FE Modelling of Spudcan - Pipeline Interaction

L. Kellezi
GEO – Danish Geotechnical Institute, Lyngby, Denmark

G. Kudsk
Maersk Contractors, A-P-Møller, Copenhagen, Denmark

P. B. Hansen
GEO – Danish Geotechnical Institute, Lyngby, Denmark

ABSTRACT: Spudcan-pipeline interaction problems were expected during a jack-up rig installation at the proximity of an oil and gas pipeline in the North Sea. Three positions of the rig were considered assessing the impact of the installation on the pipeline structure. From the available geotechnical data lower/upper bound soil profiles, consisting of sand-clay-sand soils from the seabed, are first derived. Parallel to the conventional analyses, 2D FE modelling of the spudcan penetration is carried out evaluating the soil deformation around the spudcan and at the nearby pipeline. For a more realistic evaluation of the soil conditions, the history of the previous installations was taken into account. The strength of the clay layer is re-evaluated carrying out back and consolidation analyses. The updated soil profiles are used for 2D and 3D large deformations FE analyses of spudcan-pipeline interaction. The impact of the spudcan penetration on the pipeline structure stability is discussed. The rig was installed and the results of the analyses were compared with the field observations.

1 INTRODUCTION

For jack-up rigs located in close proximity of other offshore structures, embedded or lying on the seabed, soil displacement caused by the spudcan penetration may induce deformations into the nearby structures, which can be pipelines, platform pile foundations, quay constructions etc.

Spudcan penetration is generally calculated based on the conventional analysis, Hansen (1970), Florkiewicz (1989) etc. However, for complex soil conditions numerical methods are developed and presented in Ghoah & Kikuchi (1991), Griffiths (1982), Hu & Randolph (1998), Sloan & Randolph (1982) etc. Using these methods the soil pattern at an area around the spudcan, where other structures might exist, can be investigated as in this case.

The impact of a jack-up rig installation on an existing oil and gas pipeline in the North Sea is investigated assuming the following. Virgin seabed conditions are initially considered, utilizing the geotechnical data derived from the site investigation and laboratory testing carried out before any structure installation at the location. For a more realistic evaluation the impact of the previous installation is taken into account. The investigation is generally based on the analysis employing the finite element (FE) method. The two-dimensional (2D) and 3D modelling of the spudcan penetration-pipeline interaction is carried out employing virgin and more realistic soil profiles and assuming three different rig positions.

The stability of the pipeline is investigated and discussed. The rig was installed at one of the considered positions and the field observations are compared with the FE results.

2 SOIL CONDITIONS FOR VIRGIN SEABED

Geotechnical soil investigation and laboratory testing are carried out in the area. Based on the available data, lower and upper bound soil profiles are derived applicable to spudcan penetration analysis assuming virgin seabed conditions. The impact of the spudcan penetration on the pipeline stability is evaluated by first considering those profiles.

The soil conditions, lower/upper bound, consist of an upper layer of loose to dense sand with thickness 2.0 m and 1.5 m for which friction angle $\varphi = 30°$ is evaluated. Below this layer soft to very soft clay is found to depths 7 and 5 m, respectively, The undrained shear strength $c_u = 15$ kPa and, $c_u = 20$ kPa are assessed for lower and upper bound profiles, respectively.

Below the clay layer very dense sand is encountered to approximately 30 m depth. The friction angle $\varphi = 35°$ is assessed for this layer.

The effective unit weight is also derived for the different layers according to the available data.

3 SPUDCAN AND PIPELINE DATA

The jack-up spudcans considered for installation have a contact area of about 249 m^2. Distance from spudcan base (full contact) to spudcan tip is 1.6 m. The considered lightweight (plus variable loads) is

84 MN/leg and the maximum preload is 153 MN/leg.

The rig with the skirted spudcans previously installed at the location have a full contact area of 252 m^2. Distance from spudcan base to spudcan tip is 1.8 m, to the bottom of the permanent outer skirt is 4.7 m and to the chords tip 5.2 m. The lightweight load is 71 MN/leg and the maximum preload is 123 MN/leg.

