Ground improvement using rigid inclusion for the foundation of LNG tanks

Renforcement du sol par inclusion rigide pour la fondation des réservoirs GNL

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ABSTRACT: Ground improvement using rigid inclusion has been considered and adopted instead of conventional deep foundation during the tender design of a LNG terminal project to be constructed on a reclaimed land on where several LNG tanks will be built. This paper begins with the introduction of LNG tank and the selection of its foundation. The general behavior and design methodology of rigid inclusion under vertical loading and seismic loading will be discussed. The focus will be given to the lateral behavior of RI which determine the necessity of rebar reinforcement. It is concluded that plain concrete rigid inclusion is an alternative solution for the foundation of LNG tank with regard to safety, construction schedule and economic benefit, compared to other methods. It allows reducing substantially the total settlement and minimizing the different settlement under static condition. In seismic case, if significant localized shear is not present or in other word the loose sand layer is removed by dredging, the concrete RI without reinforcement can sustain a certain amount of soil lateral displacement derived from kinematic and inertial effects.

RÉSUMÉ : Renforcement du sol par inclusion rigide a été retenu et adopté au lieu de fondation profonde classique lors d'un appel d'offre d'un projet du terminal GNL à construire sur un remblai hydraulique sur lequel des réservoirs GNL seront installés. Cet article commence par l'introduction du réservoir GNL et de la sélection de sa fondation. Puis, le comportement et la méthodologie de dimensionnement de l'inclusion rigide sous charge verticale et sismique seront discutés. Le comportement latéral sera concentré ce qui est la clé pour répondre à la nécessité de renforcement dans l'inclusion. La conclusion a montré que l'inclusion rigide en béton est une solution économique et adapté permettant réduire considérablement le tassement total et gommer le tassement différentiel dans la situation statique. Dans le cas sismique, si le cisaillement localisé significatif ne paraît ou autrement dit absence de sable lâche en dessous du remblai, l'inclusion rigide sans armature peut subir à certain degré le déplacement latéral d'origine des interactions cinématique et inertiel.

KEYWORDS: Foundation of LNG tank; ground improvement, rigid inclusion; design methodology in static and seismic cases.

1 INTRODUCTION

Increasing of world's energy demand results in the need of more and even larger LNG (Liquefied Natural Gas) storage tank. LNG is natural gas that for storage has been turned into liquid. When natural gas is cooled to about minus 160° Celsius it condenses and its volume is reduced about 600 times. This makes it easier to transport over long distances by ship and to store it in large quantity.

Typical LNG terminals have aboveground storage tanks with capacity ranging from 160,000 m^3 to 225,000 m^3 corresponding to tank diameter from 80 to 100 m and height from 30 to 50m. In the case of a containment failure, the economic damage would be substantial and the danger to life, property and environment correspondingly great.

Basic characteristic design issues of LNG tank foundation are a relatively large foundation load and restricted differential settlement criteria. Secondary issues are load variation during time, groundwater level and construction schedule requirements.

LNG storage plants are located in coastal areas. Soil conditions are most likely to be marine and alluvial deposits to great depth. The ground water level is close to ground level. Common foundation loads are typically 70 to 140 kPa for the empty tank, 200 to 400 kPa for the full loading condition, and 250 to 500 kPa during hydro testing. The high foundation pressure applicable to full tank area results in stress increase to great depth, up to 120 m (1 to 1.5 times the diameter of tanks). Therefore settlement of clay and sand deposits are of great importance. Furthermore, the rigidity of concrete tanks demands relative strict (differential) settlement requirements.

