

# Spudcan Penetration

## FE Simulation of Punch-Through for Sand over Clay

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### Abstract

A theoretical study regarding finite element (FE) modelling of punch-through behaviour for the prototype of a model spudcan penetrating in soil conditions consisting of sand overlying soft to firm clay is carried out. The FE large deformation analyses are performed with the commercial program Abaqus applying Adaptive – Lagrangian - Eulerian (ALE) formulation. Results from published centrifuge tests are used to adjust the FE model correlate the parameters applied and compare the results. The Abaqus model is then updated and used for the engineering assessment of a particular jack-up rig installed at a location of interest. The soil conditions at this location are multi-layered and more complicated. The FE analyses results are compared with the conventional predictions and the field observations.

### Keywords

Conventional analysis, finite element (FE) analysis, centrifuge test, jack-up structure, punch through behavior, failure mechanism, soil plug,

### Introduction

Prediction of the jack-up spudcan penetrations with increasing installation loads is an important issue in the process of rig installation. Unexpected sudden and rapid penetrations or severe differential spudcan settlements can be of major risk for the stability and equilibrium of the jack-up structures.

Classical conventional solutions [1-4], which are applications of bearing capacity equations for homogeneous soil conditions and modified procedures for layered soil profiles, are normally used for spudcan penetration prediction. However, for layered soil condition the modified conventional procedures may not always be sufficiently accurate and realistic compared to field observations. As analytical or conventional procedures have several limitations alternative analyses based on numerical modeling [5-7] are investigated and presented through the years. The conventional analyses are based on classical plasticity theory for sand, clay or layered soil at different levels of spudcan penetration. The numerical analyses are generally based on FE method and consist of large deformation analyses, [8-11].

Conventional spudcan penetration predictions often carried out by the authors have generally shown to be in good agreement with observations during rig preloading in case of homogeneous or layered soil conditions. For

complicated multi-layered profiles the conventional analyses are often combined with FE modeling for a better understanding of the failure mechanism. Large deformation analyses, in which no assumptions have to be made regarding the failure mechanism, are carried out using Abaqus, Standard and Explicit, Elfen and Plaxis commercial programs [12-13] etc. The penetration predictions based on conventional and FE analyses are often verified from the field measurements. They are further developed and improved by back analyses when slight changes existed between the prediction and the observation. In the process of further developing our design methods, a theoretical study regarding FE modelling of the punch-through behaviour for the prototype of a model spudcan penetrating into soil conditions consisting of sand overlying soft to firm clay were recently carried out. The findings are applied in the engineering assessment of a particular jack-up installed at a location of interest. Results from centrifuge testing taken from the literature are used to adjust, correlate and compare the FE results parallel to the conventional prediction.

### Conventional Analysis

The interaction between jack-up spudcans and the seabed soil are commonly analyzed on the basis of assumption of the application of a static vertical load at the centre of an idealized footing. All shallow foundation design is based on two-dimensional (2D) analysis considering the three-dimensional (3D) effect by including empirical shape factors derived from model tests and practical experience.

The conventional analyses GEO applies, among other authors, are mainly based on [14]. Based on many years of experience, for multilayered soil conditions the analyses are further developed and implemented in an in-house program. These analyses satisfy regulations given in [15]. In assessing the bearing capacity of the spudcan in layered soil conditions where punch-through risk exists, two methods of analysis are commonly employed.

1. The projected area method, which uses the concept of an imaginary footing of increased area at the interface between a strong layer and a weaker underlying one. The method is generally applied for sand overlying soft to firm clay as shown in Fig. 1.

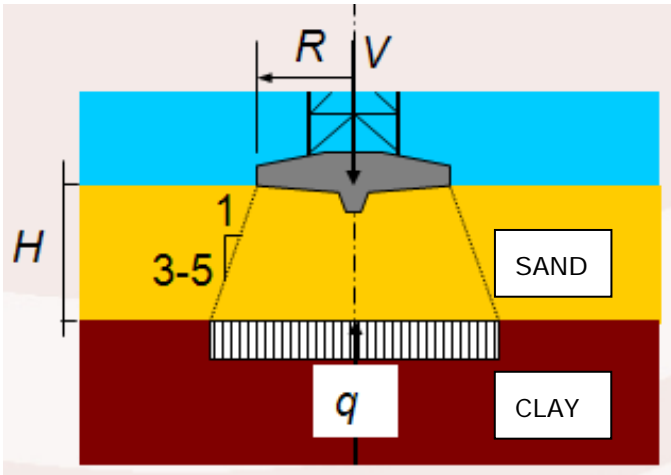


Figure 1 Projected area method, sand overlying clay

2. A vertical punching shear mechanism which uses the concept of an imaginary footing of the same area at the interface between a strong layer and a weaker underlying one, associated with the friction at the interface of the cylinder plug created under the spudcan during the penetration after full base contact. The method is generally applied for stiff or hard clay overlying soft to firm clay as shown in Fig. 2.

