Consolidation settlement of skirted foundations for subsea structures in soft clay

Consolidation d'jupe fondation pour structures sous-marines dans de l'argile molle

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ABSTRACT

Skirted foundations are a viable solution for subsea structures in most offshore developments. In an attempt to estimate long term settlements of skirted foundations installed in soft clays, this paper presents results of numerical consolidation analyses in which a remoulded zone adjacent to the skirted foundation wall is accounted for. In particular the effects of thickness, strength and stiffness of this zone are investigated. The calculated settlement values indicate that without taking into account the remoulded zone the long term settlement might be understimated.

RÉSUMÉ

Les jupe fondation pour structures sous-marines offrent une solution adéquate et fiable alors que l'exploitation de champs s'amplifie. Afin d'estimer le tassement à long terme d'jupe fondation dans de l'argile molle, cet article présente les résultats de consolidation par modélisation numérique lorsqu'une zone remaniée adjacente à la paroi de l'jupe fondation est prise en compte. En particulier, les effets de l'épaisseur, de la résistance au cisaillement, et de la rigidité de cette zone sont étudiés. Les valeurs des tassements obtenues indiquent que si la zone remaniée n'est pas prise en compte, l'évaluation du tassement à long terme risque d'être sous-estimée.

Keywords : skirted foundations, consolidation analyses, numerical analyses

1 INTRODUCTION

Skirted foundations and anchors are typical foundations for subsea structures and anchors for mooring systems for floating production platforms in deep water developments. Compared with other technologies, e.g. driven piles or drag embedment anchors, skirted foundations and anchors provide an attractive and convenient solution. Among its advantages are their installation method and their capacity to withstand environmental loads. The installation and behavior of skirted foundations and anchors have been widely studied and reported elsewhere (e.g. Andersen and Jostad, 1999; Sparrevik 2001; Andersen, et al. 2005), but further investigation to better understand the soil deformation behaviour of skirted foundation as a foundation of subsea systems such as manifolds (Figure 1), trees and pump stations is still ongoing.

Evaluation of consolidation settlements of a skirted foundation in soft clay is not a simple task since the skirted foundation geometry differs from typical foundations. Settlement evaluation for offshore foundations under permanent downward loads has been done by the traditional Terzaghi's consolidation theory. This method relies on assumptions about the stress distribution between the skirt and at the base, but for skirted foundations such assumptions are not always accurate because roughness factors along the inside and outside skirt wall need to be accounted for. Lack of monitoring settlement records for calibrating the numerical assumptions makes the calculation uncertain.

During the installation phase, which comprises penetration by self weight and penetration by underpressure, the skirt wall disturbs the adjacent soil and changes the initial effective stresses due to displacement of the soil and generation of excess pore water pressure. This also creates a remoulded zone along the skirt wall. The soil properties in this remoulded zone are assumed to be similar to that of remoulded material and would directly influence the long term skirted foundation behavior and therefore the resulting settlement.

This paper presents results obtained from numerical consolidation settlement analyses by modeling a skirted foundation with a remoulded zone adjacent to the skirt wall. The remoulded zone is modeled by varying parameters such as thickness, strength and compressibility. The importance of using compressibility parameters, obtained directly from laboratory oedometer testing on remoulded clay, for modeling the thin zone is highlighted.

Figure 1. Manifold for a field development in the Gulf of Mexico. (Photo: Stephen Reid, Aker Solutions)

The evaluation of consolidation settlements has been conducted using FE analyses where the soil is modeled using a soil model with a non-linear stress-strain relationship both during compaction and shear deformations. On the basis of the

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results, a comparison between analyses is conducted, and recommendations on improving the accuracy of long term skirted foundation settlements are given. Modeling of the shear strength change with time and the effect of increased pore pressure due to installation effects in the remoulded zone are not included in this study.