2 FOUNDATION OF LNG TANKS

Selection of foundation types is often dominated by local site conditions, schedule requirements and cost. The procedures for selection of the foundation of above ground LNG tanks are as follows:

- The solution of shallow foundations on untreated or treated massive soil is firstly considered. It is preferable if the foundation soil can guarantee the stabilities and settlements acceptable for the structures;
- If at least one of these two criteria is not satisfied, then the conventional alternative would be the solution of deep foundations that have been designed to carry the entire load. Load is transmitted to the piles via a rigid element, which performs the role of distributing forces among the piles. This solution is generally overdesigned and not necessarily safe especially under earthquake loading (e.g. damage to structural connection of pile cap, and high seismic demands);
- In most cases, ground improvement with inclusion-type reinforcement elements can be regarded as intermediate solution which can overcome the limits and constraints of shallow and deep foundations to satisfy the project requirements, and they can be classified into two categories: (1) soft inclusions (sand and stone columns), (2) rigid inclusions (deep mixed column, cement grouted column, plain concrete column, reinforced column, steel pipe, etc). The soft inclusions can provide drainage thus accelerating the consolidation of soft soil; however, they typically have relatively low bearing capacity and shear strength causing bulging failure and resulting in large settlement. The rigid inclusions have much higher shear strength, compressive strength, and bond strength to support high loading from LNG tank and reduce efficiently total and differential settlements. In addition to its cost-effective advantage compared to conventional deep foundations, rigid inclusions provide a reduction of dynamic loading, shear force and localized stress in both pile and raft under seismic loading due to no connection between the tank base slab and foundation, and a decrease of construction period when considering concrete column using screwed or pressurized CFA (continuous flight auger) installation techniques compared to stone column.

This paper focuses on the ground improvement solution of plain concrete rigid inclusion (RI) for the foundation of LNG tanks. Its mechanical behavior and design methodology of RI under vertical loading and seismic loading will be described. An application case of RI to a LNG tank project is also discussed. From the best of the author's knowledge, this would be the very first case of RI application to LNG tank.

3 GROUND IMPROVEMENT BY RIGID INCLUSION

3 .1 *Rigid inclusion under vertical loading*

A general recommendation for the design and construction of RI can be found in ASIRI (2012). An extensive parametric study on the behavior and performance for optimized design of RI using three dimensional finite element analysis was discussed in Hor et al. (2015).

The RI is also known as disconnected or non-connected piled raft solution and it is often confused with pile solution due to the use of same material property. However, a load transfer platform (LTP, usually made of granular material) placed between the raft and soil, make it behave differently from the conventional piled method. The LTP plays a very important role to ensure the transfer of loads to the ends of the RI and to uniform settlements. The interactions of this foundation concept are a complex phenomenon including the load transfer in LTP and the load transfer along the piles as shown in figure 1.

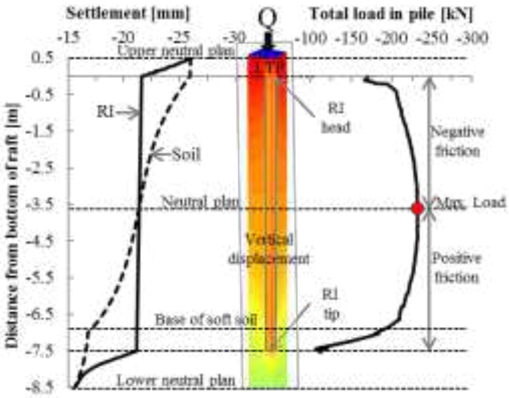

Figure 1. Load transfer mechanism of RI under vertical load of an example case study (Hor et al., 2015)

Under the relatively rigid raft, the equal settlement (upper neutral plane) is forced to coincide with the raft lower face at an elevation lower than raft level. Below the equal settlement upper plan, as the soil settles more than the RI (and the area above the RI), negative skin friction develops along the RI. This causes additional load to be transferred to the RI. As load is transferred from the soil to the RI, the relative settlement decreases with depth until it reaches equilibrium (neutral plane or equal settlement lower plane) where the soil and the RI show equal settlement. Below the neutral plane, the RI settles more than the surrounding soil and therefore the load is now transferred from the RI to the soil through positive skin friction. The remainder of the load in the RI is then released in the bearing layer at its tip.