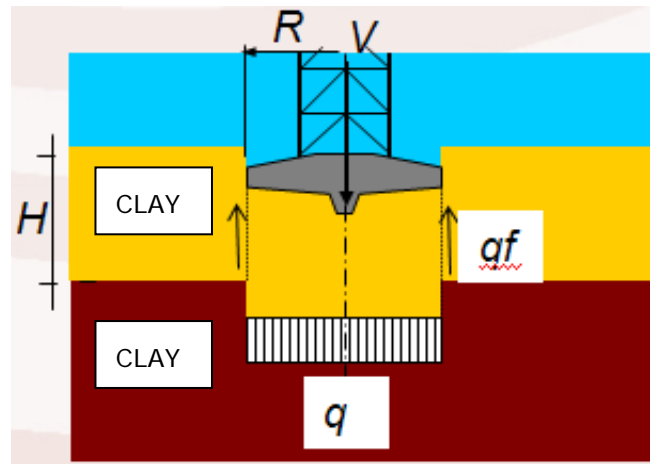


Figure 2, Punching shear mechanism, stiff clay overlying soft to firm clay

In both methods the mechanism involved is generally the lateral squeezing of the confined weaker layer. The punch through potential is associated with sudden rapid increase in spudcan penetration when the bearing capacity is dominated by the weaker layer.

The conventional methods applied in the following parallel to numerical analyses, are developed to partly take into account the geometric distortion of the soil layers and creation of the soil plug below the spudcan during penetration. Soil hardening or softening and remolding are however ignored. The initial stress conditions prior penetration or installations are also not considered. Only soil conditions consisting of sand overlying soft to firm clay and a multilayered variant of this type are elaborated in the following.

## Centrifuge Model Tests

Centrifuge model tests are presented in [16-20], Results from the tests and conventional computations clarify on the mechanisms the spudcan foundation of an independent leg offshore jack-up structure can penetrate deeply into the seabed through both uniform and stratified deposits. Particular consideration is given to the so-called punch-through mode in layered soil profiles, where a strong layer mainly consisting of sand, overlies a weaker one consisting of soft to firm clay.

The series of tests given in [16-17] are carried out on model spudcans of 14 m in prototype diameter installed in dense sand overlying firm clay with constant undrained shear strength. More data regarding these tests are given in the next section where the prototype is chosen for numerical FE analyses. The series of tests given in [19] are carried out on model spudcans of 10 m in prototype diameter installed in Toyoura sand overlying Malaysian kaolin clay. The test results revealed a distinct transition in soil failure mechanism from the overlying sand to soft clay below.

Not sufficient evidence is however found to support the mechanical basis of methods of analyses commonly used in the offshore industry where foundations often have dimensions in excess of (10 – 15) m while conventional laboratory models have rarely exceeded 100 mm. The model tests performed in a centrifuge with stresses comparable to offshore foundations show different mechanisms not accounting for in the analytical predictions. Therefore, the need for alternative analyses supplementing on the existing ones is evident. Where large volumes of soils are displaced during large spudcan penetration, computational analyses should explicitly address the mechanism of soil flowing around the footing and the new reality of the geometry and strength of the soil profile after installation.

## FE Analyses of Punch-Through for Sand Overlying Clay

The results from the centrifuge tests [16-17] for a model spudcan prototype as shown in Fig. 3 on a sand layer overlying soft to firm clay, have been chosen to compare with FE simulations. ABAQUS version 6.6, [21] is employed to carry out the analyses.

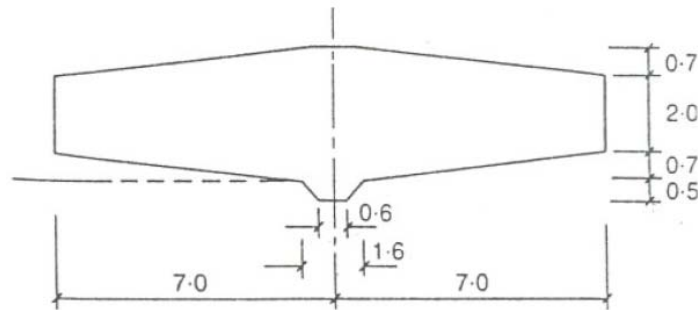


Figure 3, Spudcan prototype geometry applied in the centrifuge test [16] and FE Analyses

The axisymmetric FE model is shown in Figure 4; Thickness of the top sand layer is  $H = 7$  m (half of spudcan diameter); Material data applied for the sand are: Friction angle  $\phi = 38^\circ$ , Effective Unit Weight  $\gamma' = 10$  kN/m<sup>3</sup>, Young Module  $E = 30000$  kPa, Poison Ratio  $\nu = 0.3$ . Material data applied for the underlying CLAY are: Undrained Shear Strength  $c_u = 42$  kPa,  $\gamma' = 7$  kN/m<sup>3</sup>,  $E = 4200$  kPa,  $\nu = 0.459$ .

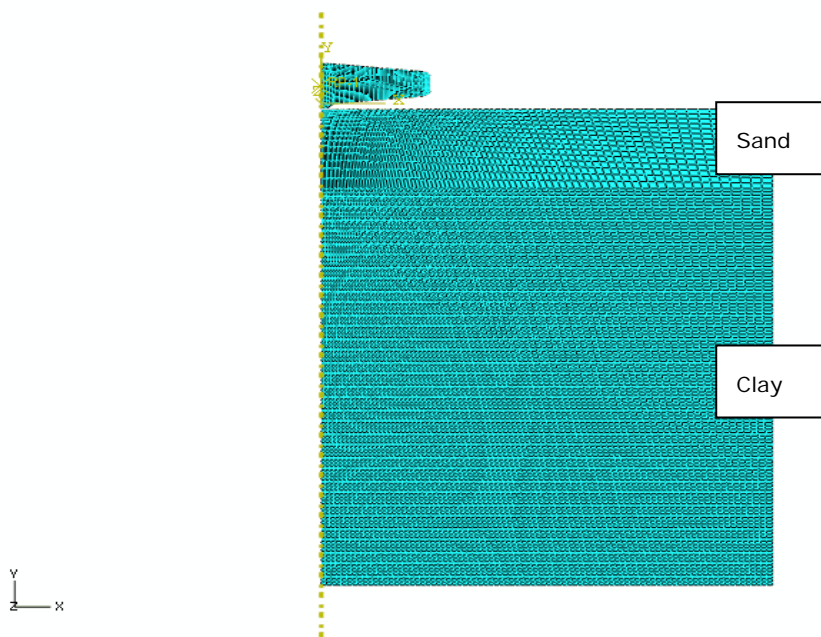


Figure 4, Abaqus FE model at the initial state (the spudcan tip touches the seabed)  
Geometry and FE mesh

