

NUMERICAL INVESTIGATION OF SPUDCAN FOOTING PENETRATION IN LAYERED SOIL

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Abstract. Spudcans are a type of foundation for mobile jack-up rigs and are connected to each of the three or four independent legs of a rig. These rigs are widely operating in the offshore industries such as oil and gas exploration and offshore wind park constructions. The diameter of a spudcan is typically between 10 and 16 m, but has steadily increased in recent years with some exceeding 20 m.

An accurate prediction of the leg or spudcan penetration is required to assess the minimum leg length of a jack-up rig and to predict any hazards such as risk of rapid leg penetration that can destabilize the rig and lead to catastrophic accidents. Rapid and sudden leg penetration can occur in layered soils where a strong layer overlies a weak layer. This type of failure mechanism in soil is called “punch through”.

The current state-of-practice to assess the penetration depth of a spudcan is to evaluate the bearing capacity of the footing applying analytical methods at discrete depths. Analytical bearing capacity methods strongly simplify the penetration process and rely on empirical factors. Continued investigation of the spudcan penetration process by means of physical or numerical models can reduce the amount of empiricism in applied methods in practice, thereby increase accuracy in penetration predictions and reduce risk of rig instability.

The results of a finite element numerical model to investigate the spudcan penetration process in layered soils are presented in this paper. The numerical model combines conventional Lagrangian elements, which represent the spudcan, with Eulerian elements that idealize the soil. The utilization of this so-called Coupled Eulerian-Lagrangian finite element method enables the numerical simulation of large deformation processes such as the spudcan footing penetration. Preliminary results are presented and compared with state-of-practice analytical solutions.

1 INTRODUCTION

Spudcans are used as footing foundations for offshore mobile jack-up rigs to allow the easy installation and extraction of the legs while providing temporary stability during the operation of such rigs. The legs of the rig are jacked into the seafloor to hold the rig in its position and ensure stability against horizontal and vertical forces during the operational phase. These rigs are widely used in the offshore industries such as oil and gas exploration for drilling wells, maintenance work or temporary production, as well as for the installation of offshore wind energy plants.

Spudcans generally have a polygonal shape but can be approximated to be circular and mostly have a conical underside (about 15° to 30° to the horizontal). Additionally, a spudcan can incorporate an acute tip, called a spigot, centered on the bottom, which improves its sliding resistance. The top face also exhibits a conical shape with angle to the horizontal similar to the one of the underside. Figure 1 depicts a typical shape of a spudcan-footing.

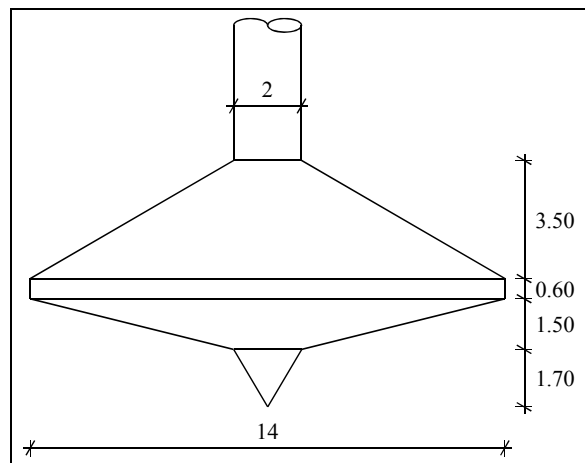


Figure 1: Typical geometry (dimensions in [m]) of a spudcan [14]

Guidelines on the site specific assessment of jack-up rigs and its components are provided in the International Standard ISO 19905 [10] and in the Technical and Research Bulletin 5-5A of the Society of Naval Architects and Marine Engineers (SNAME) [18]. Further guidelines on geotechnical assessments including foundation design can be found in ISO 19901 [9] .

2 OVERVIEW OF METHODS

During deep penetration of a spudcan footing, several failure mechanisms can occur within the soil. In homogenous soil, general shear failure occurs, similar to conventional shear failure of shallow foundations for which well-known bearing capacity equations have been developed. In layered soils, squeezing of soft soil between harder layers and/or punch through of the spudcan through a hard layer to a weaker or soft soil layer can occur. Of the different mechanisms, the latter presents a significant risk to the stability of a mobile jack-up rig since sudden and rapid leg penetrations can occur.

