# FEM analysis of jack-up spudcan penetration for multi-layered critical soil conditions

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## Introduction

Mobile jack-up drilling platforms are used extensively in offshore exploration of oil and gas at water depths up to 150 m. The foundation at the seabed level of this kind of offshore structure can be based on the plate, single foundation concept, or independent (normally three) footings foundation concept.

The first type is usually used when very soft soil conditions dominate in the seabed and the second type when there are varying soil conditions. In the last situation, the footings of the single jack-up rig legs, which approximate inverted cones, are called spudcans. Sometimes skirt structures are mounted at the outer perimeter of the spudcans to avoid scour and erosion potential.

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

Initially classical conventional analyses [1-4], which are applications of bearing capacity equations for homogeneous soil conditions and modified procedures for layered soil conditions, are normally used for penetration prediction.

However, for multilayered critical soil profiles the modified conventional procedures seem to be generally unrealistic. It is well-known that these analytical procedures have several limitations.

For these reasons alternative analyses based on numerical modeling, [5-7] are investigated and presented. Spudcan penetration analyses are carried out and presented here analytically and numerically for a jack-up rig structure founded in multi-layered critical soil conditions in the North Sea.

The conventional analysis is based on classical plasticity for sand, clay or combined soil profiles at different levels of spudcan penetration. The numerical

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analyses are based on finite element method, FEM, (Abaqus, Elfen) and consist of large deformation analyses, [8-11].

Conventional spudcan penetration predictions often carried out by the authors have shown to be in good agreement with observations during rig loading in case of rather homogeneous soil profiles. However when complicated multi-layered profiles are encountered FEM modeling has been needed.

Large deformation analyses in which no assumptions have to be made about the failure mechanism, are carried out using Abaqus Standard and Explicit and Elfen FEM programs.

Considering the available soil parameters different constitutive soil models are used. Effective stress analyses are carried out. The spudcan foundations are modeled based on the real geometry and the non-linear soil-spudcan-interaction during penetration is modeled. Abaqus Explicit and Elfen, which have the capability of mesh adaptivity, are used when large penetrations are expected.

Our FEM design procedure is verified by classical plasticity solutions for rather homogeneous soil conditions and by monitoring results for complicated multi-layered critical profiles. Possible punch through, rapid penetration or squeezing failure is investigated based on the failure mechanism.

## Conventional spudcan penetration 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 2D analysis considering the 3D effect by including empirical shape factors derived from model tests and practical experience. Our conventional analysis is based on [12] which for multilayered soil conditions is further developed based on the new experiences. This analysis satisfies regulations given in [13].

In assessing the performance of the spudcan in layered soil strata where punch-through might be a possibility, two methods of analysis are commonly employed. The projected area method which uses the concept of an imaginary footing of increased size at the interface between a strong stratum (sand) and a weaker one beneath. However a near vertical punching shear mechanism might dominate for a strong clay stratum over a soft clay layer.

The conventional methods take no account of the geometric distortions of the soil layers during substantial penetration. Soil hardening/softening and remoulding are ignored. The initial stress conditions with penetration increase is also not considered.

For layered soil profiles there are generally two main situations: soft soil over stiff soil, stiff soil over soft soil or a combination of more than two layers alternating stiff and soft soil.

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

For the present spudcan-soil model described in the following section, analytical solution is derived first. The penetration versus vertical load curve is given in Figure 1 together with the results of the numerical analyses. From the penetration curve the conventional analysis shows a potential for punch through for the current situation.

## Abaqus FEM analyses of spudcan penetration

FEM analyses are carried out for a typical spudcan foundation during rig preloading at an oil field in the North Sea, British Sector.

First a soil profile at the actual location is determined from the relevant boreholes, CPT's and laboratory tests. The analysis was considered necessary as the above conventional analysis showed critical and possibly conservative results. An upper bound and a lower bound soil profile were considered. Only the results of the lower bound profile are presented in this paper.

An axisymmetric model for the soil and the spudcan, which for vertical loading can accurately represent the 3D problem, is used. Large penetrations are modeled in Abaqus Standard and Abaqus Explicit, which take into account geometrical non-linearity and the last one in some way mesh adaptivity.

