SLOSHING RESPONSE OF A LNG STORAGE TANK SUBJECTED TO SEISMIC LOADING

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ABSTRACT

The number of Liquefied Natural Gas tanks is continually increasing. These tanks are very large and their capacity is about 150000$[m^3]$. According to safety standards these kinds of tanks consist of an inner steel shell, containing the LNG, and an outer reinforced concrete shell. Nevertheless, they represent a great risk if they fail during an earthquake. Several types of tank failures have been observed. Tanks may be damaged for different reasons. Large shell hoop tensile stresses, resulting from a combination of hydrostatic pressure and hydrodynamic pressure, due to horizontal and vertical ground motions, could fail the tank. A more common type of failure is known as "elephant's foot buckling"[3]. This is caused by the large overturning base moments, resulting from the impulsive and convective liquid loading on the tank wall during an earthquake. The high vertical compressive stresses, which develop in the tank wall, may cause the buckling of the structure.

The aim of this work is to simulate the seismic behaviour of an LNG tank during an earthquake. The analyses have been performed with Ls-Dyna code using a Lagrangian

approach [1],[5]. The applied seismic loads have been registered during a Richter magnitude 7.1 earthquake (Magnitude Moment 6.9). Simulations have shown that fluid motion and fluid-structure interaction are responsible of a failure type known as "elephant's foot". 3-D results of the large model (76 [m] in diameter) have been visualized with the support of a multi-wall screen at CETMA Virtual Reality Centre (CVRC). This BARCO visualization system is based on ORAD pc cluster with Digital Video Graphics DVG-10, with tracking and stereo capabilities. The FEM model consists of a flat anchored bottom and a cylindrical metallic wall in contact with the LNG:

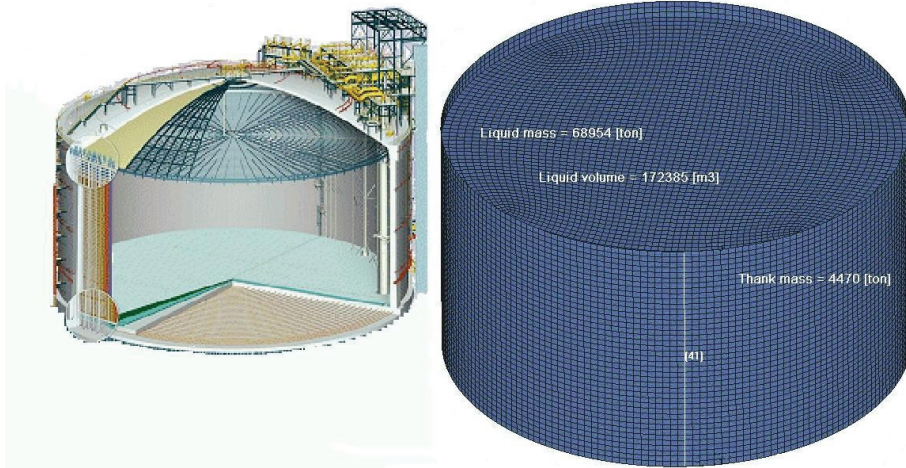|	
Diameter	76[m]
Wall high	41[m]
Liquid level	38[m]
Liquid volume	172000[m^3]
Tank mass	4470[ton]
Liquid mass	68954[ton]

Figure 1 3d full scale model and dimensions: 41[m] in high, diameter76 [m]

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KEYWORDS:

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Tank sloshing, earthquake, LS-DYNA, Fuel sloshing, fluid-structure interaction, elephant's foot buckling, finite element method, computational methods, Lagrangian model