The current state-of-practice to assess the depth of spudcan penetration is to determine the vertical bearing capacity of the spudcan at discrete depths below the seabed and plot the

bearing capacity versus footing penetration. The maximum expected load (or pre-load) is compared to the bearing capacity graph to predict final penetration and any hazards such as risk of rapid and sudden leg penetration or “punch through” risk. Closed-form, analytical bearing capacity solutions are applied based on theories developed for shallow foundations. These solutions have been modified through the use of factors to account for backflow (during deep penetration), conical spudcan shapes, spudcan-soil interface roughness and mobilized soil strength among others. Thus, these analytical methods for spudcan penetration assessment may have significant limitations, especially when encountering complex soil conditions, such as highly layered soil profiles [11].

In homogeneous clay, standard practice [10], [18] is to apply bearing capacity and depth factors from Skempton [17] as suggested by Young et al. [22] for an average of the undrained shear strength to a depth 0.5 diameters below the level where maximum spudcan diameter is in contact with the soil. Other bearing capacity factors that take into account the cone angle, spudcan roughness, embedment depth and shear strength increase, such as those from Houlsby [8] are also recommended. The international standard [10] presents the bearing capacity factors proposed by Martin [12] to evaluate the bearing capacity of a spudcan in homogeneous sand. These bearing capacity factors are derived for flat, rough circular footings and for friction angles between 20° and 40° [1], [2].

If the soil is layered, other failure mechanisms can occur. This paper focuses on the case of a hard sand layer overlying a soft clay layer where “punch-through” mechanism may be likely to happen. For sand overlying clay, common methods applied are those by Hanna & Meyerhof [5] and the load-spread method, both adopted in ISO 19905 [10] and SNAME [18]. The punch-through bearing capacity developed by Hannah and Meyerhof considers forces on the assumed vertical failure surfaces in the upper sand layer, which is taken as the total passive earth pressure inclined at an average angle and acting upwards.

An alternative method recommended by Young et al. [22], is the load-spread method. The method is empirical and idealizes the punch-through failure mechanism by simply projecting the bearing capacity of the footing on to the lower layer. This allows a variation of load-spread gradients 1:n to be considered. Values of load-spread gradients between 1:3 and 1:5 are recommended in [10] and [18]. It is noted in [10] and [18] that both methods for punch-through capacity of sand over clay can significantly underestimate the actual bearing capacity.

In recent years, the assessment of spudcan penetration has been investigated applying numerical methods. Classic Finite Element Analysis (FEA) methods using Lagrangian elements have been used to model a spudcan [13]. However, such analyses are limited to small-deformation problems. As the spudcan penetrates further into the soil, large deformations of model elements occur leading to numerical and convergence problems, as well as the distortion of the elements affects the accuracy of the simulation. The large deformations in the model cause significant distortions of the mesh and its elements as well as contact problems between the spudcan and the soil [3], [7], [14].

More recently, using Coupled Eulerian-Lagrangian (CEL) elements in ABAQUS has been shown to be able to model large-deformation problems. [20] first applied the CEL method for the assessment of spudcan penetrations. This approach has been benchmarked and validated for application in other large-deformation, geotechnical problems. There are several other recent publications documenting the applicability of the CEL method for spudcan penetration assessments [13],[14],[15], [19], [21].

3 FINITE ELEMENT MODELING

The CEL method in ABAQUS combines the advantages of Eulerian and Lagrangian elements to analyze problems involving both small and large deformations, which is generally not feasible with conventional Lagrangian FEA methods. In geotechnical applications, the CEL method allows the soil, which may undergo large deformations, to be modeled using Eulerian elements while solid structures with little deformations can be modeled using Lagrangian elements. Numerical convergence problems associated with stress and strain concentrations at the edge of a solid structure are overcome since the Eulerian soil element is able to move freely.