The sand layer flow around the spudcan when the spudcan is pushed downwards causing large deformations. Remeshing is required and thus ABAQUS Explicit is chosen for this kind of application due to capacity for adaptive meshing ALE (Adaptive Lagrangian Eulerian). ALE is a tool that makes it possible to maintain a high quality mesh throughout an analysis even when large deformations occur, by allowing the mesh to move independently of the material. This technique in Abaqus Explicit combines the features of pure Lagrangian analysis in which the mesh follows the material, and Eulerian analysis in which the mesh is fixed spatially and the material flows through the mesh.

However, Abaqus Explicit solves the problem as a dynamic approach. The calculation is performed upon the implementation of an explicit integration rule together with the use of diagonal 'lumped' element mass matrices. The equations of motions are integrated using the explicit central difference integration.

Since the sand will flow around the spudcan it is important to have all corners of the spudcan rounded. Reducing the fillet radius implies the need of finer mesh and thus an increase in the calculation time. Abaqus Explicit applies first order rectangular finite elements using reduced integration, except for tetrahedrons and triangles, which however, are not allowed for adaptive meshing. To avoid hour-glassing modes the elements need to use some hour-glassing control factor where the default factor normally is too high. If a too low factor is used the solution becomes unstable. The preferred value is checked by doing analyses with different values, until a reasonable solution is achieved compared to conventional or centrifuge results.

The mesh has to be tuned and the mesh seed is mainly proportional to the fillet radius. Since a quasi-static solution is expected and the ramp displacement is applied slowly, mass scaling is applied for reasonable solution times. A large time step will correspond to solving the problem in a very short time and thus there will be a lot of kinetic energy. Mass scaling in the model is used for computational efficiency. The inertia forces will slightly stabilize the solution therefore, proper mass scaling and loading rate application are important.

For the sand soil a Drucker-Prager model with dilation angle defined to zero or maximum half of the friction angle is applied. To minimize the shear stiffness the cohesion has been chosen as low as possible. For the clay soil the 'Mises' plasticity model has been applied. No rate dependent softening is accounted for.

Despite the spudcan-sand interface modelling, to avoid unwanted deformations one node in the spudcan has been tied to the corresponding node in the sand. Since the spudcan is much stiffer than the sand, the spudcan node is defined as the master node. To save some computer time the spudcan is considered a rigid body and displacement is applied as 'Boundary, Amplitude = ramp' investigating different time periods under step 'Dynamic, Explicit'.

The models are validated in the sense that Abaqus can closely converge to conventional bearing capacity solutions [14] of footings and spudcans on homogeneous clay and sand soil profiles. Some comparisons with centrifuge results for homogeneous soil are also made. However, there are differences between conventional solutions and conventional and centrifuge measurements for sand and clay soils.

Typical penetration curves from different FE modelling and results are shown in Fig. 5. Comparison of the results from the conventional analysis, the centrifuge test and Abaqus FE analysis are given in Fig. 6. The conventional analysis, which is based on [14-15] and the gathered experience with penetration predictions, shows lowest bearing capacity.

Abaqus FE analyses gives slightly lower bearing capacity compared to the centrifuge test results. However, some extrapolation is involved in prototype engineering when using the results from the centrifuge tests. When footing size is large as in the case of jack-up spudcans, then data extrapolated from centrifuge tests on model footings can be erroneous. The centrifuge tests show clearly that the self-weight and resulting stiffness of an upper sand layer are significant parameters in the determination of the punch through mechanism.