INTRODUCTION

Natural gas is a fossil fuel composed primarily of methane (typically, at least 90%) and small quantities of nitrogen, oxygen, carbon dioxide, sulphur compounds. The liquefaction process that produces LNG removes any oxygen, carbon dioxide, sulphur compounds, and water. Methane liquefies under critical pressure of 45,96[bar] with a critical temperature of -82,62°C; at atmospheric pressure natural gas liquefies when temperature is of approximately -161,52°C. At liquid state it is ready for storage and shipping with LNG tanker. LNG receiving terminals and re-gasification facilities store LNG before its re-gasification for pipeline transportation.
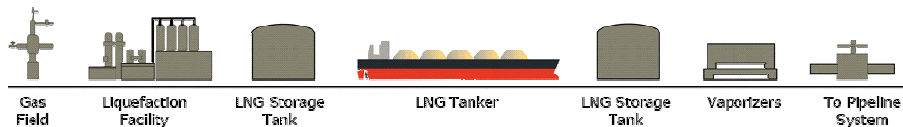
Figure 2 Lng chain: extraction, transportation and re-gasification

Natural gas is liquefied and transported by ship from remote and localized reserves of URSS, east Europe (about 38%) and middle eastern countries (about 30%). Usual temperature of Lng tanks are about –161°C with a pressure that slightly exceed atmospheric threshold value. LNG storage tanks built recently around the world are designed as full containment tanks. A full-containment tank is designed and constructed so that both the inner tank and the outer tank are capable of independently containing the stored liquefied gas. The inner tank, in contact with the liquid, is made of materials suitable for cryogenic service. It has a flat metallic bottom and a cylindrical metal wall both built of materials suitable for cryogenic temperatures (usually nine percent nickel steel). The outer tank has reinforced concrete walls that supports the outer roof and is intended to contain the LNG.

The aim of this work is to provide a support during industrial risk evaluation due to seismic events with predictive calculation and cae instruments.

FINITE ELEMENT MODEL

This tank has very large dimensions in fact 76[m] in diameter and 41[m] in height. The tank is filled with liquefied natural gas to a height of 38[m]. Simulation and analysis are referred to inner tank only, in figure 1 finite element model shows cryogenic steel primary containment. Four nodes shell elements (Belytschko-Tsay) have been used for steel discretization and solid elements for lng liquid part.

The material model used for the container is mat 24 with following data corresponding to cryogenic steel: density: 7800[Kg/m^3], Young modulus E = 210000 [MPa], σ_{yield} = 517[MPa] and $\sigma_{strength}$ = 1050[MPa]. Only the bottom surface of the tank have been modelled as rigid. The material model null (mat 9) was used for lng ($\rho = 400$[kg/m^3]), this material allows equations of state to be considered without computing deviatoric stress. Linear-polynomial and Gruneisen equations of states where evaluated. Both definitions yielded very similar results, the Gruneisen eos was chosen in this simulation.

For an incompressible liquid near atmospheric pressure, all parameters are set to zero, $C_0=C_2=C_3=C_4=C_5=C_6=0$ except for $C_{sound\ speed\ in\ lng}=2345$[m/s].

Different formulations for fluid simulation in LS-DYNA are possible in fluid sloshing problem: Lagrange, Euler, ALE and SPH [1],[5]. Lagrangian model provide rough results of the fluid motion because fluid retain the shape of the container. When deformations and deflections on the water surface can be neglected as regards impulse of the fluid towards tank wall, Lagrangian approach seems much more appropriate.

The model was also loaded with the constant gravitational acceleration (g = 9,81 [m/sec^2]). Dynamic relaxation has been used in the beginning of the solution to obtain the initial stress and displacement field due to gravity. Automatic nodes to surface contact algorithm has been used for liquid tank interaction. Model constraints are applied at base locking x,y,z rotations. Seismic loading have been assigned at base with acceleration vs time diagrams in x, y, z directions as shown in figure 3.

