Seismic behavior of LNG storage tank considering soil-foundation-structure interaction with different foundation types.

Comportement sismique du réservoir de stockage de GNL en tenant compte de l'interaction sol-fondation-structure avec différents types de fondations

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ABSTRACT: Seismic loads acting on the foundations and the structure have been estimated from the surface free field motion, but those can be changed by the soil-foundation-structure interaction (SFSI) effects. SFSI effect is difficult to evaluate exactly because of the variety of the phenomena depends on such as the soil profiles and the foundation types. In this research, the amount of the dynamic centrifuge tests was performed to observe the seismic behaviors of the liquefied natural gas (LNG) storage tank with different foundation conditions. Test specimens were composed of dry silica soil layer, foundation and LNG storage tank model. Two typical foundation types were used: shallow foundation and pile foundation. In cases of the pile foundation tests the embedment depth of slab was changed. For the input motion, Ofunato and Hachinohe earthquake records with increasing intensity were used to observe the frequency and the intensity effects of the seismic behavior of LNG tank system. From the dynamic centrifuge test results, the accelerations at soil surface, slab and structure were compared.

RÉSUMÉ : Les charges sismiques agissant sur les fondations et la structure ont été estimées à partir du mouvement du champ libre de surface, mais celles-ci peuvent être modifiées par les effets de l'interaction sol-fondation-structure (ISFS). Les effets de l'SFSI sont difficiles à évaluer précisément en raison de la variété des phénomènes dont elle dépend tels que les profils de sol et les types de fondations. Dans cette étude, la quantité de tests à la centrifugeuse dynamique a été effectuée pour observer les comportements sismiques du réservoir de stockage de gaz naturel liquéfié (GNL) avec différentes conditions de fondations. Les échantillons d'essais étaient composés d'une couche de silice sèche, d'une fondation et d'un modèle de réservoir de stockage de GNL. Deux fondations typiques ont été utiliseés : les fondations superficielles et les fondations profondes sur pieux. La profondeur d'encastrement de la dalle a été modifiée pour les essais de fondation profondes. Pour le mouvement d'entrée, les enregistrements sismiques d'Ofunato et Hachinohe avec une intensité croissante ont été utilisés afin d'observer la fréquence et les effets d'intensité du comportement sismique du système de réservoir GNL. A partir des résultats du test de la centrifugeuse dynamique, les accélérations au niveau du substrat rocheux, de la surface du sol, de la dalle et de la structure ont été comparés.

KEYWORDS: LNG tank, Soil-Foundation-Structure Interaction (SFSI), Centrifuge Tests, Seismic Load

1 INTRODUCTION.

Many liquefied natural gas (LNG) plant projects are underway due to the increase in demand and interest in LNG worldwide, and LNG storage tanks and facilities are emerging as major social infrastructures. These LNG storage tanks can cause serious damage to society in general when destruction occurs at the time of earthquake. Therefore, it is necessary to accurately evaluate the behavior of LNG tank structure during earthquake (Zhang et al., 2011).

To date, in conventional seismic design, the seismic load acting on the LNG storage tank is estimated based on the free-field surface motion of soil layer. Such a simplified seismic load estimation method for designing an onshore LNG storage tank has limitations on accurate seismic behavior evaluation and economical design. This is because the real seismic loads on the foundation and the structure change differently due to the influence of the Soil-Foundation-Structure Interaction (SFSI). SFSI effect is very difficult to evaluate exactly because of the variety of the phenomena depends on the soil profiles, the foundation types. Although numerous studies have been done on SFSI influences through analytical and numerical analysis, it is required to directly observe complex earthquake behavior of LNG storage tank system through reliable experiments.

The objective of this study is to assess the seismic behaviour of LNG storage tank considering SFSI effects using dynamic centrifuge tests. Two typical foundation types were used such as shallow foundation and pile foundation, and particularly for the pile foundation tests, the embedment depth of foundation slab was changed to investigate the effects of side soil layer.