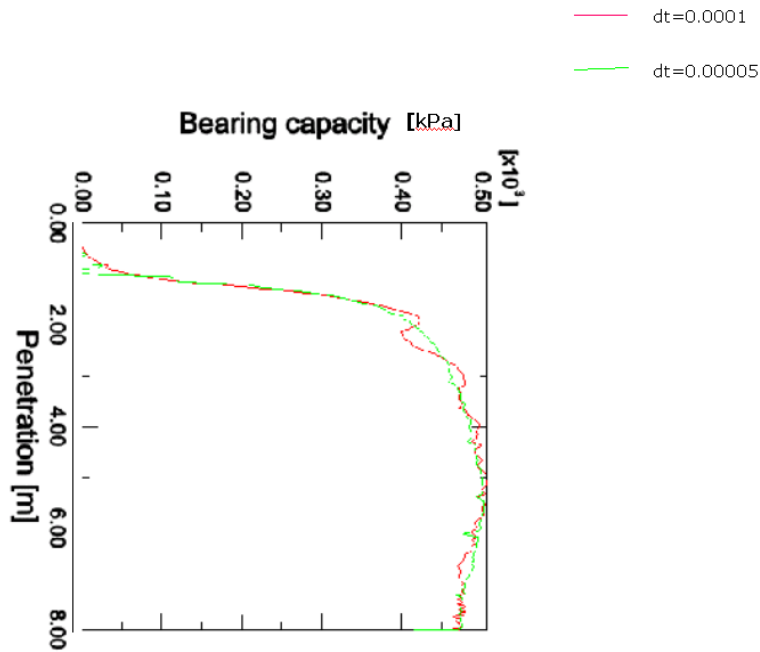


Figure 5, Abaqus FE spudcan penetration curves for different time steps

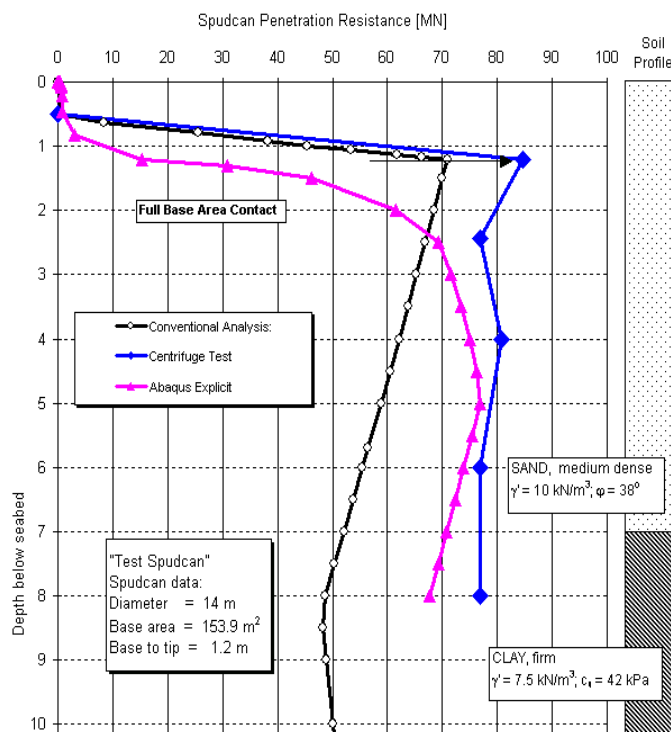


Figure 6, Conventional, centrifuge and Abaqus FE spudcan penetration curves

Total displacements from the Abaqus FE modelling are given in the Fig. 7. Other results like Mises strains are given in Fig. 8 and equivalent plastic strains in Fig. 9.

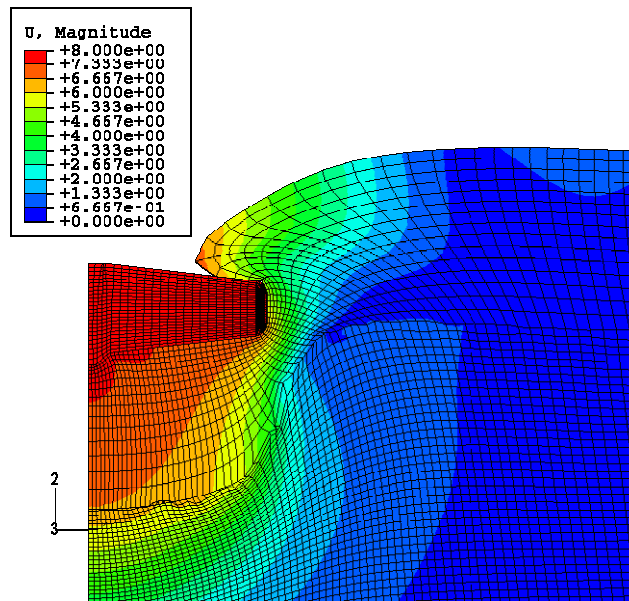


Figure 7, Abaqus FE analysis, total displacement  $U$

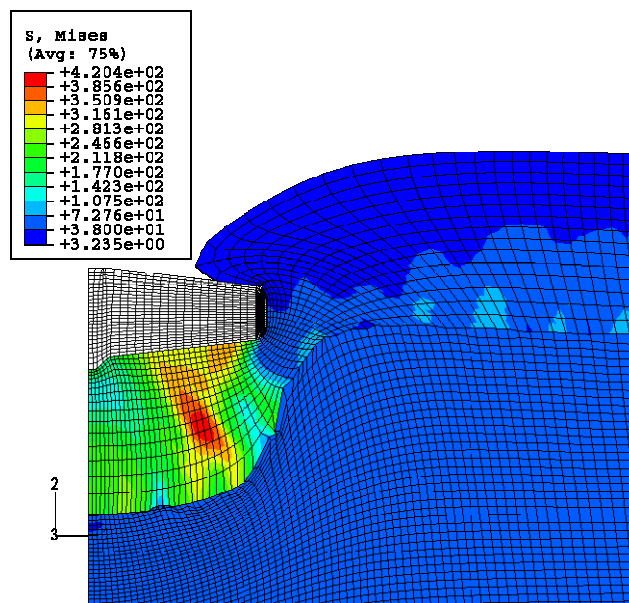


Figure 8, Abaqus FE analysis, Mises strains  $S$

Based on the results achieved from the FE modeling it can be concluded that the spudcan punch-through behavior can more or less be simulated with Abaqus Explicit when considering: The mesh needs to be fine enough, to follow the geometry around the spudcan. The spudcan has to have rounded corners. The default hourglassing factor is normally too high for this application and should be reduced. Mass-scaling required having reasonable solution times should be used with care. Variable mass scaling is applied in the current analyses with time step as shown in Fig. 5. Adaptive mesh is important, at least for the layers closest to the spudcan. Distortion control might be helpful, can't, however, be used in regions with adaptive meshing. Cohesion for the sand should be as low as possible. Displacement rate effect should be considered applying different time periods.