The pipeline is constructed from steel API5LX52 material. The concrete coating, the corrosion coating and the steel covers existing along the length near the considered spudcan make the pipeline a composite steel-concrete structure. The pipeline is 30 to 50% buried at the investigated location.

4 SPUDCAN - PIPELINE INTERACTION, 2D FE ANALYSIS, VIRGIN SEABED CONDITIONS

Conventional spudcan penetration analyses based on new developments of Hansen (1970), which satisfy DNV (1992) and SNAME (2002), are initially carried out for lower/upper bound soil profiles. From the analyses, no punch through risk is found at the location and spudcan penetrations varying from 6.0 to 7.5 m are predicted.

To analyze the soil push up at the pipeline location 2D axisymmetric FE modelling of the spudcan penetration is carried out using the Elfen FE program, (Elfen V.3.0.4. (2001)). Implicit large strain elasto-plastic analysis was chosen. The Mohr-Coulomb soil constitutive model is applied considering the available soil parameters.

Adaptive re-meshing, which is a powerful tool of Elfen, is incorporated to avoid excessive element distortion. An error indicator based on stress norm projection, (L2 Zienkiewicz-Zhu projection type, Elfen V. 3.0.4 (2001)), is applied. Additional re-meshing regions in critical areas (outer & inner corner at the bottom of the spudcan and its outside edge) are created.

A Coulomb friction contact between the spudcan and the soil is simulated. An updated penalty method was used to solve the contact interaction forces. A friction coefficient of 0.6 is chosen for steel-sand contact conditions.

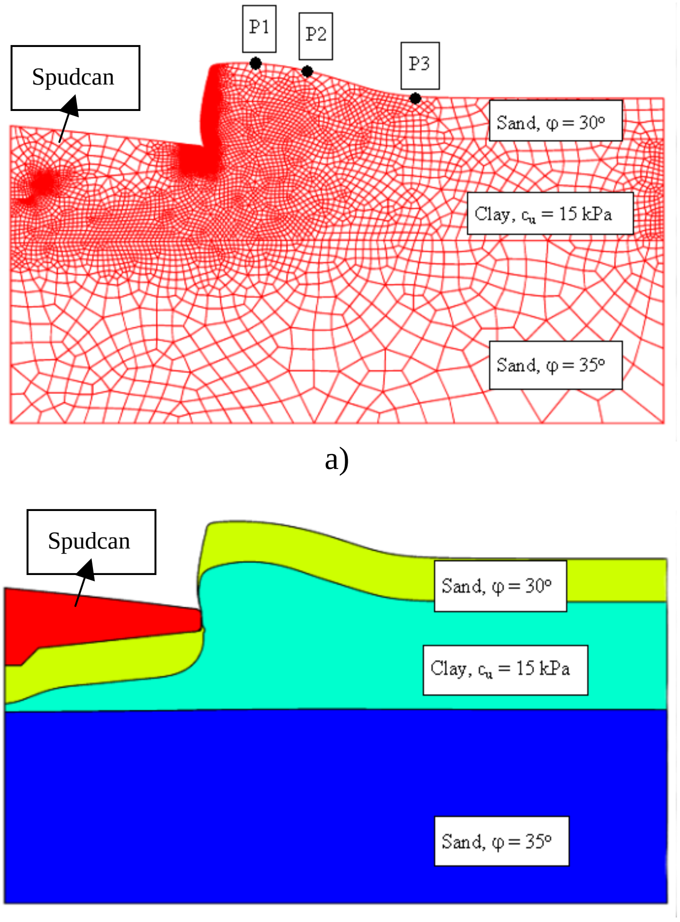
Geostatic stresses and gravity loading are applied to simulate the initial conditions.

Instead of a vertical load, an axial deformation or a rigid body movement is applied to the spudcan axis of symmetry and the reaction forces at the spudcan-soil interface are recorded.