2 CENTRIFUGE MODELLING

Geotechnical centrifuge modeling uses centrifugal acceleration to increase the self-weight stresses in a small model to simulate the self-weight stresses in prototype. Centrifuge modeling with shaking table equipment can provide an excellent opportunity to observe the SFSI in a scale model. (Ha et al., 2014). In this study, the beam-type centrifuge facility in KAIST was used to perform all the tests reported herein. This facility has a platform radius of 5 m and a maximum capacity of 240 g-tons (Kim et al., 2013a). The earthquake motions can be generated by a self-balanced arthquake simulator mounted on the centrifuge (Kim et al., 2013b). All centrifuge tests were conducted at 50g of centrifugal acceleration. The test specimens were composed of of dry silica soil layer, foundation slab and LNG storage tank model.

2 .1 *Soil layer modelling*

Dry silica sand artificially produced by a hammer crusher with basic properties shown in Table 1, was used in the experiments. The soil model was made using the sand pluviation for about 80% relative density. The crosshole bender elements were installed in soil layer during the centrifuge tests to obtain the shear wave velocity profiles of soil layer (Kim and Kim, 2010). The average shear wave velocities were about 200 m/s in 50g of centrifugal acceleration and corresponding site period of the prototype soil was estimated at 0.5 s.

Table 1. Basic soil properties of the tested silica sand

Properties	**Silica sand**
Unified soil classification (USCS)	SP
Median particle size (D50), mm	0.22
Curvature coefficient (Cc)	1.11
Uniformity coefficient (Cu)	1.96
Maximum void ratio (emax)	1.130
Minimum void roatio (emin)	0.611

2 .2 *LNG storage tank and foundation modelling*

The prototype of the LNG storage tank is a 1/5 model of a general LNG storage tank with a diameter of about 16 m and a height of about 7 m, and the bottom slab has a diameter of 19.25 m and a thickness of 1.5 m. The tank structure consists of external and internal tank structure, but in this research we modeled only the inner structure to focus on the seismic behavior of inner tank. Based on scaling laws such as the dimension, the model structure was reduced from the prototype structure. In addition, the fluid in the LNG tank can also affect the overall earthquake behavior. To simulate the fluid mass considering dynamic fluid-structure interaction, the lumped masses were installed along the tank wall as depicted in Figure 1. Additional fluid masses per unit length adopted in this study was determined by Kim et al. (2015).

The impact hammer test is executed to investigate the dynamic characteristics of the LNG model structure. The natural frequency of the model structure is about 12 Hz in circular shape and the damping ratio of it is negligible.

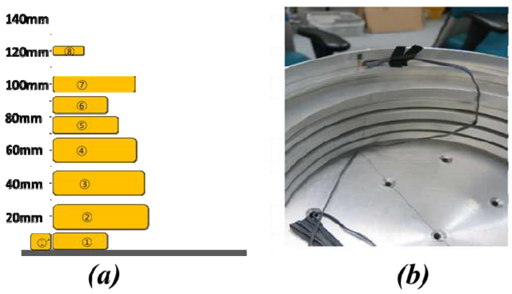

Figure 1. Lumped mass to simulate the fluid inside LNG tank;
(a) schematic of lumped mass (b) picture of installed lumped masses.

The prototype of pile foundation has an external diameter of 1.1 m and a length of 24.5 m. Pile foundations under the LNG storage tank structure was made by the aluminum with applying appropriate scaling law of flexural stiffness, because of the difficulty of fabricating small model piles from concrete. The pile foundation was designed to be fixed with the lower slab of the LNG storage tank and seven sets of strain gauges were installed for each depth to measure the bending moment of the pile foundation under the earthquake.

2 .3 *Modelling procedure and schematic diagrams*

The representative modelling procedure for the test specimen is described in Figure 2. The sand layer was made by pluviation of dry sand, and at specific depth the measuring sensors were installed like the benders for the measurement of the shear wave velocity and the accelerometer for the measurement of the earthquake response. In case of pile foundation tests, twenty-one piles were fixed at the bottom of the model box before the soil pluviation to simulate the end-bearing condition of pile foundation. When the soil layer reached the target height, the foundation slab was installed, and the LNG tank structure was placed on it.