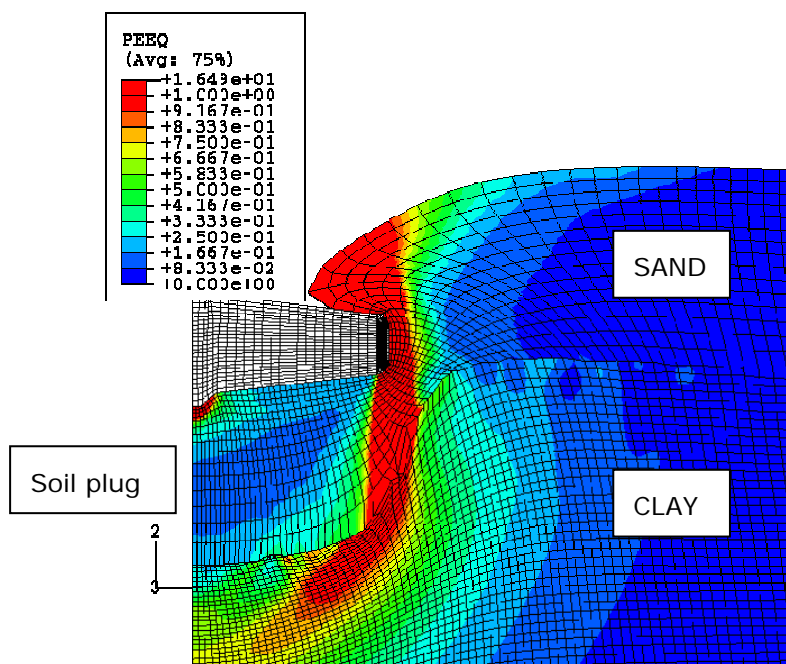


Figure 9, Abaqus FE analysis, equivalent plastic strain, PEEQ

From the FE analyses carried out with Abaqus Explicit it can however, be concluded that modelling of spudcan punch-through behaviour for a soil profile consisting of sand over soft to firm clay is not a easy issue. Abaqus is an option, but the results will particularly depend on the mesh and other parameters applied and should be interpreted from an experienced engineer. Considering the program limited capacity with regard to mesh update, further investigation is needed applying Eulerian formulation.

## FE Analysis of Spudcan Penetration at a Considered Location

The FE Abaqus model constructed above in comparison to results of centrifuge tests is applied as part of a jack-up rig spudcan penetration prediction at a location of interest. The soil conditions at the location are determined based on the results of the seismic survey and geotechnical investigation carried out. Using the available bore-hole, laboratory tests and cone penetration tests (PCPT) data and considering the uniformity of the soil conditions one generalized lower and upper bound soil profile is assessed applicable for the jack-up engineering assessment.

The soil profile at the spudcan locations consist of a deep very soft clay layer from the seabed to about 7.5 m depth followed by a layer of loose sand overlying clay layers with varying strengths with depth..The lower and upper bound soil profiles and soil parameters applied in the conventional penetration analyses are shown in Fig. 10 and the profile and parameters applied in the Abaqus FE analyses are shown in Table 1 and Fig. 11. The conventional analysis starts with the spudcan tip in contact with the seabed very soft soil. The FE model due to complexity of the soil conditions is simplified by starting the analysis with the spudcan tip in contact with the sand layer at 7.5 m depth and assuming the weight on the upper very soft clay as a distributed load over the sand. A more layered profile is derived for the FE analysis for the clay soil underlying the sand compared to the conventional method due to flexibility of the FE technique.

Some restriction applies to both methods of analyses, analytical and numerical. The main uncertainty is the implementation of the backflow while the penetration increases. To avoid this uncertainty both analyses are carried out ignoring the backflow for comparison. The results of FE analyses in comparison to the conventional one,

(not accounting for backflow), are given in Fig. 10 where the observed measurement during installation (which are influenced by the soil backflow) are also included.