2 EXPERIENCE WITH SKIRTED FOUNDATIONS

As far as the author's know, no literature source has reported *in situ* long term settlement measurements for skirted foundations. Experience with monitoring gravity platforms whose foundation comprises skirted walls is available; Lunne (1999) presented a comprehensive study showing settlement records obtained from skirted foundations of platforms in the North Sea for continuous monitoring periods that varies from approximately 7-8 months to 40 months. However, this experience could not be transferred directly to skirted foundation analyses because these platforms measurements are restricted to small depth to width ratio. More recently, Svanø et al. (2007) reported settlement records from the Troll A platform foundation in the North Sea after 10 years of continuous monitoring.

Centrifuge tests provide an alternative to further investigate skirted foundation long term settlement evaluation. So far, a number of centrifuge tests have been performed worldwide to better understand issues such as installation and capacity but no emphasis has been placed yet on long term settlement.

Chen and Randolph (2007) reported results from a series of centrifuge tests where instrumented suction anchors (simulating a suction anchor prototype of 14.4 m length, 3.6 m diameter, 0.06 m wall thickness and 230 kN self weight) were modeled in normally consolidated reconstituted kaolin. Although their main objective was to investigate the external radial stress changes around suction anchors only, they reported that after the suction anchor was installed to target penetration depth, followed by one hour of consolidation (equivalent to 1.7 years at prototype scale), the settlement of the suction anchor model was 0.10 mm (equivalent to 2 cm at prototype scale). This settlement was however only due to suction anchor self weight. Larger settlement is anticipated once additional loads are considered as the case of manifold and pump stations.

3 SKIRTED FOUNDATION RESPONSE TO VERTICAL DOWNWARD FORCES

Skirted foundations will be subjected to vertical downwards loads, horizontal loads and moments. The origin of these loads is mainly the presence of subsea structure modules, e.g. manifolds, trees and pump stations, which are pivotally-supported at the top of the skirted foundation. Since skirted foundation stability must be guaranteed during service lifetime, both short and long term capacity analyses must be verified.

The short term skirted foundation capacity is a function of the load combination and the undrained soil response. Even if short term stability is guaranteed, however, long term settlement tolerances need to be fulfilled because the presence of jumpers and pipelines connectors in the subsea structures modules may require maintaining accurate alignment during service life.

The long term skirted foundations behavior depends on the friction along the outside and the inside of the skirts and pore water flow with time. In this respect, water flow is directly influenced by whether or not the water outlet in the top of the skirted foundation is kept fully sealed during service life.

If the water outlet in the skirted foundation top is completely sealed during the lifetime, the case analysed in this paper, the load transfer mechanism is assumed to change slowly with time. This means that the pore water pressures will dissipate slowly and consequently vertical and horizontal soil stresses are expected to change slowly with time and at some stage the shear strength will be more dependent on drained parameters, e.g. friction and cohesion. Figure 2 shows the forces acting on the skirted foundation. The soil resistance to overtake the loads induced by manifold and skirted foundation weights is obtained from pore pressure increase and outside and inside friction. Pore pressure dissipation is a function of the drainage distance and since the top outlet is supposed to be closed for the analyses herein, it is believed that the soil response is similar to an undrained behavior during the first months and probably the first years. As described by Andersen and Jostad (2002; 2004), outside and inside friction is expected to increase with time. They reported that after the penetration of the skirted foundation to the target depth, a set up effect due to reconsolidation occurs. This effect depends on three mechanisms; i) dissipation of excess pore pressure, ii) increased effective stresses and iii) thixotropy.

In this study the vertical settlement has mainly been estimated after 30 years of consolidation. It was assumed that the skirted foundation penetrated to contact between top plate and soil after installation and that the top vents are closed after installation.