### Soil modeling

The soil conditions at the location are determined from two boreholes with CPT‘s, nine CPT's and triaxial laboratory testing. The investigations show rather uniform profiles with an upper layer of very soft clay. Below this at depths between 6.8 and 9.8 m medium dense to dense sand is found. The sand layer, which has a thickness between 5.9 and 10.8 m, is at depths varying between 13.7 and 17.6 underlain by firm to stiff clay until approximately 37 m below seabed.

Among other profiles the soil profile given in Table 1 is derived from the results of the geotechnical investigations and considered with respect to spudcan penetration. The elastic parameters for sand and clay are derived based on our experience. At this location the water depth is about 119 m. An effective stress analysis is carried out and effective unit weight of the layers is used.

The penetration through the first, very soft clay layer of 7.0 m thickness at the seabed is calculated first and when the foundations touch the second layer, the sand layer, the top clay layer is excluded from the FEM model and replaced by a distributed load over the sand.

The reason for this modification is that the strength of the top clay layer is very small and rapid penetration occurs for small preload values. This gives extremely distorted finite elements, which can no longer model the field. So in the second-phase the model contains three different soil layers, which are sand - clay - clay.

Table 1 Calculation soil profile

| Soil Type | Depth of Layer (m) | Unit Weight $\gamma'$ (kN/m$^3$) | Angle of internal friction $\varphi$ (°) | Undrained shear strength $c_u$ (kN/m$^2$) |
|---|---|---|---|---|
| CLAY, very soft | 0 - 7.0 | 7 | - | 5 |
| SAND, medium dense to dense | 7.0 - 13.7 | 10 | 33 | - |
| CLAY, firm to stiff | 13.7 - 22.5 | 8 | - | 50 |
| Clay, stiff to very stiff | 22.5 -30.0 | 8 | - | 100 |

As a first order approximation and considering the available soil parameters a Mohr Coulomb (MC) elastic-plastic constitutive soil model was formulated for sand and clay layers. Based on the same parameters extended Drucker Prager (DP) parameters for sand and von Mises (Plastic) parameters for clay were derived and used in the final FEM calculations. The MC model assumes that failure is independent of the value of the intermediate principal stress, but the DP model does not.

The DP model is used to model frictional materials, which exhibit pressure – dependent yield, (the material becomes stronger as the pressure increases). This allows the material to harden and volume change with inelastic behavior. The flow rule defining the inelastic straining gives simultaneous inelastic dilation and inelastic shearing.

The E-modulus for clay is taken approximately $E = 200*c_u$ where $c_u$ is the undrained shear strength. Poisson’s ratio $\nu = 0.495$ is used. For sand $E = 4*q_c$, where $q_c$ is the tip resistance from the CPT data, and Poison’s ratio $\nu = 0.3$. The dilatation angle for sand is calculated $\psi = \varphi - 30°$ for $\varphi > 30°$ and $\varphi = 0°$ for $\varphi < 30°$ for the MC models, where $\varphi$ is the friction angle. The DP model was derived from the MC model, [14-15]. Elementary boundary conditions are placed far enough from the foundation not to effect its plastic behavior.

## Spudcan modeling

The spudcan foundation is modeled based on the real geometry. It consists of an approximated inverted cone with maximum diameter about 18.0 m and height of tip to full base 1.6 m. It is considered to behave elastically and high values of E-module, steel material, is assigned.

The two axisymmetric parts (the ‘soil’ and the ‘spudcan’), are modeled first separated and then assembled together in the initial phase. In this phase the spudcan is considered weightless and is placed over the top clay layer, level 0.0 m, with the spudcan tip in contact with this layer.

### Spudcan-soil interaction modeling

‘Contact pair’ models the non-linear soil-spudcan-interaction during penetration. The bottom spudcan area is modeled as ‘Master Surfaces’ and the sea bottom area is modeled as ‘Slave Surface’.