The results of the FE analysis are given in Figure 1 for the lower bound soil profile and Figure 2 for the upper bound one, where the geometry of the soil profiles and the soil strength parameters can be seen. The deformation parameters are evaluated based on authors experience with the soil in the North Sea.

The results consist of deformation pattern and adaptive mesh design given in Figure 1a, 2a and deformed model and material regions Figure 1b, 2b.

As mentioned above, no punch through risk is expected during rig preloading. However, the soil profiles with the soft layer of clay under the sand and the large spudcan penetration makes possible severe squeezing of the soft clay and large soil heave or uplift around the spudcan.



a)

b)

Figure 1. a) Deformed and adaptive mesh, lower bound soil profile
b) Deformed model, material regions, lower bound soil profile

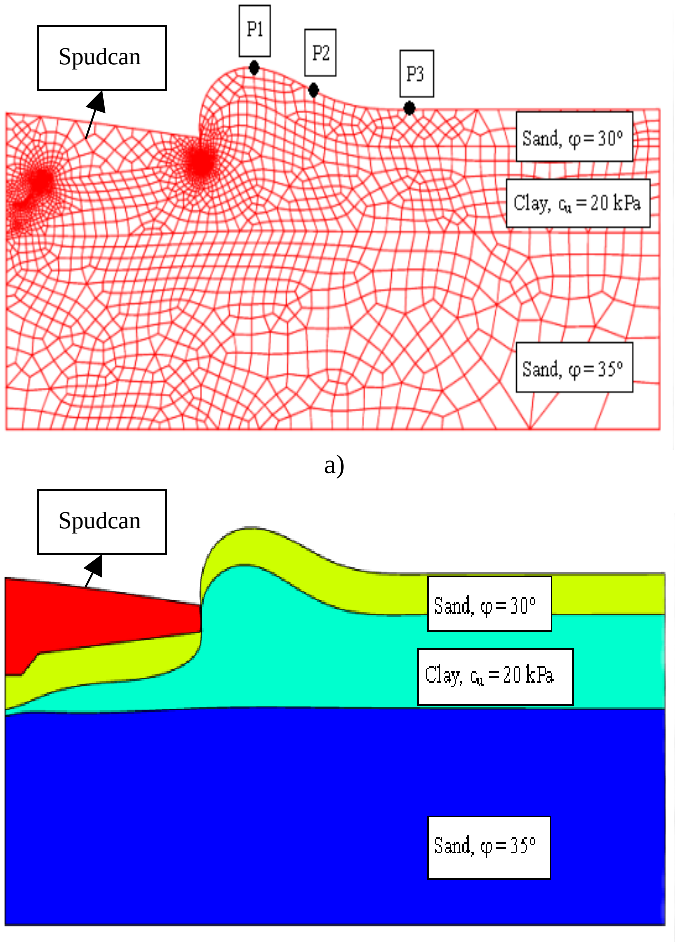
The amount of the soil heave in relation to spudcan penetration can be seen from Figure 1 and 2. For the amount of the spudcan penetrations as given in the above figures, only 39% and 71% of the maximum preloads are applied for lower and upper bound soil profiles, respectively.

Because of the large deformations and especially the geometry of the soil profiles, at a certain spudcan penetration the sand layer is cut off and the clay layer is exposed through the sand and the calculation in Elfen can not further continue for larger preload. This shows a limitation of the program found also in other previous analyses carried out by the authors using Abaqus, and Elfen FE program, Kellezi & Stromann (2003).

There can be different failure mechanisms for the pipeline during spudcan penetration. From the above

2D axisymmetric FE modelling it can be investigated that the soil heave, up-lift or push-up is maximum at the P1 pipeline-spudcan location. For these spudcan penetration levels, the soil push up at the three considered pipeline-spudcan relative positions P1 (2.3 m from the spudcan periphery), P2 (5.0 m), P3 (9.5 m) are 1.8 m, 1.25 m, 0.2 m and 1.7 m, 0.8 m, 0.1 m, for the lower and the upper bound soil profiles, respectively.