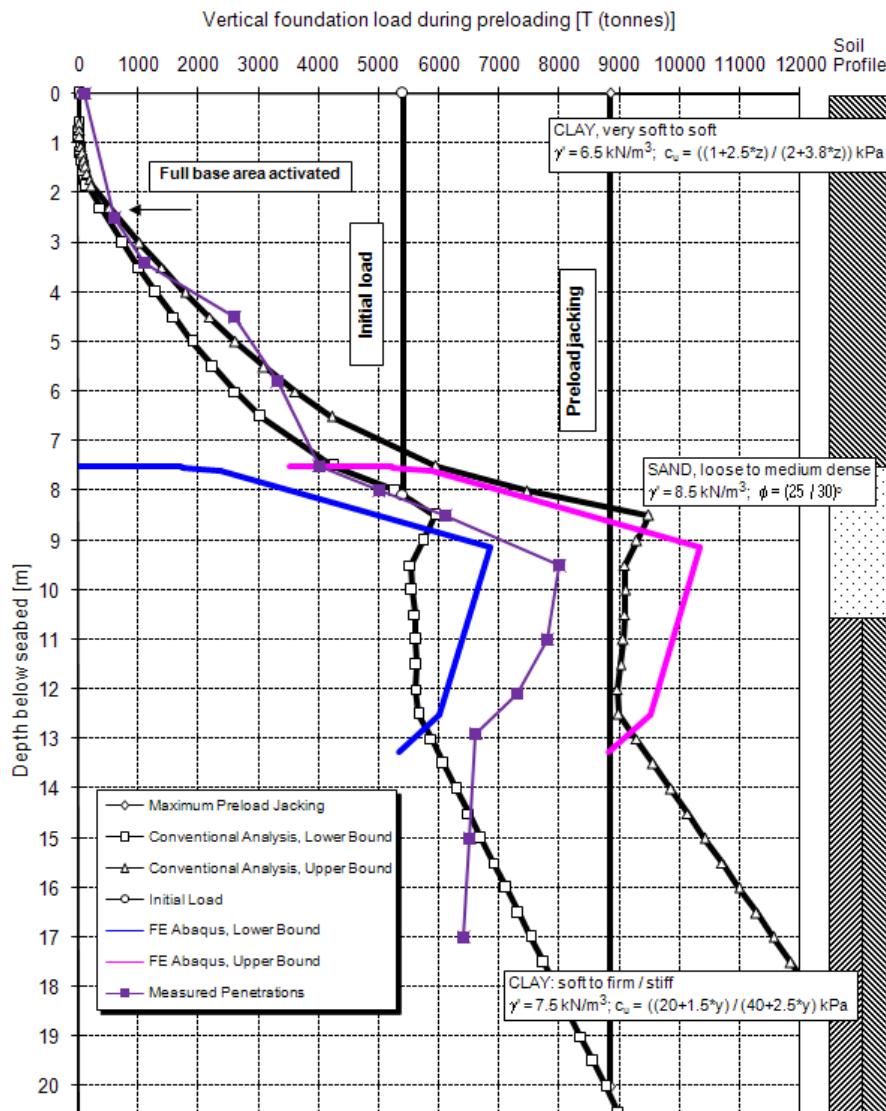


Figure 10, Conventional and FE spudcan penetration predictions (no backflow assumed) and measured penetrations (effected by the backflow)

Table 1, generalized soil profile with lower and upper bound soil parameters applied in the Abaqus analyses

Soil Type	Depth of Layer (m)	Unit Weight $\gamma'$ (kN/m <sup>3</sup> )	Undrained Shear Strength $c_u$ (kPa)	Angle of Friction $\phi$ (°)	Deformation Module E (kPa)
Pressure over the sand layer $7.5 \times 6.5 = 48.75 \text{ kPa}^*$					
Sand, loose	7.5 – 10.5	8.5	-	25 / 30	30000
CLAY, soft to firm	10.5 – 22.0	7.5	28 / 38	-	5700
CLAY, firm	22.0 – 26.0	7.5	42 / 56	-	8400
CLAY, firm	26.0 – 31.0	7.5	52 / 69	-	10400
CLAY, firm to stiff	31.0 – 42.0	7.5	65 / 86	-	13000

\*The seabed clay layer is modelled as load pressure over the sand layer.

The differences between the conventional and numerical penetration curves given in Fig. 10 are also influenced from the fact that soil conditions are implemented in different ways. Other results from the FE analyses like

deformed mesh during penetration and maximum and minimum principal plastic strains are given in Fig. 11 – 14.

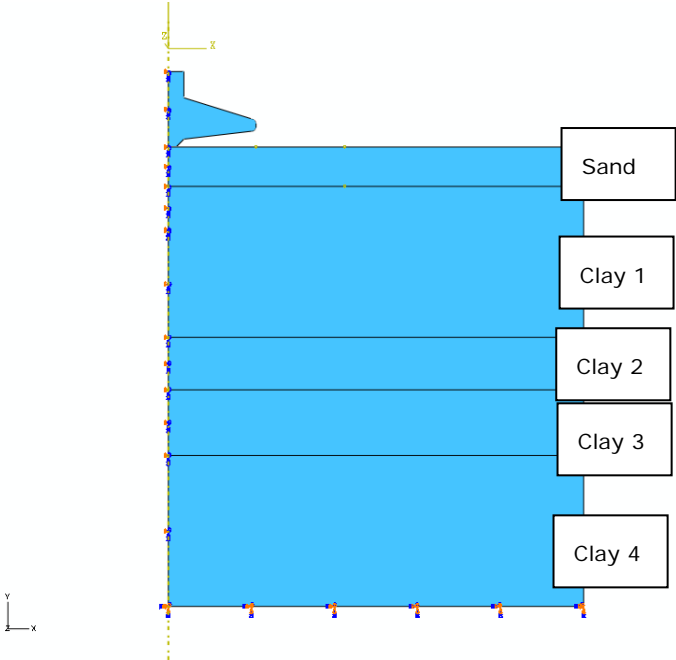


Figure 11, FE Abaqus model for generalized lower and upper and bound soil profile