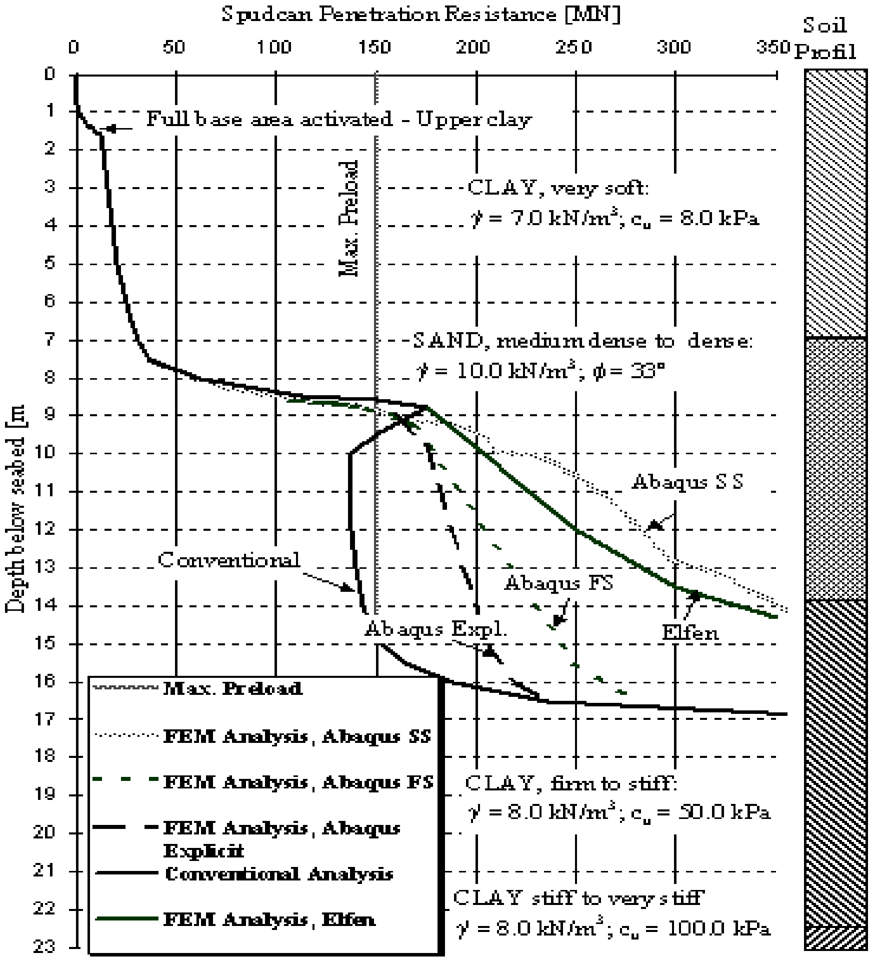

Figure 1 Soil resistance versus penetration, conventional and FEM solutions

For Abaqus Standard calculations ‘Small Sliding, SS’ formulation was used first, followed by the ‘Finite Sliding, FS’ formulation, [14]. ‘FS’ formulation allows for arbitrary separation, sliding and rotation of the surfaces in contact. The ‘SS’ formulation assumes that the surfaces may undergo arbitrary large rotations but that a ‘Slave Node’ will interact with the same local area of the ‘Master Surface’ throughout the analysis.

A friction coefficient with value f = 0.6 is used for the tangential behavior between the spudcan contact surface and soil, based on the parameters of the soil layer in contact. An elastic slip of 0.005 m is defined.

## Calculations and results

To accurately investigate large deformation effects on the amount of penetrations different models were built up in Abaqus Standard, which take into account geometrical nonlinearity.

As an alternative, Abaqus Explicit, which except geometrical nonlinearity has also some capabilities of, ‘Mesh Adaptive Techniques’, [15], is used as well when the solutions given by Abaqus Standard differ for different contact modeling.

Adaptive meshing 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, [8-11].

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).

This type of adaptive meshing is often referred as Lagrangian-Eulerian (ALE) analysis. ALE can be applied to the entire model or to the individual parts of the model, as for example only to the first layer of the soil. For the current analysis ALE was applied to the sand and the underlying clay layer.