As expected, for maximum preload the spudcan should penetrate deeper until it is in contact with the bottom sand layer, giving larger soil push-up evaluated to be over 2.0 m. This means that the pipeline structure, depending on its rigidity is uplifted possibly at that height, approximately along 10 m length, at the location close or tangent to the spudcan.



a)

b)

Figure 2. a) Deformed and adaptive mesh, upper bound soil profile
b) Deformed model, material regions, upper bound soil profile

5 MODIFIED SOIL CONDITIONS DUE TO PREVIOUS RIG INSTALLATION

Considering the results derived from section 4 and the calculated large amount of the soil push-up at the possible pipeline location, a more realistic assessment of the current soil conditions was found necessary. In this framework the history of previous rigs installed at the location is considered.

Using the data from the field, only one rig with skirted spudcans was previously installed in the area, almost at the current position, operating for a period of 1.5 years. The geometrical profile for the skirted spudcan of this rig is given in section 2.

Conventional skirted spudcan penetration analysis was carried out for this rig from the authors, where the same lower/upper bound soil profiles as discussed in section 3 were applied. The predicted spudcan penetration was 4.6 m as upper bound value and 7.0 m as lower bound value. From the field observations the penetration of the spudcan at the position near the pipeline was 4.6 m, which corresponds to the upper bound soil profile.

Considering the observations for skirted spudcan penetration and the time of the rig operation a re-evaluation of the soil conditions is carried out at the spudcan, near the pipeline.

Firstly, the observed penetration of skirted spudcan shows that the lower bound soil profile is very conservative. The upper bound profile seems more realistic although the borehole and the CPT data near the area support more the lower bound data. So, only the upper bound soil profile will be considered further. Secondly, the soft clay layer, which lies under the surficial layer of sand has been consolidated during a period of 1.5 years due to previous rig installation and operation. This fact is taken into account below.

5.1 *Soil consolidation analysis*

The (2D) axisymmetric FE analyses are carried out for the skirted spudcan employing Plaxis FE program, Plaxis V.8.2 (2002). The effect of the previous installation, loading and unloading, in the increase of the soil strength due to the soil consolidation, is investigated. The FE model and the results are given in Figure 3.

A 2D axisymmetric model satisfies the 3D conditions for vertical loading. The initial geostatic stresses are first calculated employing a coefficient of lateral pressure K_0 = 0.5 based on the available data.

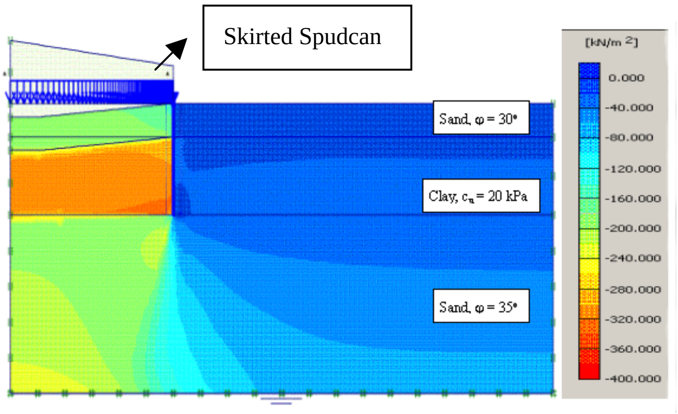


Figure 3. Consolidation analyses mean effective stresses

The spudcan and the skirt are modelled as rigid weightless bodies, with Mohr-Coulomb elasto-plastic constitutive soil model. Drained condition is applied for the sand and undrained conditions for the clay layers.

From the observed spudcan penetration no conclusion can be derived related to the strength of the clay layer. Because of the skirt structure the spudcan can be preloaded to maximum preload if the strength of the clay is c_u = 20 kPa or larger, giving the same penetration, as long as the skirt touches the sand.