The interface between the two elements defines the boundary of the Lagrangian body. The Lagrangian body occupies a region in the Eulerian mesh, while it pushes the Eulerian material out of the elements since there is no material flow of Eulerian material in the Lagrangian body [19]. The CEL method is particularly advantageous in simulating installation processes in geotechnical engineering, which typically involve large soil deformations. The installation of foundations, such as piles and/or footings, can be simulated realistically beginning at the ground surface in contrast to modeling pre-embedded foundations.

3.1 Development of CEL Model

The spudcan penetration analysis under purely vertical loading is an axisymmetric process, which could, in principle, be analyzed as a two-dimensional problem. However, ABAQUS provides only one Eulerian element type that is a 3D element requiring eight nodes [16]. Therefore, a 3D model of the spudcan and soil mass was created in this study; however, the model was optimized by utilizing symmetry conditions. Two planes of symmetry were established and only one-fourth of the spudcan and soil domain was modeled (see Figure 2). Boundary conditions were applied to the planes of symmetry, which inhibit material movement normal to the planes of symmetry. The type of boundary condition in the ABAQUS model was set to “no-flow-boundaries”. This type of boundary condition enforces zero velocity in the boundary, in the direction of the given boundary condition.

The model contains a spudcan with radius 7 m (Diameter (B) = 14.0m) and a soil domain with radius 28 m, which is equal to four times the spudcan radius (Figure 2). The dimensions of the numerical model are thus expected to be large enough to avoid any boundary effects. The height of the numerical model in case of homogenous soil (model a) was defined to 56 m, which is equal to four times the diameter of the spudcan. This allows penetration of the spudcan up to a multiple of its diameter without boundary effects. In addition, an initial void region above the soil mass provides enough space for the soil heave.

In case of layered soil analyses (model b), the height of the numerical model was equal to the thickness of the upper sandy layer (T) which was varied according to the spudcan diameter (B), plus the depth of the underlying clay layer which was defined to 46.0 m beneath the upper sandy layer. Also an initial void region above the soil mass provides enough space for the soil heave during the analysis (see Figure 2).

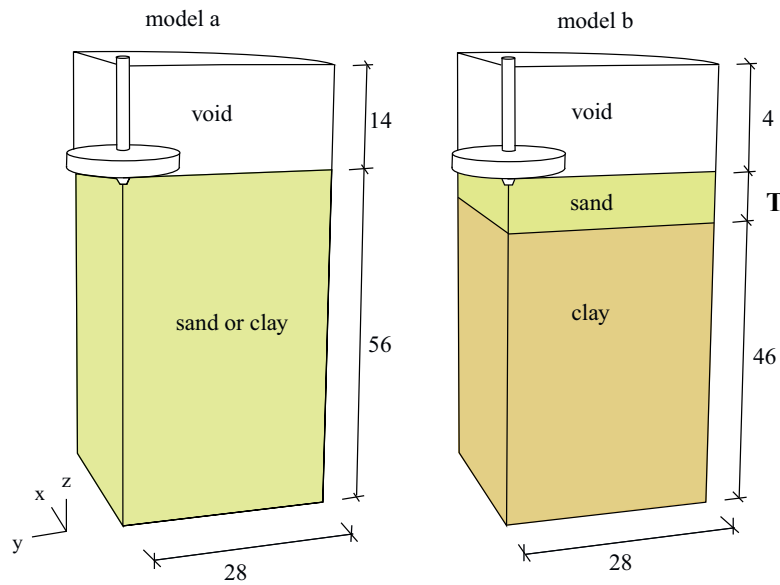


Figure 2: Dimensions and geometry of spudcan penetration model

In the CEL model, the soil mass and initial void regions above the soil were assigned with Eulerian elements while the spudcan itself was assigned with Lagrangian elements. A fine mesh was applied in proximity to the spudcan while a coarser mesh was applied to the model parts close to the boundaries. This allowed an optimization of total number of elements in the model without compromising on accuracy of calculated soil movements in proximity to the spudcan. The linear elastic-plastic with Mohr-Coulomb criterion constitutive law was chosen to represent the behavior of different soil layers. Table 1 & 2 contain the required soil properties for the Mohr-Coulomb constitutive law which were applied in the numerical model. For the sand layers, a negligible value of cohesion was assumed to overcome numerical instabilities.

