the global value has been calculated using the unfiltered signal.
The response of the table, measured in the different experimental tests was not the same, even if the same accelerograms were used; this because of some problems with the control system. To overcome this problem the comparison have been realized in terms of spectral accelerations S_a, (5% of damping), calculated in the frequency range 10 ÷ 20 Hz for the impulsive component, and 0.35 ÷ 0.45 Hz for the sloshing component. Impulsive and sloshing forces have been represented as functions of the relative spectra acceleration, whereas the total force has been plotted versus the spectral ordinate used for the impulsive component (Figure 12).
In the same figures the interpolation curves of the experimental data are also shown for the fixed (FBR: black

line) and isolated base cases (IBR: red line, IBM: blu line).

From Figure 10, in which the maximum total base shear is represented versus S_a for all accelerograms, clearly come out the effectiveness of both isolation systems, where a considerable reduction of the total force acting on the tank wall is shown. However, whereas the effectiveness of EM isolators does not practically vary with S_a, the effectiveness of EP devices is reduced for low values of spectral acceleration, and is practically negligible for S_a<0.3g. Moreover for FBR case the interpolation function is linear, whereas IBR and IBM cases clearly show a nonlinear behaviour, especially for high values of spectral acceleration.

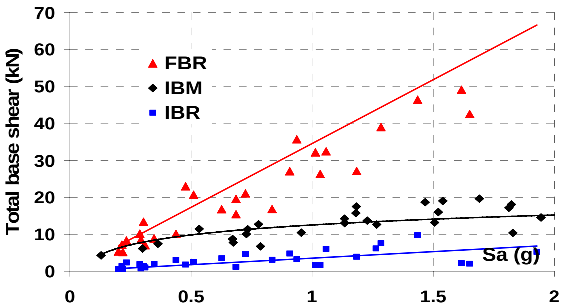

Figure 10. Total base shear for FB, IBR and IBM configurations v/s spectral acceleration

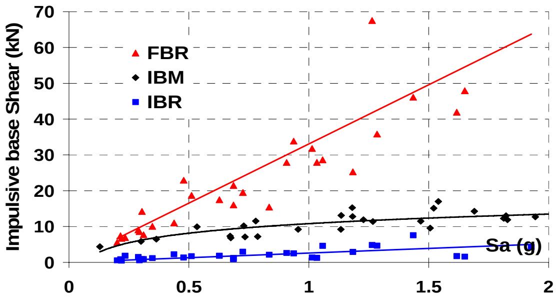

Figure 11. Impulsive base shear for FB, IBR and IBM configurations v/s spectral acceleration

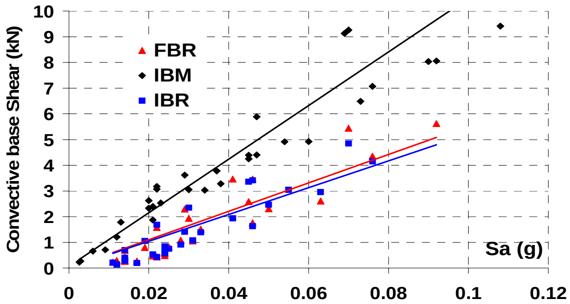

Figure 12. Convective base shear for FB, IBR and IBM configurations v/s spectral acceleration

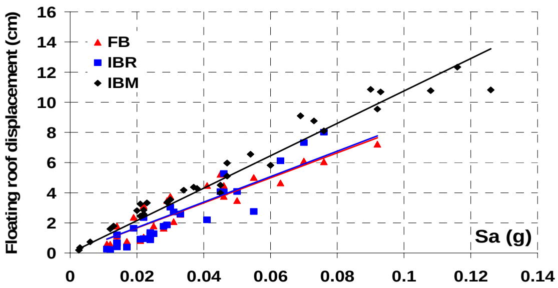

Figure 13. Maximum displacement of the floating roof for FB, IBR and IBM configurations v/s spectral acceleration

This fact is due to the friction effects, often neglected for this kind of devices, but particularly relevant for the tanks in which the gravity mass, represented by the entire liquid volume, is greater than the dynamic one, which is only the impulsive mass (in the present case only the 30% of the total one). Therefore, to win the friction, appreciable levels of acceleration are needed. This problem is not present for elastomeric devices.

This behaviour could represent an interesting advantage recognizable to the elasto-plastic devices. In fact, for low levels of seismic intensity, it could be convenient to use an isolation device with a reduced slip, which instead is required for more strong events in order to have a full employment of the dissipation capability of the devices.

For the impulsive component (Figure 11), the reduction is considerably important, as already observed for the total base shear; on the contrary, the sloshing component (Figure 12) remain practically unchanged for elastomeric isolators, whereas an increasing has been observed for elasto-plastic devices. This increasing has not any influence on the values of the stresses in the tank wall. The negative effect is related to the floating roof oscillations, which could generate in some cases a breaking of the gaskets and the leakage of inflammable materials.

Unfortunately, the base isolation technique does not reduce this movement, even though the increasing of the damping reduces its duration and probably the risk of a gasket breaking as well. However, even if the increasing of the convective pressures, measured for the elasto-plastic base isolation case, could appear worrying for the possibility of a consistent increasing of the floating movement, the experimental results have shown a rather moderate increasing of vertical displacements, not particularly relevant.

5. CONCLUSIONS

This paper deals with the main results of an experimental campaign carried out on a mock-up of a steel liquid storage tank, equipped with the floating roof, excited at base by the six d.o.f. shaking table installed at the Research Centre of ENEA "La Casaccia" (Rome). The mock-up is a reduced scale model of a big steel tank used in industrial plants for the storage of petroleum and its products.

The tests have been performed using different experimental configurations: fixed base with and without floating roof, isolated base with elastomeric or sliding bearing with elasto-plastic dampers. During the tests, the tank has been subjected both to accelerograms histories, which reproduce records of natural and artificial seismic events and appropriate signals for the dynamic identification of the system.

The results show the effectiveness of both the isolator typology in reducing the total pressure generated by the earthquake on the tank wall. On the contrary, a low increasing of the oscillation amplitude of the liquid surface, and consequently of the floating roof, has been observed. It is partially compensated by a sensible increasing of damping, which drastically reduces the number of the high amplitude oscillations of the floating roof, after the end of the seismic event.

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