SIMULATION RESULTS

The tank without an isolation system is exposed to seismic loading at base with x, y ,z accelerations time curves recorded during 40 seconds of earthquake. Figure 3 shows the tank with accelerations time curves [m/sec^2] recorded during earthquake and peak values concentrated in the first 15 seconds.
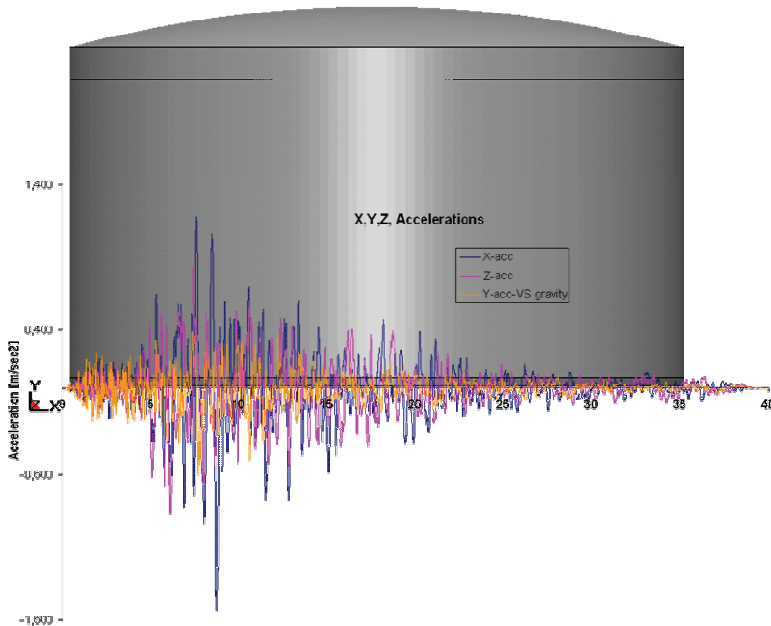
Figure 3 X, Y, Z, accelerations time curves [m/sec^2] recorded during earthquake

Applied seismic loading is focussed during peak accelerations, simulation time cover a 20 seconds range. The most important result for evidence is a plastic strain at tank base, a local buckling defined Elephant-foot [4],[6]. This kind of deformation appears about 8 seconds after the begin of the earthquake. All around the tank perimeter a plastic deformation occurs as depicted in figure 4. In this figure a real earthquake damage to storage tank is reported for comparison. Earthquake forces transmitted directly to the structure without isolation devices caused this serious damage. Preliminary simulation results without base anchorages have confirmed the importance of anchorage during earthquake highlighting tank upsetting. Sloshing liquid caused also elastic deformation of the top of the tank wall.
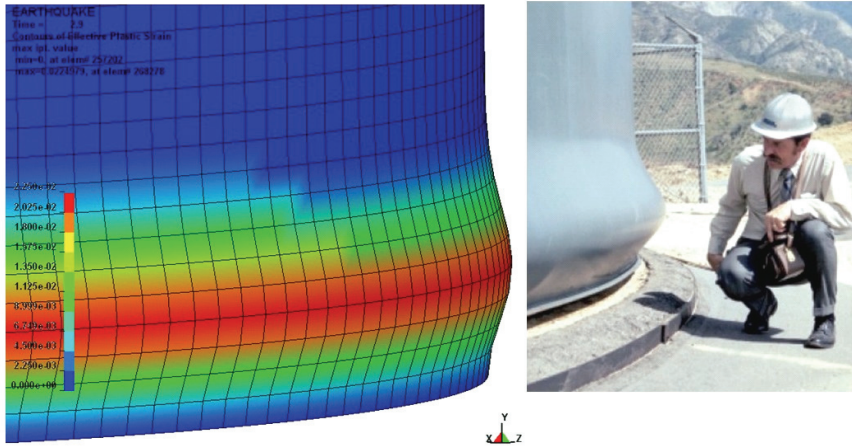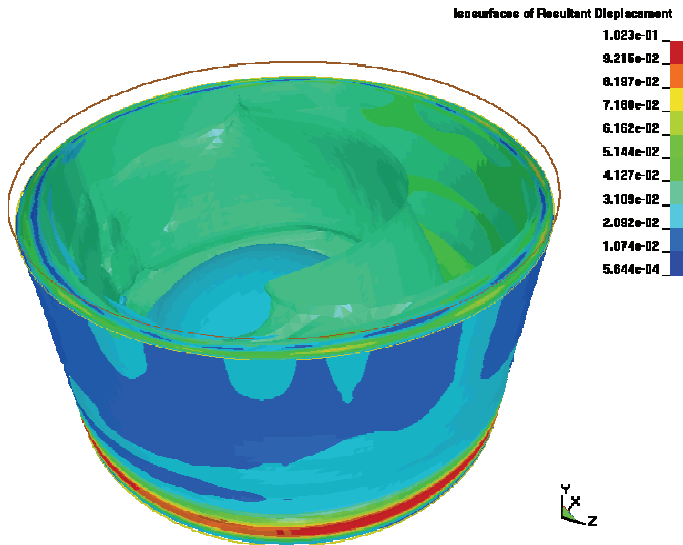
Figura 4 Elephant foot buckling localized at tank base