Table 1: Applied soil properties for sand layers

Parameter	Sand (S1)	Sand (S2)
Unit weight	9 kN/m ³	11 kN/m ³
Young's modulus	30.0 MPa	50.0 MPa
Poisson's ratio	0.25	0.25
Friction angle	30.0°	38.0°
Dilatation angle	0.0°	8.0°
Cohesion	0.01 kPa	0.01 kPa

Table 2: Applied soil properties for clay layers (undrained)

Parameter	Clay (C1)	Clay (C2)
Unit weight	7 kN/m ³	8 kN/m ³
Young's modulus	2.0 MPa	10.0 MPa
Poisson's ratio	0.49	0.49
Friction angle	0.01°	0.01°
Dilatation angle	0.01°	0.01°
Cohesion (c_u)	10.0 kPa	50.0 kPa

ABAQUS provides the general contact method to define the interaction between the Lagrangian and Eulerian material, which allows finite sliding of two separated surfaces. This aspect is essential for the spudcan penetration analysis, where the soil continuously moves along the spudcan surface. The definition of a friction coefficient represents the roughness of the spudcan surface. The interaction property is stated as a penalty contact with assumed friction coefficient of 0.5 (interface friction angle $\delta=26.57^\circ$).

The numerical analysis is generally performed in two steps. The initial step defines the geostatic stress field, which is induced by self-weight of the soil under gravity. The second step applies loads in the model to initiate the analysis and includes the spudcan penetration process. The latter step is a dynamic, explicit type analysis. The time period of the step was defined in relation to the penetration rate of the spudcan and penetration depth to be reached (with penetration depth/time period = penetration rate).

3.2 Validation of the Numerical Model

The numerical results of the spudcan penetration analysis were compared to results from analytical methods. Analytical methods to estimate the spudcan penetration depth were applied using Fugro in-house software, which calculates spudcan penetration in accordance with latest state-of-practice standards, i.e. ISO 19905 [10] and SNAME [18] .

Two models considering homogeneous sand (S1 properties) and homogeneous clay (C1 properties) were initially investigated.

Figure 3 depicts the comparison of numerical and analytical results in terms of spudcan reaction versus penetration depth in homogeneous sandy soil (S1). The penetration depth D is defined as the depth of the spudcan's widest bearing area below the seafloor.

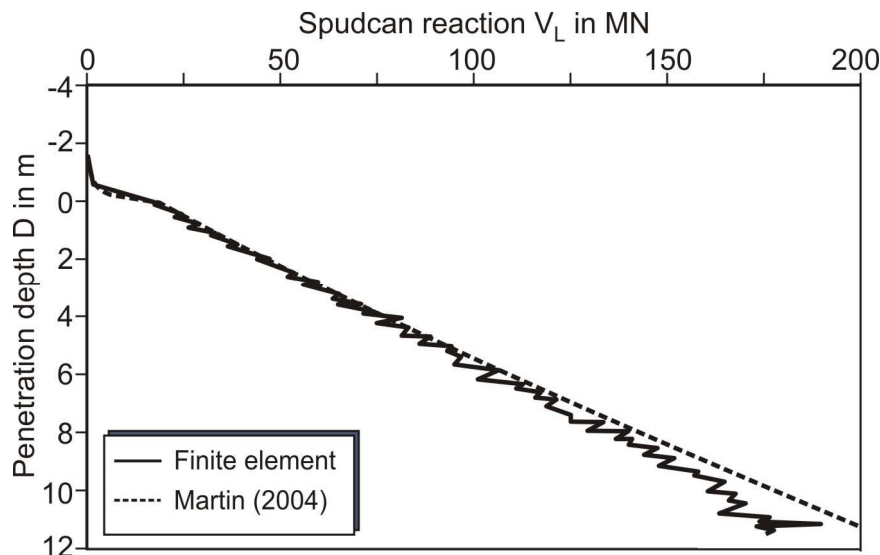


Figure 3: Comparison of finite element and analytical results (Sand S1)

For the spudcan at ground surface, the method of Martin [12] results in similar spudcan reactions, which are in good agreement with the FE results. The bearing capacity reaction determined with Martin's method is almost identical with FE results up to penetration $D = 4$ m (during partial spudcan embedment or penetration). At penetration depth $D > 4$ m (at deeper penetration), the bearing capacity results of the FE analysis still matches very well the results applying Martin's method..