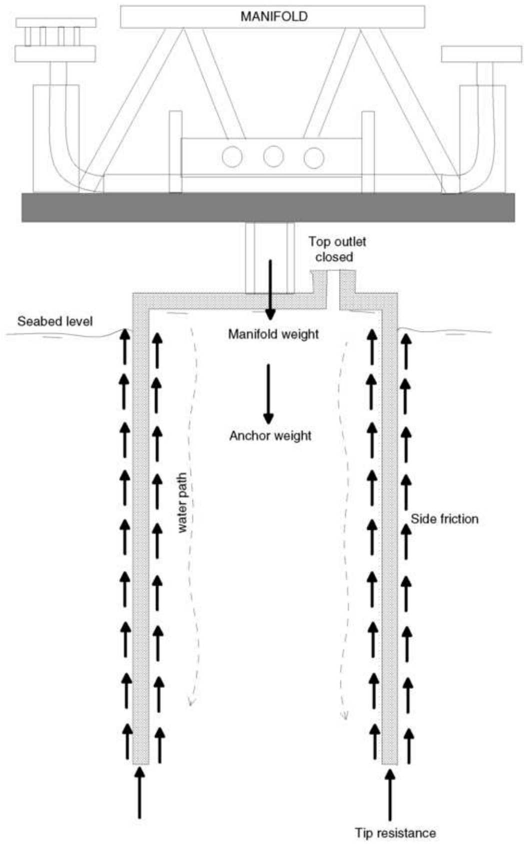

Figure 2. Forces acting in a skirted foundation foundation after a subsea module has been connected.

4 FINITE ELEMENT ANALYSES

4.1 *Geometry and finite element mesh*

For simplicity, a rectangular skirted foundation having a cross-sectional area equivalent to a 5 m diameter circle (3.92 m x 5m) was used in all analyses reported herein. This assumption facilitated modeling the thin remoulded zone along the skirt. This assumption did prove to give satisfactory results for holding capacity analyses as reported by Andresen et al. (2008) and it is expected to give results in close agreement to a cylindrical anchor for settlement analyses. The assumed length of the pile is 20 m depth, and it was modeled numerically in a full 3D model. The assumed vertical load is 2500 kN, including the anchor self weight. The Plaxis 3D version 2.2 program was used (Plaxis, 2007). Lateral loading is not included at this stage of this study since further analyses are being conducted. The model geometry was idealized by a finite region close to the skirted foundation (region I) and a by a semifinite region far from the foundation (region II). In addition a thin remolded zone around the skirt wall was idealized as shown in Figure 3. The model was discretized using 15-noded elements, 37000 number of elements and 99000 number of nodes.

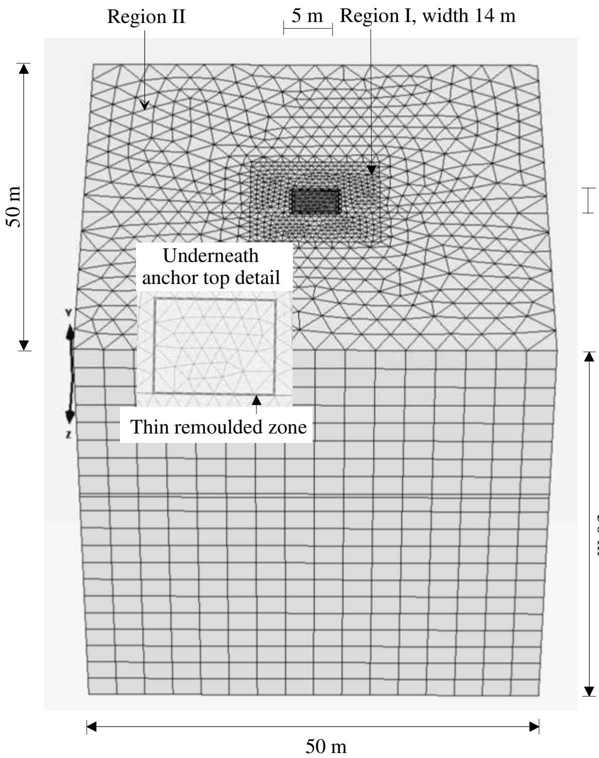

Figure 3. 3D Finite element mesh for skirted foundation.

4.2 *Soil shear strength*

A hypothetical undrained shear strength profile assuming conditions similar to those found in deep water areas at the Gulf of Mexico was chosen. Plaxis allows entering either the undrained shear strength with increasing strength with depth or entering drained parameters, c' and ϕ'. For this case, the chosen profile is supposed to represent normally consolidated clay. The strength at seabed is considered to be s_u = 1 kPa, increasing linearly with depth, i.e. s_u (kPa) = 1 + 1.2·*z*, where z is the depth below seabed. For simplicity the effect of increased shear strength due to increased effective stresses is neglected. The fully drained shear strength given by the drained friction angle (and a small cohesion) is generally larger than the undrained shear strength.