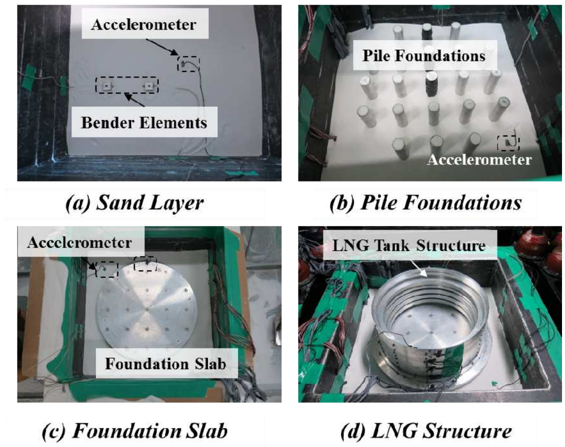

Figure 2. Modelling procedure of the test specimens

In order to observe the different seismic behaviors due to the foundation types, four types of foundation were utilized as shown in Figure 3. Foundation types in this research are divided into shallow foundation and pile foundation. For the pile foundation, three tests were carried out depending on the amount of embedding of the foundation slab in the adjacent ground such as embedded, surface and floating.

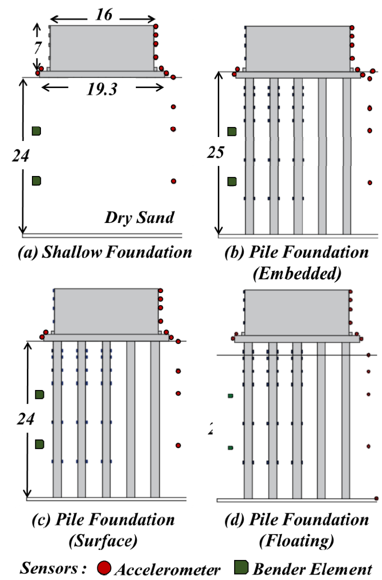

Figure 3. Schematic diagrams of the experiment layout

2.4 *Input earthquake motion*

One of the important factors to affect the SFSI behavior during the earthquake is the characteristic of the input excitation such as the frequency contents and intensity. For observing the effects of the input excitation, two real earthquake motions were utilized for the base input motion as depicted in Figure 3. Hachinohe and Ofunato earthquakes, which represent the relatively long period and short period motion respectively, were loaded at the bottom of the model box by increasing the peak intensity in stages.

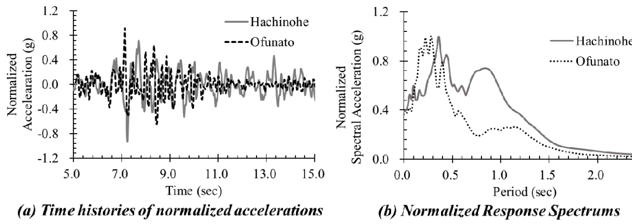

Figure 3. Input earthquake motions; (a) time histories of normalized accelerations (b) normalized response spectrum

3 CENTRIFUGE TEST RESULTS

3 .1 *Soil surface and foundation slab behaviors*

Figure 4 compares the peak accelerations of the soil surface and the slab for the four foundation cases, shallow foundation, pile foundations (embedded, surface, floating), under excitation of (a) Hachinohe and (b) Ofunato earthquake motions.