The behavior of the RI shown in figure 1 is based on a unit cell model (UCM). The UCM not only allows calculating the stress distribution in RI, but also the improved equivalent modulus (E*) of the composite material. The difference of loading at the center (liquid) and edge (wall) of the LNG tank results in different equivalent modulus at center area (E^*_{center}) and at edge area (E^*_{edge}). These equivalent modulus are then used in the global finite element model (FEM) to calculate the total and differential settlements of the tank (figure 2).

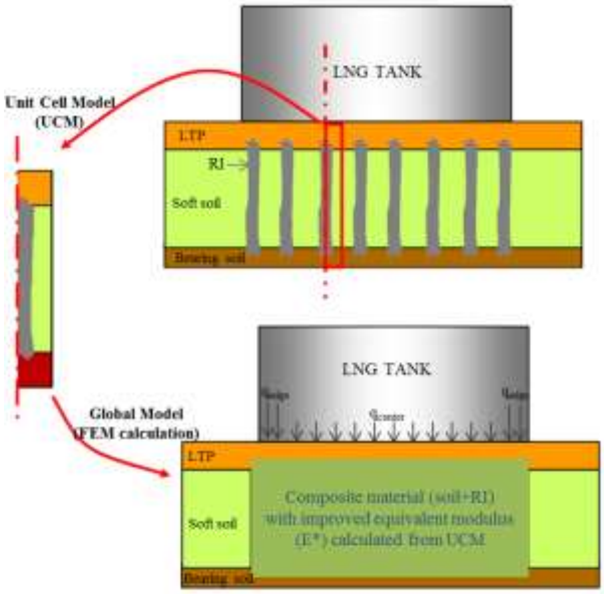

Figure 2. Design methodology of LNG tank under vertical loading

3 .2 *Rigid inclusion under seismic loading*

During an earthquake event, the ground and the tank structure are shaking creating the so-called kinematic effect (K) and inertial effect (I). The cumulative effect of K and I as well as the horizontal load transferred from the superstructure needs to be considered for conservative approach. The technical guide AFPS (2012) describes the procedures of RI under seismic loading.

The kinematic effect which is the free-field soil deformation profile $g_K(z)$ can be evaluated rigorously by site specific response analysis. Alternatively, the $g_K(z)$ can be estimated in function of ground acceleration and shear wave velocity:

$$g_K(z) = a_N \cdot \left(\frac{2h_s}{\pi . V_s} \right)^2 . \cos\left(\pi \frac{z}{2h_s} \right) \quad (1)$$

where a_N is normalized ground acceleration considering the PGA at bedrock, the soil class, importance of structure, and topographic effect; V_s is average shear wave velocity; h_s is soil thickness; and z is depth from ground surface.

The inertial effect derived from the horizontal load and overturning moment of the tank induces the ground movement $g_I(z)$ which can be estimated by modeling a 3D FEM on homogenized ground. The result will be used to check the overall tilting of the tank.

The combination of kinematic and inertial effects g(z) is calculated as:

$$g(z) = \sqrt{g_K(z)^2 + g_I(z)^2} \quad (2)$$

The shear force and moment of RI are determined by imposing the total soil displacement g(z) as illustrated in figure 3. The ratio M/N (M being the moment and N being the axial force in RI) shall be less than 1/8 to ensure no tensile force developed in RI so that rebar reinforcement is not necessary. The shear strength is verified in compliance with Eurocode 2 where shear stress τ_{cp} shall be lower than the allowable designed shear resistance f_{cvd} of RI. The standard p-y curve for rapid loading can be used to define the lateral soil/RI interaction.