The clay is modeled as being elasto-plastic using the PLAXIS isotropic hardening material model. This model assumes stress dependency of soil stiffness (Plaxis, 2008).

The skirt wall was considered very stiff compared to the soil, and the skirt is modeled as steel and being rigid enough to avoid large deflections.

As the main objective of this study is to evaluate the effect that the thin remoulded zone around the skirt wall will have on the settlement, the behavior of the soil-skirted interface was taken as rigid, meaning that the interface does not influence the strength of the surrounding soil. Instead a thin zone all around the skirted wall was modeled by varying its properties as discussed below.

4.3 *Soil deformation properties*

When dealing with deepwater projects, sample disturbance and consequence of stress relief during the process of sample retrieval to the surface become an issue (Schroeder et al., 2006; Lunne et al., 2007). Results obtained from actual constant rate of strain oedometer (CRSC) tests, from a specific Gulf of Mexico site, were used as the main source for selecting adequate soil deformation parameters. Only results from high quality recovered samples were selected by following the criterion recommended by Lunne et al. (1997). Figure 4 shows two oedometer curves from two samples obtained at the same depth and its best estimate match using the hardening model in Plaxis. Actual oedometer curves at four different depths were used for estimating the deformation properties to be used in the model. This evaluation was conducted by calibrating theoretical oedometer curves obtained from the hardening model in Plaxis with those obtained in the laboratory for each corresponding depth as shown Figure 4. The obtained soil deformation properties are summarized in Table 1. These basic properties are used to model all mesh elements as presented in Figure 3 but soil properties for the elements in the thin zone are varied in order to investigate their effect on settlement evaluation.

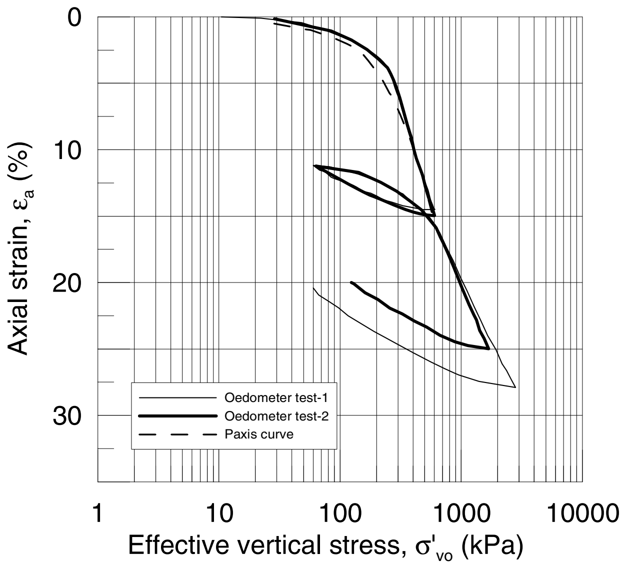

Figure 4. Laboratory oedometer curves of samples recovered at the same depth and its calibrated curves modeled in Plaxis 3D foundation.

4.4 *Remoulded zone due to penetration*

During penetration, the skirt wall disturbs the soil adjacent to it, and a thin zone of remoulded clay is formed. The undrained shear strength at this zone becomes equal to the remolded shear strength (Andersen et al., 2004) and the soil compressibility values decrease accordingly. Figure 5 shows the variation in stress-strain response of two oedometer curves conducted on intact and remolded normally consolidated clays. The figure also shows the calibrated curves obtained from Plaxis 3D using the hardening soil model.

