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Assessment of the seismic effect of insulation on extra-large cryogenic liquid natural gas storage tanks

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A R T I C L E I N F O

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A B S T R A C T

Insulation is typically used in extra-large double-walled cryogenic storage tanks that are used to store liquid natural gas (LNG). These vessels have been designed with the assumption that the insulation offers negligible structural resistance that might cause structural damage. Observation of the deformation of the insulation in such tanks leads to concern that the insulation may become sufficiently compacted to cause significant load transfer between the inner and outer tank. The inner tank, though protected from most external events by the outer tank, is only designed to contain the liquid gas. It is therefore much more sensitive to seismic effects. In this investigation, simplified and 3D finite element models are used to simulate the interaction effects of the fluid, inner tank, insulation and outer tank. This paper presents an initial analysis of the potential effects of LNG tank insulation under earthquake conditions and assesses the potential for structural damage by comparison of models that do or do not consider the insulation layer. The data reported and statistically sorted include the overturning moment, the base shear, the tank wall stress, and the wave height in the tank. The results show that the insulation layer has certain influence on seismic design of LNG tanks.

1. Introduction

Extra-large double-walled cryogenic cylindrical tanks containing insulation are used to store liquid natural gas (LNG). Such LNG tanks, which are considered to be lifeline projects, pose specific requirements that arise mainly from the cryogenic temperatures at which they operate and from the potentially serious consequences of any accidental release of liquid natural gas. The inner tank is much more sensitive to seismic effects, for which the outer tank provides little protection. And the design requirements of some indicators of the tank, such as base shear, are fairly stringent.

Originally the design of storage liquid tank was based on the Housner's theory in which the tank wall was assumed as rigid wall. But this theory is not suitable for storage liquid tank in many cases. For example, many liquid storage tanks designed using this method were destroyed in the Alaska earthquake, which prompted the further study of storage liquid tank (Korkmaz, Sari, & Carhoglu, 2011; Paolacci, Giannini, & De Angelis, 2013). The elastic tank wall was considered for seismic response of storage liquid tank in the later studies (Haroun & Housner, 1983; Veletsos & Kumar, 1984). These methods are widely used in the design of LNG tank. Christovasilis and Whittaker (2008) presented a comparison studies for 3D LNG tank model and simplified model. The results showed that some key indicators such as base shear were consistent between 3D model and simplified model. However, in all of these studies, the dynamic interaction between the inner tank and outer tanks was neglected.

Generally, in designing LNG tanks, it has been assumed that the insulation layer offers negligible structural resistance. However, observations of insulation layer compaction have resulted in concern that the insulation layer may become sufficiently compacted to cause significant load transfer between the inner and outer tanks after many loading cycles, possibly causing structural damage. In the explosion analysis of LNG tank, the seismic effect of annular insulation had been considered, the annular insulation transferred loads between the tank walls enhancing their individual strengths (Thompson, 1986). But the seismic effect of insulation on LNG needs to be assessed.

The 3D finite element models are built for the anchored LNG tanks with and without an insulation layer. The comparison between considering and without considering insulation layer is performed. The data reported and statistically sorted include the base shear, the Von Mises stress, the wave height, and the

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overturning moment. The seismic effect of insulation layer is judged by these data.

2. Layout of the LNG tank

A LNG tank consists of an inner steel tank and an outer concrete tank which is used to protect the inner tank, with insulation placed between the two tank walls (Fig. 1). The inner tank is designed only to contain the LNG and is protected by the outer tank against most external events.

Although documentation is not enough, it can be still found that thermal cycles and vibrations may made perlite materials compacted (Issa, Peters, & Jones, 1995; Plannerer & Romero, 1995). As the perlite becomes compacted, there is a possibility of significant load transfer from the inner to the outer vessel that may structurally affect the inner vessel.

In the insulation layer, a resilient blanket is attached to the outer wall of the inner tank, which is compressed, due to lateral deformation of loose perlite (Fig. 2). The resilient blanket is designed to compensate for the shrinking of perlite particles and of the inner tank due to variations in temperature. Similar shrinking could occur during an earthquake. In this initial study, the material nonlinearity of perlite is not considered, and the insulation layer is assumed to be sufficiently compacted to represent a continuous medium of a different elastic modulus.

3. Dynamic properties

3.1. Fluid motion equations

The continuity equation of tank liquid can be written as:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0 \tag{1}$$

where v_x, v_y and v_z are the velocities of the fluid in the x, y and z directions.