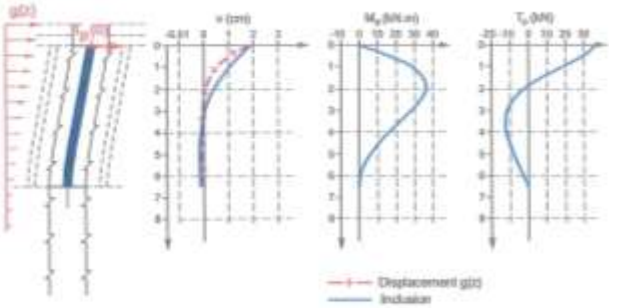

Figure 3. RI subjected to soil displacement g(z) to evaluate deflection, moment, and shear force (ASIRI, 2012)

4 AN APPLICATION CASE OF RIGID INCLUSION TO LNG TANK

A LNG terminal will be constrcuted on a reclaimed land using hydraulic fll of surface area about half million square meter and sand material volume about two million cubic meter, on which several LNG tanks will be built.

During the tender design, the RI solution was considered over conventional piled foundation due to the technical and economic advantages as discussed above. 30m length and 1.5m diameter bored reinforced pile were replaced with plain concrete RI of the same length, 1.2m diameter at the tank center and 1.5m diameter at tank edge with a 2.5m thickness LTP. The spacing of RI at both center and edge locations is 3.6m. Concrete material of RI has a 28-day characteristic strength fck of 30MPa and an elastic modulus of 28GPa. The overall geometry of the LNG tank, loading conditions and RI foundation dimension are presented in figure 4.

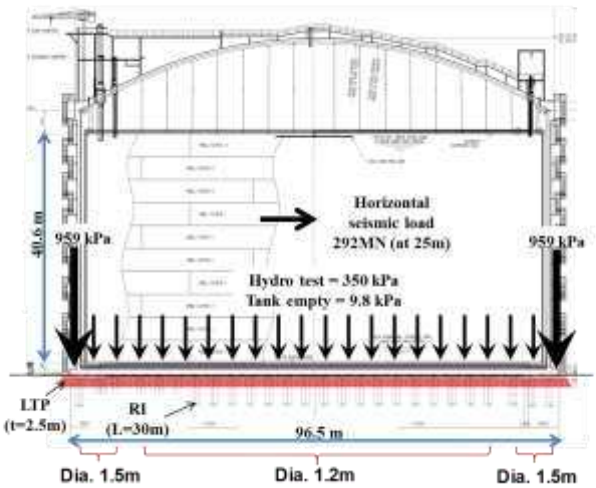

Figure 4. Overall view of LNG tank geometry, loading conditions, and RI foundation dimensions.

The total tank base slab diameter is 96.5m and the inner maximum height to store LNG is 40.6m. The thickness of the reinforced concrete base slab is 1.3m at center and 1.5m at edge (over 3m width). Service loading at tank center q_{center} for tank empty and hydro test cases of 9.8 and 350kPa respectively are considered in the analysis of tank settlements. The prestressed concrete ring wall presents a significant pressure q_{edge} of 959kPa (over 2.25m width). It should be noted that the inner steel tank at 45m radius from center of the tank gives a line load of 109kN/m (not shown in figure 4). In seismic condition, the normalized acceleration was calculated to be 0.2g for a SSE (safe shutdown earthquake) of 2475 year return period determined from the site-specific probabilistic seismic hazard assessment, which results in a horizontal seismic load of 292MN applied at about 25m high from the base slab.

Geotechnical investigation information provided in the tender document and result from an additional campaign were used to derive the geotechnical parameters of the in-situ soil. The parameters of reclaimed land were predicted based on the SPT-N value target (in detailed design stage, CPT-qc criterion will be adopted for the design of reclamation) which has to satisfy the project requirements: 95% maximum dry density (MDD) of the top 3m and 90% MDD below 3m of hydraulic fill. As for LTP, a compacted gravel layer was considered. Layering and material parameters of LTP and foundation soils are summarized in table 1. Ground level elevation is at 7.5mCD and ground water level is at 2.2mCD.