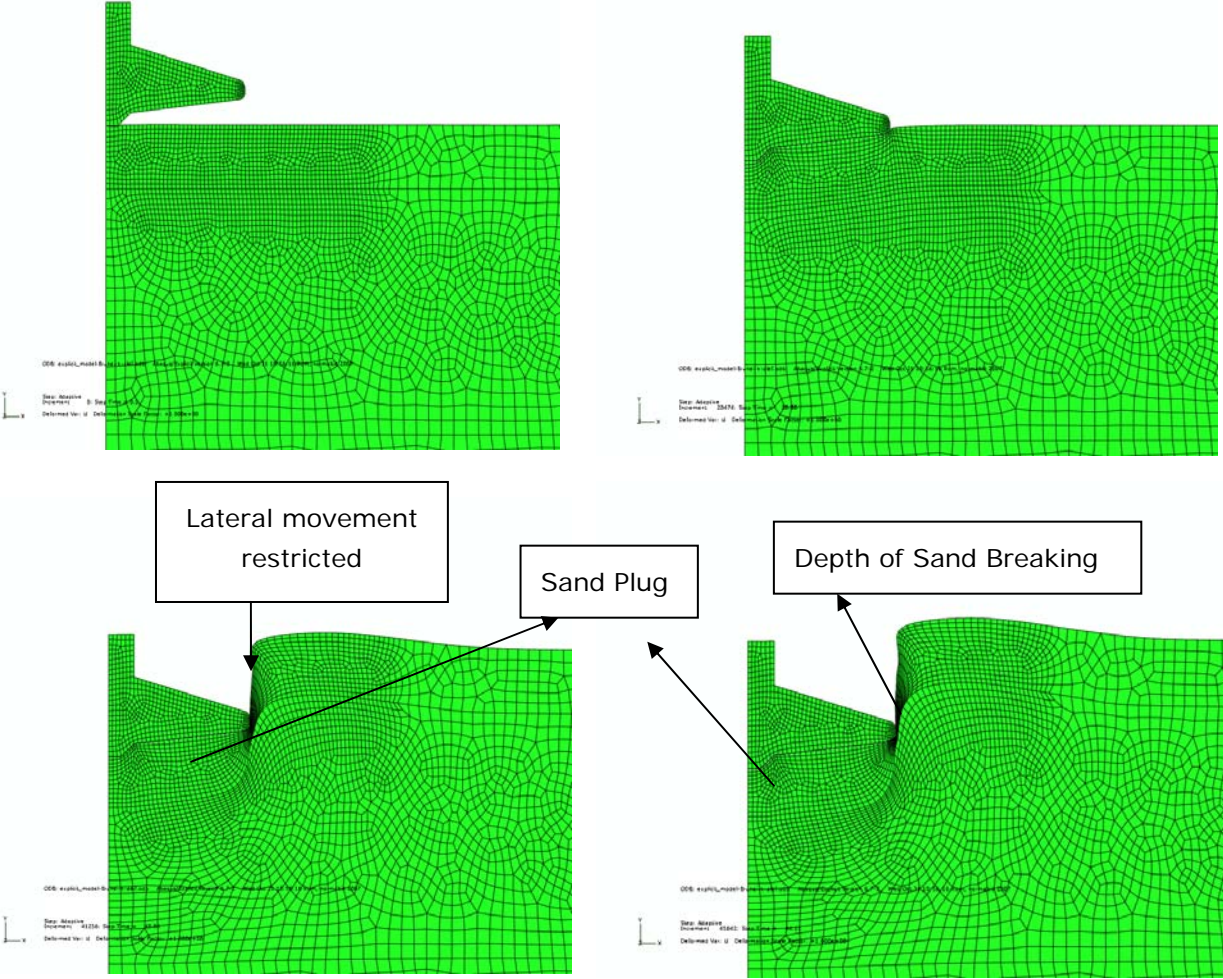


Figure 12, FE Abaqus model mesh deformation during spudcan penetration

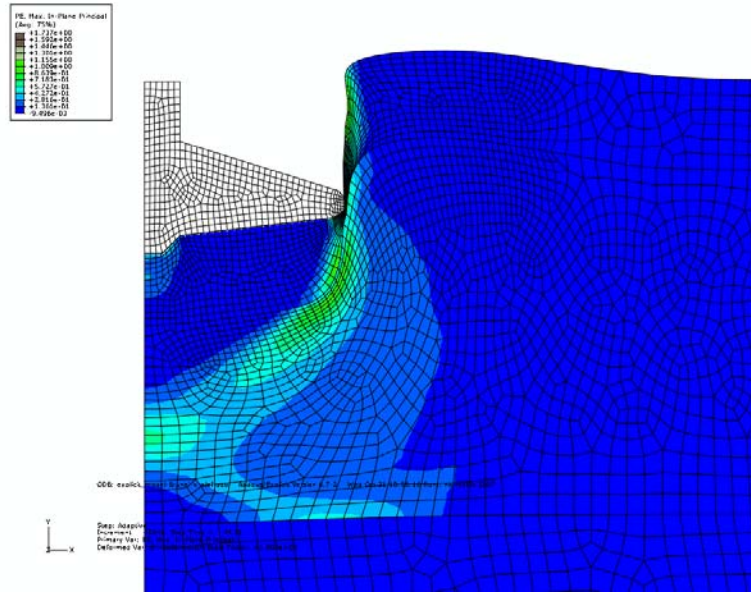


Figure 13, Failure figures (maximum principal plastic strain PE) at maximum calculated penetration

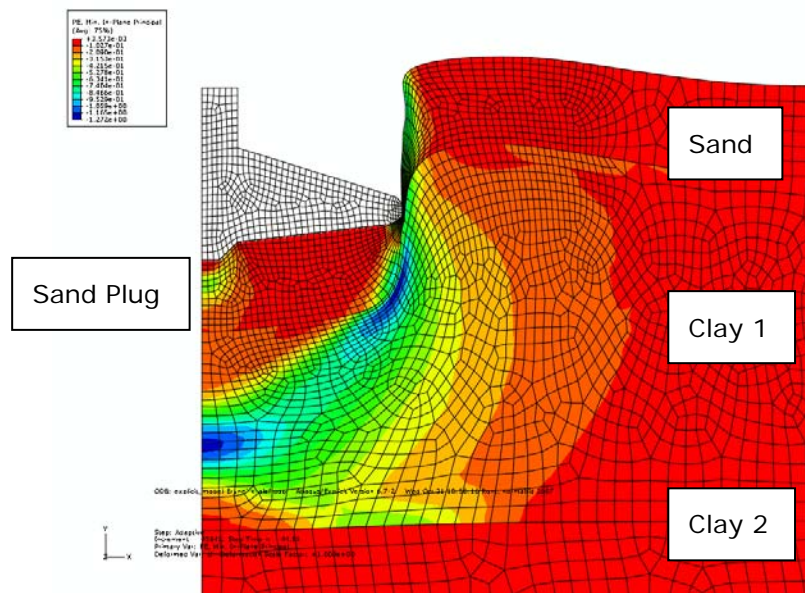


Figure 14, Failure figures (minimum principal plastic strain PE) at maximum calculated penetration