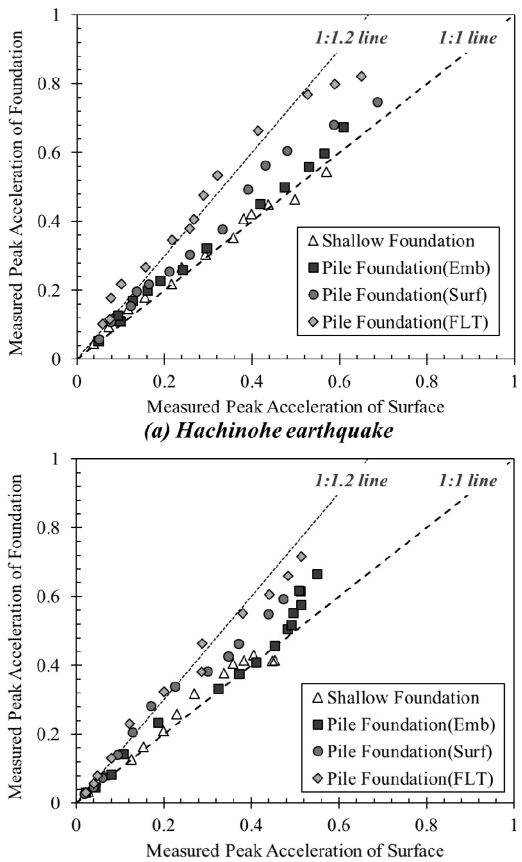

Figure 4. Peak accelerations between the soil surface and the foundation slab. (a) Hachinohe (b) Ofunato

Horizontal behavior of the foundation slab can be different from the soil surface behavior due to the kinematic and inertia effects. In the case of pile foundation with embedded slab and shallow foundations, the maximum accelerations of the slab were almost similar as the ground surface maximum acceleration. Contrary to this, when the slab was placed on the ground surface or floated from the ground surface, amplification phenomena occurred. The amount of the amplification for the floating pile foundation was the largest.

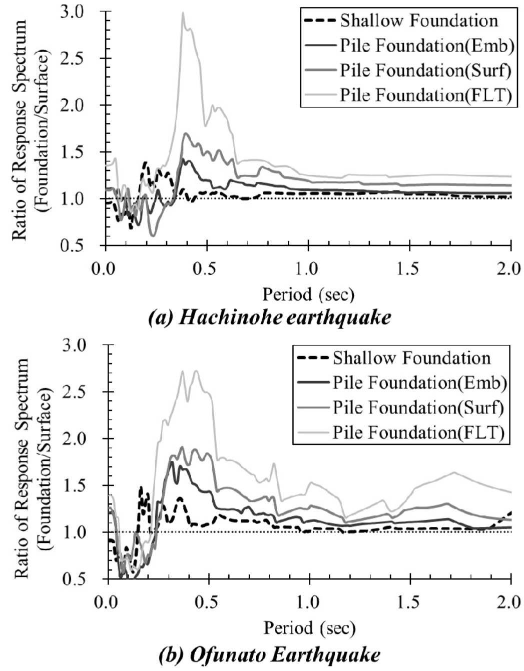

Figure 5. Ratio of response spectrum for foundation to soil surface (a) Hachinohe (b) Ofunato

When the largest earthquake is input to the model specimen, the response spectrum ratio is calculated by dividing the response spectrum of the slab motion into the motion response spectrum of the ground surface to investigate the difference between two motions in frequency domain. Figure 5 shows the calculated ratio of response spectrum (RRS). Generally, in the tests of all foundation types, the amplitude of RRS are less than 1 in the period range below 0.15 s, which means the high frequency range. It seemed that this is due to the kinematic influence that the high frequency component is filtered when the earthquake motion is transmitted from the ground surface to the foundation (FEMA 440). These phenomena were similarly show irrespective of the foundation types.

The periods and the amplification ratio of the region where the foundation slab motion was amplified differs depending on the foundation types. Foundation slab motions were amplified at the range of 0.2 – 0.3 s for shallow foundation and 0.3 - 0.5 s for pile foundations, respectively. And amplification ration increased largest at the floating pile foundation which slab is distant from the ground surface. These phenomena are considered to be due to the effect of not only the kinematic effect but also the inertia effect of the structure and foundation.

3 .2 *Dynamic behavior between the slab and top of the LNG tank structure*

The peak accelerations between the foundation slab and the top of the model structure are compared in Figure 6. The X-axis of the figure represents the peak acceleration of the slab, while the Y-axis represents the peak acceleration of the structure at the top of the storage tank model. There were no clear effects of the input motion types in the horizontal acceleration of the soil surface and foundation slab, but the motion at the top of the structure was much dependent on the input motion.

In the case of the Hachinohe earthquake motion, regardless of the foundation type, the peak acceleration of the tank top increased, on average, to 1.1 times with increasing acceleration of the slab. In the case of the Ofunato earthquake motion, the trend of the peak acceleration of the tank structure was different.