Table 1. Material parameters of LTP and foundation soils

Parameter	*Thickness (m)*	*γ (kN/m³)*	*ν*	*SPT-N*	*E (MPa)*	*φ' (°)*
LTP (gravel)	2.5	21.9	0.25	-	100	40
Fill (top 3m)	3	18.6	0.3	40	30.6	38
Fill (below 3m)	10.5	17.7	0.3	20	15.3	33
Loose sand	4	15.7	0.3	12	9.2	30
Medium sand	4	16.7	0.3	20	15.3	33
Dense sand	6.5	17.7	0.3	50	38.3	40
Very dense sand	52	19.1	0.3	100	76.6	40

Note: γ - unit weight; ν - Poisson's ratio; E-elastic modulus = 0.766 N (Meigh & Nixon, 1961); c'- drained cohesion = 0 for all layers; φ' – drained friction angle.

It is important to note the present of loose sand below the fill which may induce the localized shear during earthquake.

Dynamic properties are estimated based on PMT correlation. Maximum shear modulus G_{max} was taken equal to 10 times PMT modulus E_m ($E_m = \alpha.E$; α being soil rheological coefficient depends on soil's nature and consolidation state). Shear wave velocity Vs is calculated from Gmax. Stiffness degradation G/G_{max} is also taken into account based on recommendation of BS EN-1998-5. Average V_{s30} is found about 200m/s.

4 .1 *Analysis under static condition*

Following design methodology described in section 3.1, the tank settlments can be calculated from a 2D axisymetric FEM using Plaxis, where the equivalent reinforced layer was adopted between the upper and lower settlement planes (see figure 1). Figure 5 presents the settlement contours under the tank for hydro test condition. Table 2 summarized the result of total and differential settlements for empty and hydro cases are compared with the results of shallow foundation without RI and verified with project requirements.

Table 2. Comparison of tank settlements under static load

Case		*Settlement criteria (mm)*	*Without RI (mm)*	***With RI (mm)***	*Reduction (%)*
Empty	Total	-	598	**101**	83
	Differential	161	543	**22**	96
Hydro test	Total	-	668	**216**	68
	Differential	161	216	**61**	72

Note: the differential settlement criteria is 1/300 between center and edge of tank

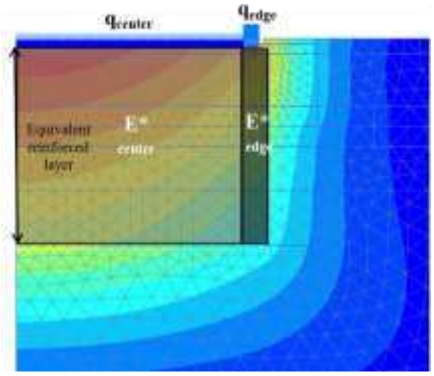

Figure 5. Tank settlement from 2D FEM with the application of equivalent modulus calculated from UCM

Regarding stability analysis, it should be noted that in the case without RI the failure below the tank wall was observed, causing large settlements for empty case. With the RI, the local and global stabilities are verified. The punching failure at RI's head with respect to Prandlt's theory was also verified. The maximum stress in RI calculated from UCM was about 5.4 MPa (for RI at edge area) much lower than the allowable compressive strength 12.75 MPa (FS > 2) based on ACI code.

4 .2 *Analysis under seismic condition*

In seismic condition, tank tilt was calculated using Plaxis 3D model with homogeinized ground E* and G* (G* equivalent shear modulus without taking into account the RI). The tilting criteria is 1/500 between the two edges of the tank equivalent to 193mm which is greater than the calculated tilt 149mm for the more critical empty case. The 3D model also provides the displacement profile $g_I(z)$ from inertial effect (figure 6).