Calculation with Abaqus Standard model is a general static calculation. It starts with the initial state where the initial stress field is determined. Then it continues with the loading steps. The load is applied as a concentrated force at the spudcan axis of symmetry.

Abaqus Explicit calculation model is based upon the implementation of an explicit integration rule together with the use of diagonal ‘lumped’ element mass matrices. The equations of motion are integrated using the explicit central difference integration. Mass scaling, in the entire model is used for computational efficiency, as the current analysis is a quasi-static one.

The results of the Abaqus calculations showed no risk of punch through. The spudcan penetration curves are given in Figure 1. Standard calculations with ‘SS’ and ‘FS’ differ much from each other at high load levels. For this reason Explicit calculations, which use balanced contact, are carried out as well. Standard calculation with ‘SS’ might underestimate the amount of penetration for load levels over the preload. However Standard ‘FS’ and Explicit calculations seems to give a more similar prediction for large vertical loads. So a penetration of 8.6-8.8 m is expected for maximum preload, however a rapid penetration should be expected for slightly increase of the preload.

The total amount of penetrations is calculated directly from the penetration curves. Results of the deformations given in meters, (U2 deformation in the z-direction) and equivalent plastic strain (PEEQ) for the whole model, at different levels of the applied loads are given in Figures 2-5.

Considering some possible uncertainties in defining the soil profile and Abaqus varying results with respect to interface modeling, calculation of the same model in Elfen was considered.

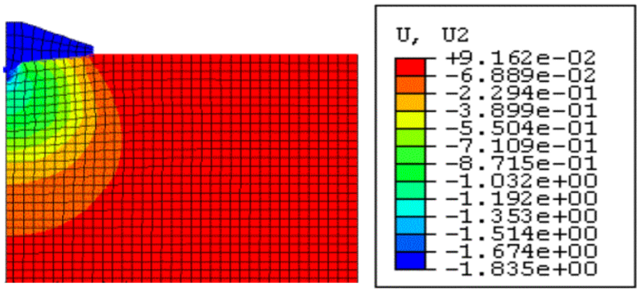

Figure 2 Spudcan penetration at maximum preload (ABAQUS)

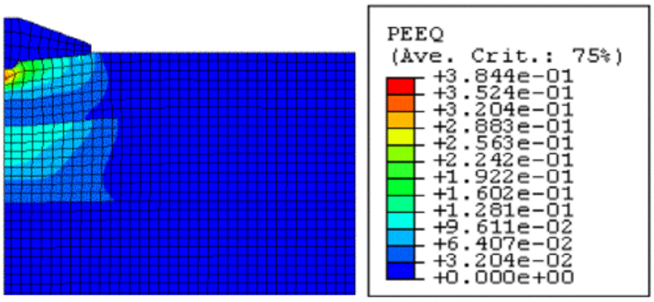

Figure 3 Equivalent plastic strain at maximum preload (ABAQUS)

## Elfen FEM analysis of spudcan penetration

The following analysis methods were used in Elfen for the same spudcan and soil profile as in the previous Abaqus calculations.

Implicit large strain elasto-plastic analysis was chosen first associated with incremental large strain analysis, [16]. Mohr-Coulomb material model was used. 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) is applied. Additional re-meshing regions in critical areas (outer & inner corner on the bottom of the spudcan and its outside edge) are applied.

A Coulomb friction contact between foot and soil is modeled. An updated penalty method was used to solve the contact interaction forces. A friction coefficient of 0.6 was chosen.

Surface pressure on the top of the sand layer is applied to take into account the 7 m soft clay layer at the seabed. Gravity loading is applied in the same way as in the Abaqus analyses.