It was observed that the peak accelerations of the structure were amplified 1.2 times or less like the Hachinohe earthquake test for the pile foundation tests. However, the peak accelerations of LNG tank structure on shallow foundation showed an almost linear increase of the amplification up to 0.4 g then a sudden increase appeared.

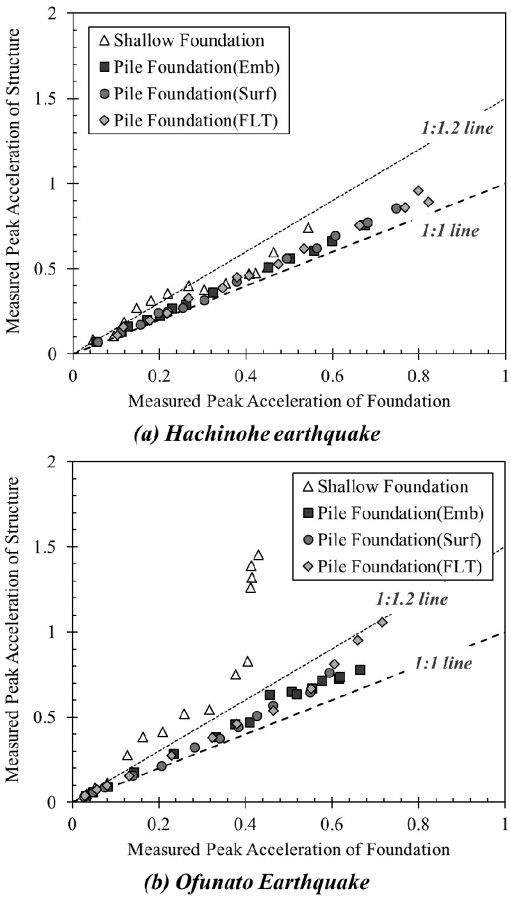

Figure 6. Peak accelerations between the foundation slab and the top of LNG tank structure. (a) Hachinohe (b) Ofunato

Figure 7 shows the calculated ratio of response spectrum between the motion of top of structure and foundation slab during the strong Ofunato earthquake. In the case of a shallow foundation, a large amplification is observed as a whole range compared to the case of pile foundation tests, and particularly the amplification became large in the period of about 0.08, 0.14, 0.2 s. Under the Hachinohe earthquake motion, the frequency components of structure for the four foundation types were similar with small amplification. From these differences by the foundation types and earthquake motion, it indicates that seismic responses of the LNG storage tank structure were affected by the dynamic characteristics of the overall foundation-structure system, such as rocking or sliding, the natural frequency of the structure, and variation of the mode shape (Park et al., submitted).

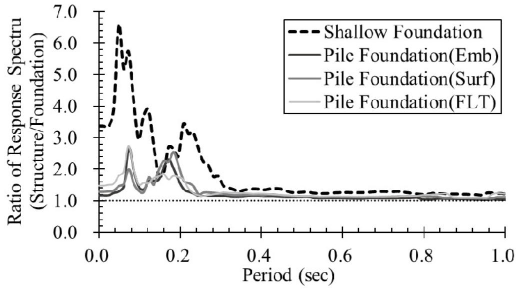

Figure 7. Ratio of response spectrum for top of structure to foundation during strong Ofunato earthquake

4 CONCLUSION

In this research, a series of centrifuge tests were conducted to evaluate the seismic behavior of the LNG storage tank with the variation of the foundation condition. Scaled-down models of the piles and upper structure were developed using the appropriate materials (with regard to rigidity) and scaling laws., and two types of earthquake were utilized.

From the test results of the peak accelerations and ratio of response spectrum, the different amplification between foundation and soil surface by the foundation types were investigated. And the large acceleration of LNG tank structure on shallow foundation during the Ofunato earthquake showed the effects of input earthquake frequency.

It is concluded that the complicated dynamic behaviors of storage tank models with different types of foundations are related to the dynamic characteristics of the overall soil-foundation-structure system. Thus, seismic design and evaluation considering the influence of SFSI are important, for important social infrastructure such as LNG storage tanks.

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