## Conclusions and Recommendations

FE modelling with Abaqus of punch through simulation for a model prototype spudcan in comparison to centrifuge test results and conventional analysis are carried out. The application of the model for a jack-up installation at a particular site seems to give promising results. However, more investigation is needed with regard to all the modelling parameters applied in Abaqus and discussed through this paper. Based on the authors experience, for engineering application purposes alternative modelling of the spudcan penetration is recommended. The different methods, conventional and numerical applied from the office, or centrifuge tests from the laboratory complete each other and give the background for reasonably accurate solutions, which often compares well with the field observations.

## Acknowledgement

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## References

- /1/ Hanna, A. M. and Meyerhof, G. G. *Design charts for ultimate bearing capacity of foundations on sand overlying clay*. Canadian Geotech. Journal, Vol. 17, 300-3003, 1980
- /2/ Georgiadis, M. and Michalopoulos, A. M. *Bearing capacity of gravity bases on layered soil*. J. of Geotech. Eng. Vol. 111, No. 6, 712-727, 1985
- /3/ Florkiewicz, A. *Upper bound to bearing capacity of layered soils*. Can. Geotech. J. Vol. 26, 730-736, 1989
- /4/ Michalowski, R. L. and Lei S. *Bearing capacity of footings over two layer foundation soils*. ASCE, J. of Geotech. Eng. Div., Vol. 121, No. 5, 421-427, 1995
- /5/ Griffiths, D. V. *Computation of bearing capacity on layered soils*. Proc. 4<sup>th</sup> Int. Conf. On Num. Meth. In Geomechanics, Vol. 1, 163-170, 1982
- /6/ Sloan, S. W. and Randolph, M. F. *Numerical prediction of collapse loads using finite element method*. Int. J. Num. Anal. Meth. Geomech. Vo. 6, 47-76, 1982
- /7/ Merifield, R.S., Sloan, S.W. and Yu, H.S. *Rigorous plasticity solutions for the bearing capacity of two-layered clays*. Geotechnique, Vol.49, No. 4, p. 471-490, 1999
- /8/ Ghosh, S. and Kikuchi, N. *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, 1991
- /9/ Hu, Y. and Randolph, M.F. *A practical numerical approach for large deformations problems in soil*. Int. J. Anal. Meth. Geomechanics, Vol. 22, 327-350, 1996
- /10/ Hu, Y. and Randolph, M.F. *Deep penetration of shallow foundations on non-homogeneous soil*. Soil and Found. Vol. 38, NO. 1, p. 241-246. 1998
- /11/ Wang, C. and Carter, J. *Deep penetration of strip and circular footings into layered clays*. Research Report No. R807 Centre for Geotechnical Research. The Univ. of Sydney., 2001
- /12/ Kellezi L. and Stromann, H. *FEM Analysis of Jack-up Spudcan Penetration for Multi-Layered Critical Soil Conditions*. Proceeding of BGA Int. Conf. on Foundations, ICOF2003, Dundee, Scotland, 410-420. 2003
- /13/ Kellezi, L. Kudsk, G. and Hansen, P. B. *FE Modelling of Spudcan – Pipeline Interaction*, Proceedings, Frontiers in Offshore Geotechnics, ISFOG 2005, September, Perth, Australia, page 551 – 557, 2005
- /14/ Hansen, J. B. *A revised and extended formula for bearing capacity*. Danish Geotechnical Institute, Bull. 28, 1970
- /15/ TR Bulletin 5-5A. *Site specific assessment of mobile jack-up units*. 1st Edition. The society of Naval Architects and Marine Engineers, 1994
- /16/ Craig, W. H. and Chua, K. *Deep penetration of spudcan foundation on sand and clay*, Geotechnique 40, No. 4, page 541 – 556, 1990
- /17/ Craig, W. H. and Chua, K. *Large displacement performance of jack-up spudcans*, Centrifuge 91, Balkema, Rotterdam, page 139 – 144, 1991
- /18/ Kenny, M. J. and Andrawes, K. Z. *The bearing capacity of footings on a sand layer overlying soft clay*, Geotechnique 47, No. 2, page 339 – 345, 1997
- /19/ The, K. L. Leung C. F. and Chow, Y. K. *Spudcan penetration in sand overlying clay*. Frontiers in Offshore Geotechnics, ISFOG – Gourvenec & Cassidy(eds), page 529 – 534, 2005
- /20/ The, K. L. Cassidy M. J. Leung C. F. Chow, Y. K. Randolph M. F. *Revealing the bearing failure mechanism of a penetrating spudcan through sand overlying clay*. Geotechnique 58 (10), page 793 – 804, 2008
- /21/ Abaqus Explicit, User Manual, Version 6.6 and 6.7