From the figure, it is clear that the deformation properties from the remolded clay differ as compared with the intact sample. The remolded sample has a higher compressibility index and a lower stiffness. After installation, the remolded zone will have a high excess pore water pressure which will dissipate with time. The effective stresses and the shear strength will thus increase. In addition a shear strength increase due to thixotropy is anticipated (Andersen and Jostad, 2002, 2005). Modeling of the shear strength change with time and the effect of increased pore pressure due to installation effects in the remoulded zone are not included in this study. These changes have to be accounted for during long term settlement analyses in order to better represent the soil behavior around the skirt wall after installation. However, in this study, these effects are only indirectly taken into account by using a shear strength in the remoulded zone equal to a factor times the intact undrained shear strength. The shear strength at the end of the consolidation phase is then assumed to be conservatively low.

Andersen and Jostad (2004) reported that the thickness of the remoulded zone adjacent to the suction wall is a parameter that requires special attention since the degree of pore water pressure redistribution is proportional to the thickness of the remoulded zone. Based on information from several authors who have conducted model tests and analytical studies (Renzi et al., 1991; Karlsrud and Nadim, 1990; Sagaseta et al., 1997; Baligh et al., 1987 and Andersen and Jostad, 2002), the remoulded zone thickness is expected to be similar to the skirt wall thickness.

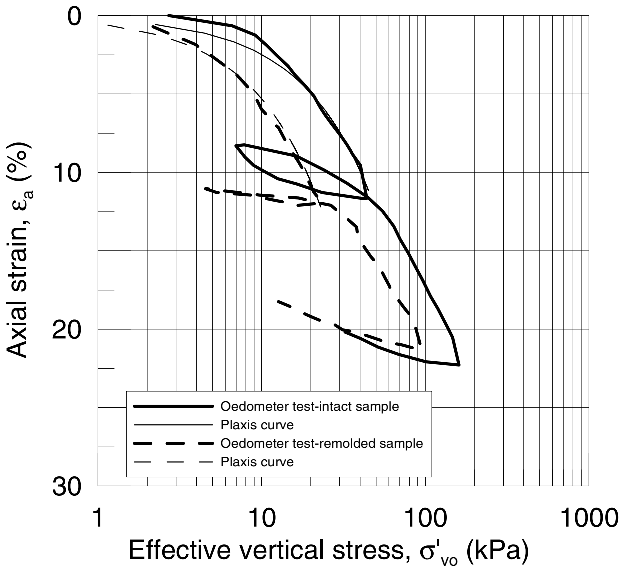

Figure 5. Laboratory oedometer curves of intact and remolded samples obtained at the same depth and their calibrated curves modeled in Plaxis 3D foundation.

4.5 *Material properties*

The clay properties used in the numerical analyses are summarized in Table 1. The shear strength is for simplicity taken equal to the average undrained shear strength, i.e. average of the stress path dependent anisotropic undrained shear strength.

Table 1. General clay properties used in the consolidation analyses.

	Hardening model
$\gamma_{dry}/\gamma_{wet}$ (kN/m^3)	16/16
e_i	1.57
ϕ' (°)	0
$c' = s_u$ (kPa)	1+1.2*z
E_{ref} (kPa)	300
E_{odo} (kPa)	727
E_u (kPa)	1450
ν	0.3
k_x (m/year)	0.00002
k_y (m/year)	0.00004
k_z (m/year)	0.00002
K_0	0.6

z = Depth below seabed

5 PARAMETRIC STUDY

As mentioned above, during skirt penetration the soil properties of the remoulded interface zone between the skirt and soil are modified such that the effective stresses are significantly decreased and thus also the strength and the stiffness. The change in strength and stiffness will influence the long term settlements. Due to arching effect the final effective stresses in the remoulded zone may be lower than the initial in situ stresses. In addition, full recovery may occur inside after dissipation of the pore pressure in the plug and it may also occur for the part of the skirt penetrated by weight. (Andersen and Jostad, 2002, 2004; Schroeder et al. 2006). In order to study the effect of the interface zone on consolidation settlement a parametric study was conducted. Emphasis has been placed on thickness, strength and compressibility only.