The reason is that after full base contact the skirted spudcan behaves as an embedded footing. This is an observation previously carried out by the authors using FE modelling of the skirted spudcans resting on different soil conditions. This is also verified by other authors such as Hu et el. (1999).

The governing equations of consolidation analysis in Plaxis follow Biot's theory. Darcy's law for fluid flow and elasto-plastic behaviour of the soil skeleton are assumed. The formulation is based on the small strain theory.

The skirted spudcan is loaded to maximum preload and unloaded to lightweight load. FE consolidation analysis for lightweight load is carried out until minimum excess pore pressure is reached.

For normally consolidated clays the ratio of the undrained shear strength to the vertical effective stress under which it was consolidated in the field show a close correlation with the Plasticity Index, Bishop & Henkel (1964). A ratio varying between 0.2 to 0.25 is considered based on the authors experience.

This judgment shows that the strength of the soft clay is increased from 20 kPa to approximately 50 to 65 kPa during rig operation. So the upper bound profile is modified increasing the strength of the clay to c_u = 50 kPa (lower bound value) and 65 kPa (upper bound value) designing more realistic soil profiles.

6 2D FE SPUDCAN - PIPELINE INTERACTION, MODIFIED SOIL PROFILES

New conventional and 2D FE calculations are carried out employing the more realistic soil profiles and the current rig spudcan to investigate the soil deformation at the P1, P2 and P3 pipeline spudcan relative positions during spudcan penetration.

The penetration curves calculated for the profile with clay strength c_u = 50 kPa and c_u = 65 kPa are given in Figure 4 where results from the conventional and FE analyses are presented.

The spudcan penetration for c_u = 50 kPa, at maximum preload, is expected to be 3.4 m and the soil push-up 1.5 m (P1), 0.7 m (P2) and negligible for P3 position..

The spudcan penetration for c_u = 65 kPa, at maximum preload, is evaluated about 3.0 m and the soil push-up 1.2 m, (P1), 0.5 m (P2) and negligible for P3 position.

The results from the 2D FE analysis carried out with Elfen in the form of deformed mesh etc. are not listed as they are similar to Figure 1 and 2 with the difference that less spudcan penetration is necessary even for bearing the maximum preload

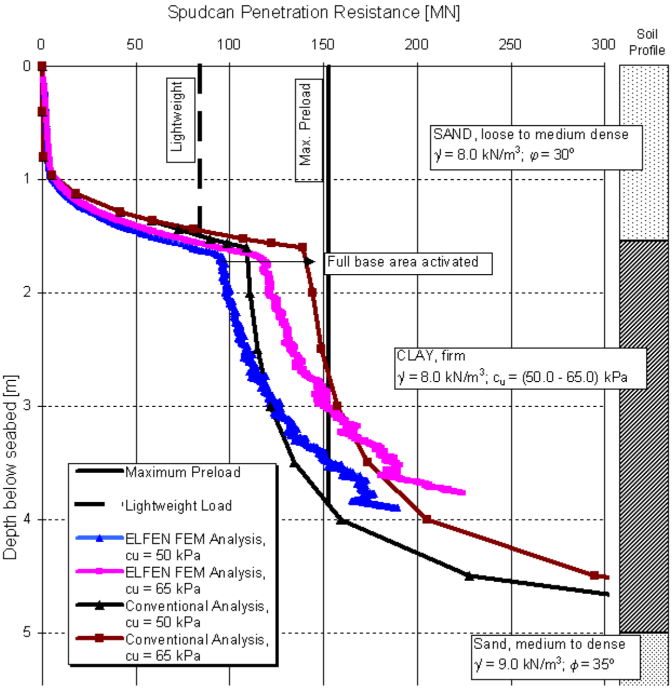


Figure 4. Spudcan penetration curves, more realistic soil profiles

From those results, for the P3 position, distance of about 9.5 m of the pipeline from the spudcan periphery, the pipeline stability should not be effected during spudcan penetration.