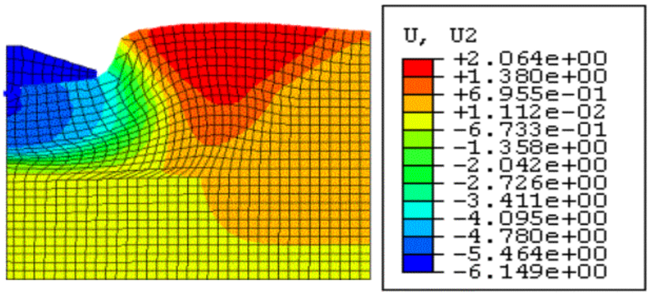

Figure 4 Spudcan penetration at double preload (ABAQUS)

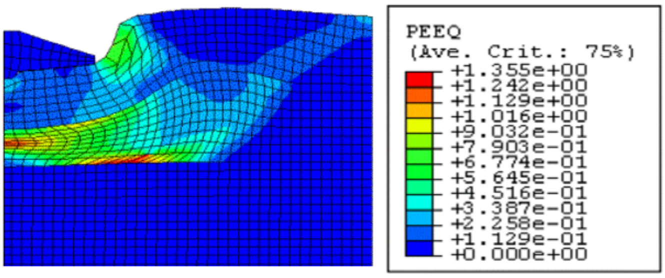

Figure 5 Equivalent plastic strain at double preload (ABAQUS)

Instead of a vertical load, an axial deformation is applied to the spudcan axis of symmetry and the reaction force at the spudcan-soil interface is recorded.

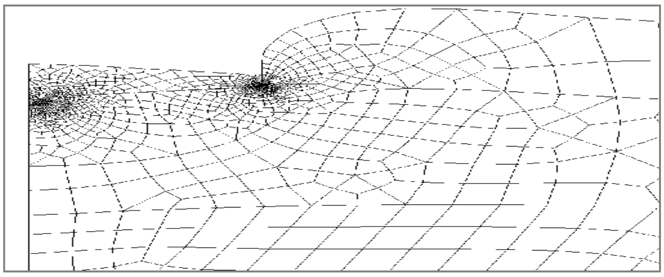

Figure 6 Spudcan penetration and adaptive mesh pattern at double preload (ELFEN)

Some of the results consisting of deformation pattern evolution, adaptive mesh design, principal stress, effective stress distribution and soil resistance versus penetration were investigated. The penetration curve is given in Figure 1 to be able to compare the results with conventional and Abaqus FEM calculations. Other results are given in Figures 6 and 7.

In Figure 6 the adaptive mesh pattern at a reaction equal to double preload is given. The remeshing capability of Elfen makes possible to eliminate numerical instability at the spudcan soil interface. In Figure 7 the principal stress distribution at double preload is given too.

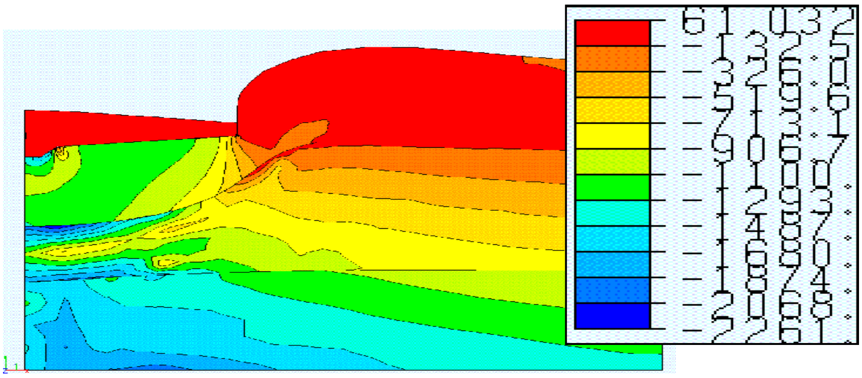

Figure 7 Principal stress distribution at double preload (ELFEN)

## Conclusions

The results from FEM modeling with Abaqus or Elfen show that there is no punch through potential at the current location. The result from Abaqus Explicit shows a risk of rapid penetration for larger preload however Elfen results stand between the Abaqus results.

The conventional analysis modified for the current layered soil profile shows a punch through risk close to the maximum preload. Although this analysis was modified based on our FEM experiences and field observations, it still gives a conservative evaluation of the current situation.

The numerical results, combined with the visual evidence from the centrifuge testing [17-18] and field monitoring allows for reassessment of the conventional methods of analysis.

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