5.1 *Effect of interface-zone thickness*

The thickness of the remoulded zone around the skirt wall was modeled. However, an attempt to model the interface thickness as being similar to the skirt wall thickness (typical values of 2-3.2 cm) was not possible because of software convergence problems. Instead, interface thickness values of 5 cm, 25 cm and 50 cm were considered. Settlements values at the center top of the skirted foundation as function of the ratio of interface thickness over suction pile radius (t/r) are shown in Figure 6. For comparison purposes, Figure 6 also shows the result obtained with no interface zone considered (t/r = 0). As expected, it is clear that the thicker the remolded zone is, the larger is the settlement.

Results obtained by assuming an interface thickness of 5 cm are anticipated to be closer to reality, and therefore this thickness was used in all remaining analyses. Figure 7 shows the excess pore pressure after full consolidation together with the deformed mesh for the case where a 5 cm thin interface was modeled.

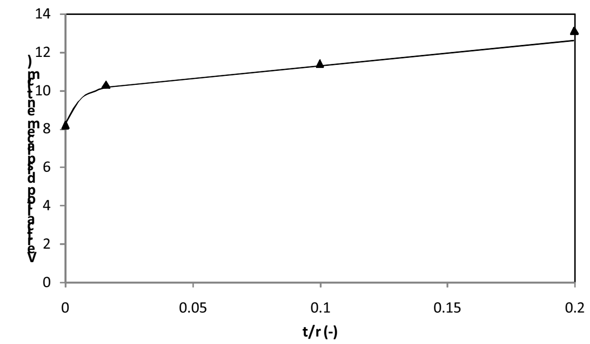

Figure 6. Effect of interface zone thickness on settlement due to consolidation.

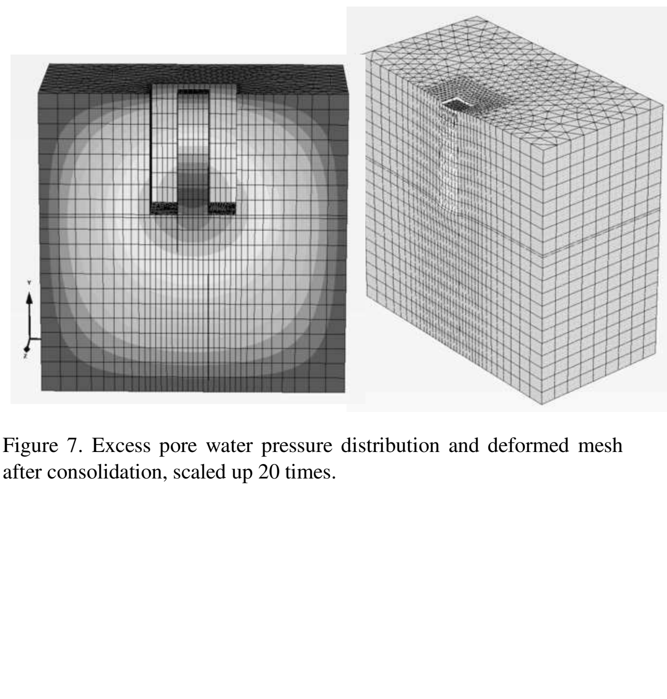

Figure 7. Excess pore water pressure distribution and deformed mesh after consolidation, scaled up 20 times.

5.2 *Effect of strength on interface zone*

The effect of strength in the remoulded zone was for simplicity investigated using the ratio between the shear strength in the interface zone and the original undrained shear strength (s_{uRem}/s_{uDSS}). The strength ratio values in the interface zone varied from 0.5 to 1. Additionally, the soil properties presented in Table 1 were used for modeling region I and II elements as idealized in Figure 3. Figure 8 shows the settlement after 10, 20 and 30 years as function of the s_{uRem}/s_{uDSS} ratio. The results follow a clear tendency with the top anchor settlement decreasing with increasing s_{uRem}/s_{uDSS} ratio. This implies that if the shear strength in the remoulded zone is lower than the original undrained shear strength, the settlement is underestimated. For instance, if an average s_{uRem}/s_{uDSS} value between 0.65 and 0.7 is assumed, typical set-up factors for undrained shear strength reported after 90% consolidation in the Gulf of Mexico clays (Andersen and Jostad, 2002; Jeanjean, 2006), a long term settlement of around 6 cm is computed after 30 years. This value is approximately 30% larger compared to the long term settlement value of 4.5 cm for $s_{uRem}/s_{uDSS} = 1$.