However, for the P3 position the spudcan is more close to the CPT, which is used as a basis for deriving the lower bound soil profile. So the spudcan could be placed over non-uniform soil conditions, partly over the consolidated soil from the previous rig installation and partly over the lower bound soil profile. This could cause non-homogeneous penetration for the spudcan to be taken into account during rig instillation.

From the seismic survey and the bathymetry data, shallow depressions or footprint are found in the seabed created due to the previous rig installation and removal. They are not considered critical and are not taken into account in the current investigation.

What happened with the pipeline structure during the partial uplifting along its length is investigated from the 3D modelling of the spudcan - pipeline interaction model presented in the following.

7 3D FE SPUDCAN-PIPELINE INTERACTION MODIFIED SOIL PROFILES

3D FE modelling of the spudcan-pipeline interaction is carried out employing the more realistic soil profiles as elaborated in section 6. One of the discussed pipeline-spudcan relative positions is considered for demonstration. The 5 m distance or position P2 is found more interesting as this is between the P1 position (most critical case) and P3 (safe case). Discussions and comments concerning the other two positions are carried out.

3D FE modelling is carried out with Elfen V. 3.3.0 2001. Explicit dynamic large strain elasto-plastic analysis is chosen different from the 2D axi-symmetric modelling where implicit static calculations were carried out.

In the 3D FE model only a quarter of the spudcan is considered using symmetry conditions. For simplification, the tip of the spudcan of height 0.8 m is removed. So the calculated penetration is corrected with the tip height when the results are interpreted.

The pipeline and the spudcan structures are both modelled. The pipeline is considered 50 % buried in the seabed and is simplified by modelling it as a solid elastic cylinder. The real dimensions of the pipeline, of the coatings and of the covers are taken into account for deriving equivalent elastic properties. In deriving those properties the fact that the covers are separated elements in contact, is taken into account.

In the dynamic analysis spudcan penetration is applied as a displacement pulse. The mass of the system is scaled, so the analysis is reduced to a pseudo-static one. The reason why explicit solution is chosen is that les requirements are regarding computer size and les time is needed for computation in comparison to implicit solution for a 3D modelling.

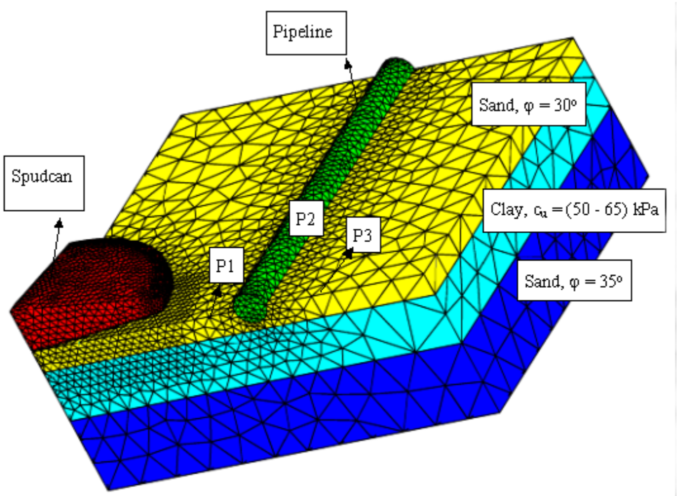


Figure 5. 3D FE model, more realistic soil profiles

As spudcan penetration or the preloading is a symmetrical action regarding soil deformation around the spudcan, only the part where the pipeline is located is considered as shown in Figure 5. Appropriate boundary conditions are applied with this respect. According to this simplification a symmetrical pipeline is assumed to exist on the other side of the spudcan parallel to the considered pipeline and symmetric to the spudcan centre. Although this is not the real situation this will not affect the evaluation of the pipeline-soil-spudcan interaction.

A Coulomb friction contact between the spudcan and soil is modelled. The two contact surfaces are the seabed and the spudcan area. An updated penalty method was used to solve the contact interaction forces. The Coulomb friction contact between the pipeline and soil could not be modelled as several problems raised in the 3D model concerning contact modelling.