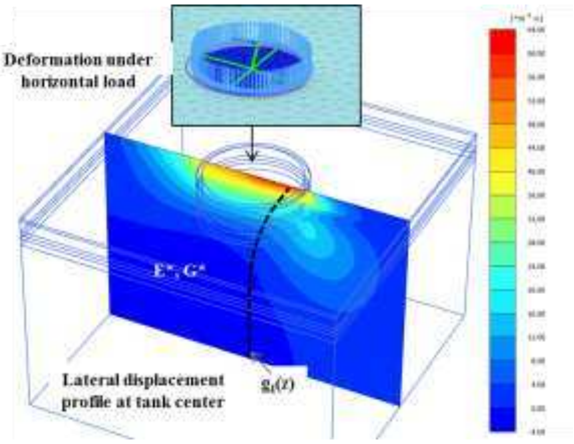

Figure 6. Lateral displacement under horizontal loading

For checking the bending moment and shear force in RI, the $g_I(z)$ is combined with the predicted $g_K(z)$ as expressed in Eq. 2. Two scenario were envisaged: inertial force opposites to the free-field displacement (K-I) and the contrary case (K+I).

The $g_I(z)$ is determined from the homogenized ground, whereas the $g_K(z)$ is estimated assuming an average Vs value. In reality, the localized shear may occur at the interface between loose sand and lower/upper layer. In this regard, we have imposed a net differential displacement of 2cm at the loose sand interface to simulate the localized shear as shown in figure 7. Figure 8 presents the calculated bending moment and shear force along the RI's length for the case K+I with localized shear. The maximum moment and shear force are 1270kN.m and 735kN respectively, leading to an extreme normal stress and shear stress in RI of 12MPa and 1.5MPa respectively. Tensile stress is also occured. In this condition with imposing localized shear, the verifications of no reinforcement in RI was not verified.

When no localized shear, the RI can be designed without reinforcement with respect to the justification rules. In this regard, it is decided to remove the loose sand layer in the detailed design stage.

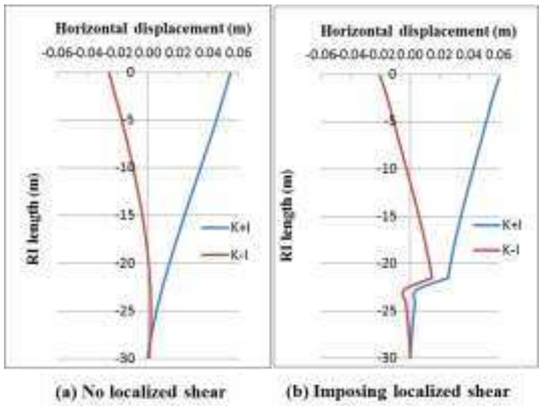

Figure 7. Different scenario of lateral displacement g(z)

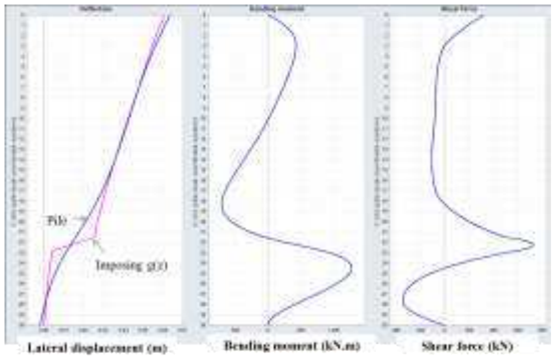

Figure 8. Deflection, moment and shear force in RI for case K+I with considering localized shear force

5 CONCLUSION

Plain concrete rigid inclusion is obviously an alternative solution for the foundation of LNG tank with regard to safety and construction schedule and economic benefit, compared to other methods. It allows to reduce substantially the total settlement and uniform the different settlement under static condition. In seismic case, the concrete RI can sustain a certain amount of soil lateral displacement derived from kinematic and inertial effects, if extreme localized shear is not occured.

Another beneficial aspect of RI is the optimization of the LNG tank structure when subjected to meduim or high earthquake. The gravel layer of RI system plays a role as base isolator which is able to lengthen the natural period of the structure to a relatively safe zone (low acceleration). This aspect is being examined in the detailed design.

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