Figure 5 Isosurface of resultant displacements in [m] at time t = 5 [sec]

Liquid displacements at time t = 5[sec] and isosurface of resultant [m] displacements are shown in figure 5. Results visualization at virtual reality centre has come very useful and fundamental to evaluate and perceive earthquake small displacements related with large capacity cylindrical tanks. Cetma virtual reality centre have three wide screen, see

figure 6, with 2 "Infitec Technology" projectors, capable of different configurations from "cad wall" to "immersive cave".
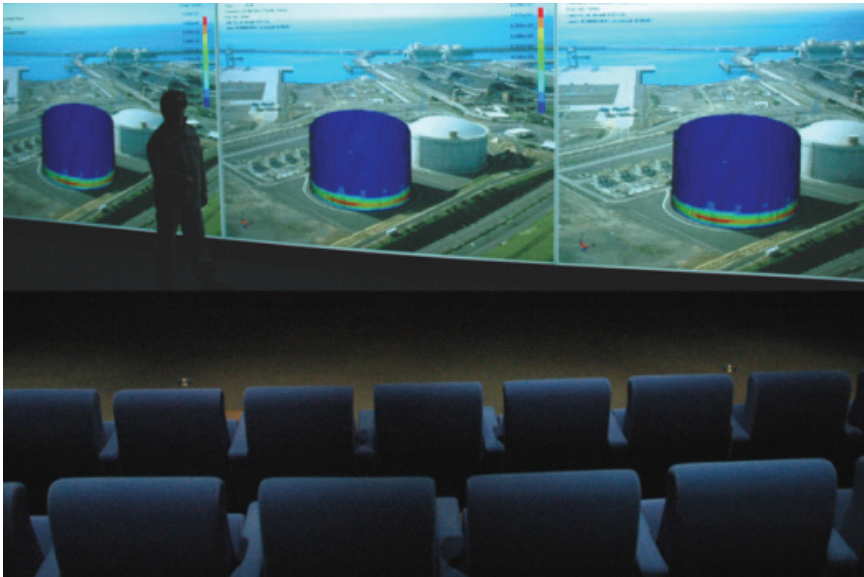

Figure 6 CETMA reality centre

CONCLUSIONS

The response of a liquefied natural gas tank (172.000 [m^3]) during Richter magnitude 7.1 earthquake have been evaluated. A 20[sec] interval have been simulated during earthquake major intensity; calculation time required were 12 hours with 2 Cpu Opteron 250, XP 64. Simulations have shown that fluid motion and fluid-structure interaction are responsible of a failure type known as "elephant's foot" [4],[6]. 3-D results of the large model (76[m] in diameter) have been visualized with the support of a multi-wall screen at CETMA Virtual Reality Centre (CVRC). This visualization system is based on a ORAD pc cluster with Digital Video Graphics DVG-10, with tracking and stereo capabilities.

Lagrangian model provide rough results of the fluid motion because fluid retain the shape of the container [5]. When the impulse of the fluid towards the tank wall is of interest and deformations and deflections on the water surface can be neglected, what is the case observed in simulations, Lagrangian approach seems much more appropriate.

Further levels of complexity can be introduced to the model as well foundation soil characteristic, isolation system and damping device. Besides circumferential welds, all vertical welding of shell plates and shell thickness variation in high may be taken into account to evaluate these effects on the structure.

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