The results of the 3D calculations for the more realistic soil profile with clay strength c_u = 50 kPa and c_u = 65 kPa are analyzed. The deformed model with material regions specified is given in Figure 6, only for the case c_u = 65 kPa.

For the considered pipeline position P2 the pipeline structure stability is investigated by the principal stress 1-1, which is maximum at the pipeline length close and tangent to the spudcan. This means that part of the pipeline is working in tension, however not necessarily critical.

The spudcan penetration at maximum preload for soil profile with clay strength c_u = 50 kPa is expected to be 3.4 m referring to spudcan tip. Correcting for the change in the spudcan geometry, this corresponds to 2.6 m penetration in the 3D model.

The spudcan penetration at maximum preload for soil profile with clay strength c_u = 65 kPa is expected to be 3.0 m referring to spudcan tip. Correcting for the change in the spudcan geometry, in the 3D model this corresponds to 2.2 m penetration as seen in Figure 6.

For illustration, the vertical deformations of the different pipeline sections, P2 position, along the y-direction, are given in Figure 7 for both cases of the clay strength values. The differential vertical deformations at y= 0 m, and y=12.5 m for spudcan penetration 2.6 m (the real penetration 3.4 m) is about 0.64 m and for spudcan penetration 2.2 m (the real penetration 3.0 m) is about 0.52 m. These are considered unacceptable. The pipeline deforms also horizontally during spudcan penetration but at a smaller rate.

From the results of the 3D FE analyses, for the pipeline-spudcan distance of about 9.5 m, P3 position, the soil deformation is negligible. This confirms the results derived from the 2D modelling.

The location of the rig, which corresponds to the P3 spudcan-pipeline relative position, was finally chosen in the field and spudcan penetrations of 2.9 m were recorded. No problems with the pipeline structure stability were observed as expected.

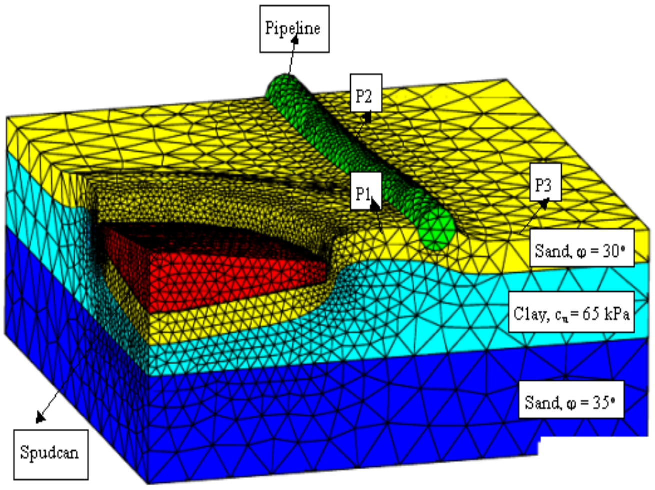


Figure 6. 3D FE model at maximum preload. Spudcan penetration-pipeline interaction

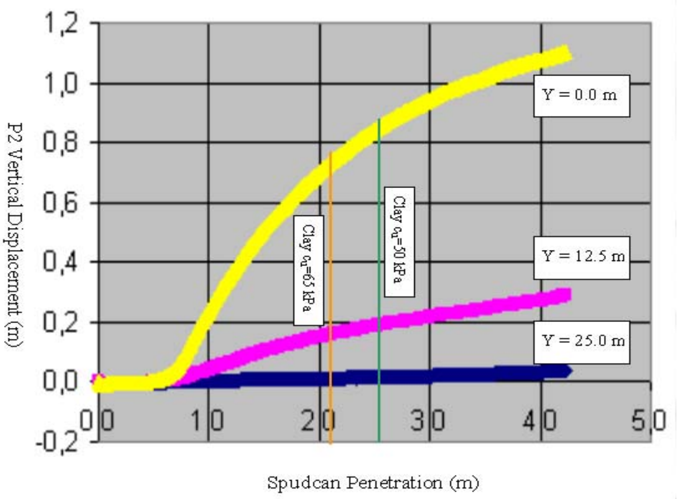


Figure 7. Pipeline vertical displacements at different sections along its length as function of spudcan penetration.