The velocities can be expressed by the function of the velocity potential $\varphi(x,y,z)$:

$$v_x=\frac{\partial\varphi}{\partial x},\quad v_y=\frac{\partial\varphi}{\partial y}\quad v_z=\frac{\partial\varphi}{\partial z} \tag{2}$$

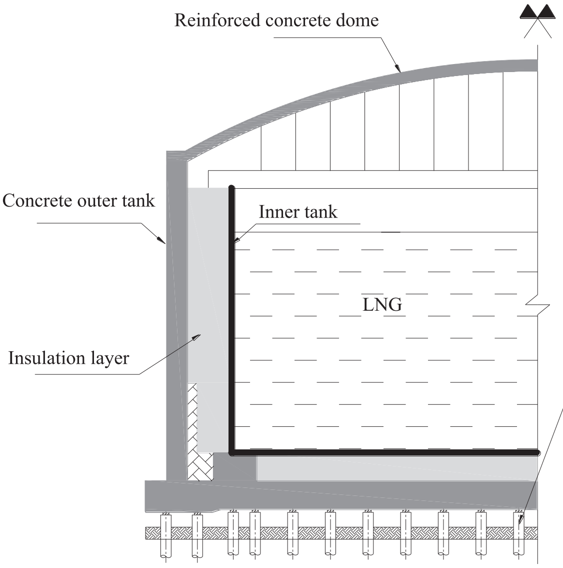

Fig. 1. Diagrammatic cross-section of a LNG tank.

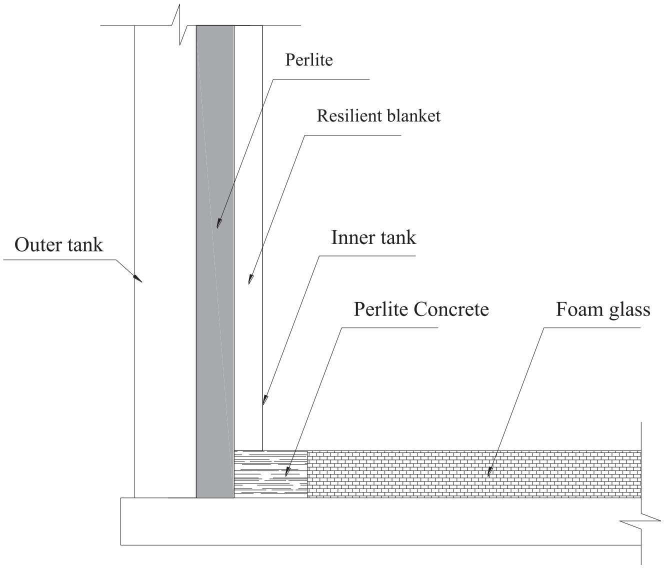

Fig. 2. Insulation layer.

The Laplace equation can be got by substituting Eq. (2) into Eq. (1):

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=0 \tag{3}$$

For the cylindrical storage tank, the Eq. (1) must satisfy two boundary conditions. First is that the velocity of fluid v_n along the normal of the wall is same as the velocity of tank wall (Fig. 3):

$$v_n=\frac{\partial\varphi}{\partial n} \tag{4}$$

The second is that the pressure of fluid is equal to atmospheric pressure:

$$p=-\rho gz-\rho\frac{\partial\varphi}{\partial t} \tag{5}$$

where ρ is the fluid density. When the wave height of free liquid surface is expressed as $f(x,y,t)$, the pressure of the fluid surface p_0 becomes:

$$p_0=-\rho gf-\rho\left.\frac{\partial\varphi}{\partial t}\right|_{z=f} \tag{6}$$

Deriving both sides of Eq. (6), it can be written as:

$$\left(\frac{\partial\varphi}{\partial z}+\frac{1}{g}\frac{\partial^2\varphi}{\partial t^2}\right)_{z=f}=0 \tag{7}$$

Because f is small, the equation $z=f$ may be replaced by$z=0$. Thus, the equations may be written in the form:

$$\left.\begin{aligned}&\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=0\\&\left(\frac{\partial\varphi}{\partial z}+\frac{1}{g}\frac{\partial^2\varphi}{\partial t^2}\right)_{z=0}=0\end{aligned}\right\} \tag{8}$$

The solutions of Eqs. (1), (2), (4) and (5) may be divided into three components. The first component is impulsive component, and the velocity v_n is the velocity of rigid body; the second