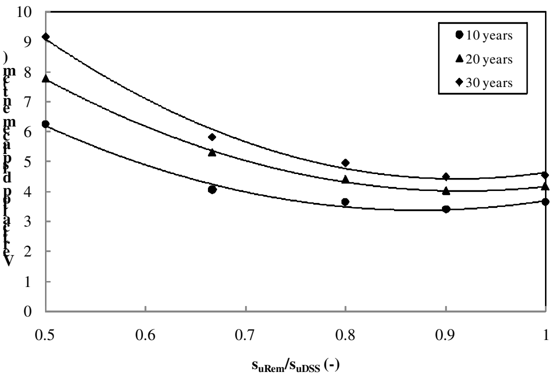

Figure 8. Effect of interface soil strength on settlement with time.

5.3 *Effect of compressibility*

Similar analyses were conducted to evaluate the effect of stiffness in the interface zone by using a modulus ratio, E_{int}/E_{rem}. The modulus ratio values used are; 1, 2, 3 and 4, being equivalent to compression index (C_c) values of 0.81, 1.63, 2.44 and 3.25, respectively. Figure 9 shows the combined effect of reduced strength (using s_{uRem}/s_{uDSS} ratios varying between 0.5 to 1.0) and reduced stiffness. From the figure it is clear that the compressibility effect is also very significant in the settlement evaluation. Again, if a modulus ratio of 1 is used, not considering the effect of remoulding during skirt penetration, the settlement is clearly underestimated.

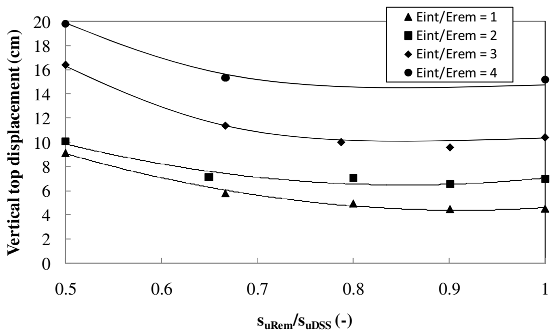

Figure 9. Effect of compressibility on settlement evaluation as function of s_{uRem}/s_{uDSS} ratio.

6 LIMITATIONS

The numerical analyses presented herein have several limitations. Among the most important are i) the accuracy of the models used could not be verified because no field measured settlements are available, ii) the cases presented in this paper only deals with skirted foundations subjected to static vertical loads. Horizontal loads and moments or combination of these loads may give a different deformation response, iii) a combination of static and cyclic loads acting on the skirted foundation may induce larger permanent displacements compared with static load only (Andersen and Høeg, 1991), iv) an important contribution due to dissipation of shear induced pore pressure in the settlement calculation is anticipated. This shear induce pore pressure is due to soil displaced by the skirt wall and it has not been included in this study and iv) the transition from undrained to drained shear strength in the remoulded zone is not modeled.

7 CONCLUSIONS

The evaluation of skirted foundation settlements due to consolidation is an important issue because of the restrictive tolerances to be accomplished. With new deep water developments where presence of soft soil is certain, long term settlement are expected to be a governing factor for skirted foundation design. This paper has reported the results obtained from numerical analyses on the evaluation of settlements for skirted foundations. Herein it has been demonstrated that it is important to take into account strength and stiffness changes in the interface-zone adjacent to the anchor walls, in prediction of the long term settlements. From the results of the parametric study carried out, it is concluded that the settlement evaluation is dependent on strength and stiffness values used in the interface zone and that without taking it into account, settlements are underestimated. The results also show that numerical analyses are a valuable tool in order to evaluate long term skirted foundation settlements due to consolidation. Nevertheless, the need of prototype long term settlement monitoring of skirted foundations that could help to validate the numerical analyses is highlighted.

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