7.1 *Rigid pipeline assumption*

For demonstration purposes and in order to investigate the effect of the pipeline rigidity in the pipeline deformation, a new 3D FE calculation is carried out for the more realistic soil profiles, artificially increasing the pipeline rigidity ten times.

The results showed that the pipeline deformation is much smaller when a rigid pipe is assumed. As the pipe cannot deform very much, the soil moves more relative to the pipeline. This kind of soil deformation and pipeline deformation mechanism cannot absolutely be ruled out as not enough details are known concerning pipeline structure rigidity, however the authors evaluate that this could have been an optimistic evaluation.

8 CONCLUSIONS

2D and 3D FE modelling of the spudcan-pipeline interaction during a jack-up rig installation in the North Sea is carried out. Three possible rig positions are investigated to assess the impact of the spudcan penetration on the pipeline. The history of the previous installation in deriving realistic soil conditions, is accounted.

Parallel to conventional, large deformation analyses with mesh adaptivity are carried out with Elfen FE program.

Although the results of the 2D and 3D model are similar, the 3D modelling is considered the best way to analyze this kind of problem. More research needs generally to be carried out in this area, particularly regarding pipeline-soil contact interaction during spudcan penetration.

9 ACKNOWLEDGEMENTS

The current work is carried out at GEO-Danish Geotechnical Institute. The authors thank ConocoPhillips Norway for supplying with the necessary data and Rockfield Software Ltd for the technical support in FE modelling with ELFEN.

REFERENCES

Bishop, W. A. & Henkel, J. D. 1964. The triaxial test. London Edward Arnold, Ltd.

DNV (Det Norske Veritas) 1992. Foundations Classification Notes No. 30.4. February.

Elfen V. 3.0.4 2001, User Manual, Rockfield Software.

Elfen V. 3.3.0 2001. User Manual Explicit Rockfield Software.

Florkiewicz, A. 1989. *Upper bound bearing capacity of layered soils*. Can. Geotech. Journal. Vol. 26, 730-736.

Ghosh, S. & Kikuchi, N. 1991. *An arbitrary Lagrangian-Eulerian finite element method for large deformation analysis of elastic-visco-plastic solid.* Comp. Meth. Appl. Mech. Eng., Vol. 86, 127-188.

Griffiths, D. V. 1982. *Computation of bearing capacity on layered soils*. Proc. 4th Int. Conf. On Num. Meth. In Geomechanics, Vol. 1, 163-170.

Hansen, J.B. 1970. A revised and extended formula for bearing capacity. Bulletin No. 28. The Danish Geotechnical Institute.

Hu, Y. & Randolph, M.F. 1998. *Deep penetration of shallow foundations on non-homogeneous soil.* Soil and Found. Vol. 38, NO. 1, p. 241-246.

Hu, Y., Randolph, M. F. & Watson, P. G. 1999. Bearing response of skirted foundation on nonhomogeneous soil. Journal of Geotech. and Geoenviron. Eng. Vol. 125, No. 11, 924-935.

Kellezi, L. & Stromann H. 2003, FEM Analysis of Jack-up Spudcan Penetration for Multi-Layered Critical Soil Conditions. Proc. of BGA Intern. Conf. on Foundations, ICOF2003, Dundee, Scotland, 410-420.

Plaxis V. 8.2 2002. User Manual 2D, Delft University Technology and Plaxis BV

SNAME 2002. T&R Bulletin 5-5A. Site Specific Assessment of Mobile Jack-Up Units. The Society of Naval Architects and Marine Engineers.

Sloan, S. W. & Randolph, M. F. 1982. *Numerical prediction of collapse loads using finite element method.* Int. J. Num. Analy. Meth. Geomech. Vo. 6, 47-76.