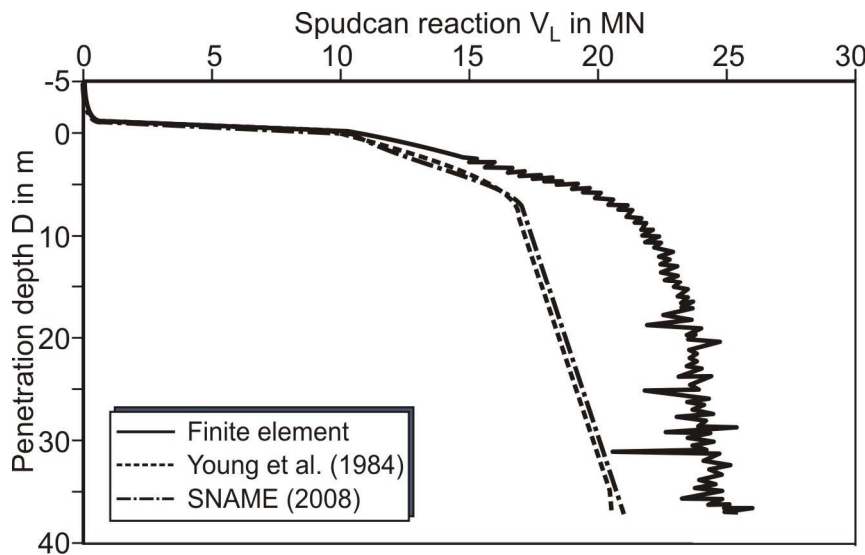


Figure 4: Comparison of finite element and analytical results (Clay C1)

Figure 4 shows the results of the spudcan reaction versus penetration depth of finite element and analytical analysis for the clay C1 ($c_u = 10$ kPa). The analytical results increase strongly at partial penetration, because the bearing capacity is mobilised due to a growing bearing area. The further increase of the spudcan reaction is due to the backflow of soft clay, which causes surcharge on top of the spudcan. After this transition, the spudcan reaction grows steadily with penetration depth.

Generally, the analytical methods exhibit a lower spudcan reaction than the results of the finite element method, which is less significant at shallow embedment, than at deep penetration (penetration deeper than eight metres). However, both of the analytical and finite element results show the same tendency regarding the behavior of spudcan in clay.

Based on the validation of the model, a convergence study on the mesh density as well as the penetration rate was performed. Different meshes with varying number of elements as well as the minimum element size were investigated. The comparison reveals no substantial differences in the calculated resistance of the spudcan due to the mesh densities used. However, bearing pressure graphs are much smoother (without excessive instabilities) as the number of elements in the model is increased. Since there were no significant differences between the different meshes, a final mesh with total element number of 100,536 was chosen for all subsequent analyses to optimize accuracy and computational time. The penetration rate of 0.5 m/s to the spudcan was adopted in the modeling. For more details on the numerical modeling, pl. refer to [4].

4 NUMERICAL RESULTS

The spudcan penetration in sand (S2) overlying clay (C1) has been modelled and compared with the analytical methods. Figure 5 shows the results of case S2-C1 using both analytical and finite element analyses, whereas the analytical calculation considers the method of Martin [12] for sand and the method of Young et al. [22] for clay. The method of Hanna & Meyerhof [5] and the load spread method are taken into account to determine the bearing capacity for punching through the sand.

Directly after penetration the spudcan reaction rapidly decreases in the case of load spread ratio method, where the reduction for the lower load spread ratio is more significant. Finally, both graphs show the same spudcan reaction in clay layer ($D > 21$ m), since the bearing capacity is calculated with the same approach for uniform clay. The method of Hanna & Meyerhof shows a high increase of bearing capacity up to $D = 0$ m. While the spudcan penetrates deeper, the assumed shear planes in the overlying sand layer become smaller and the reduction of bearing capacity increases with advancing penetration depth. The reason for this progress is that the amount of bearing capacity due to general shear in the clay underneath becomes more relevant in comparison to the shearing at the vertical planes in the sandy layer.

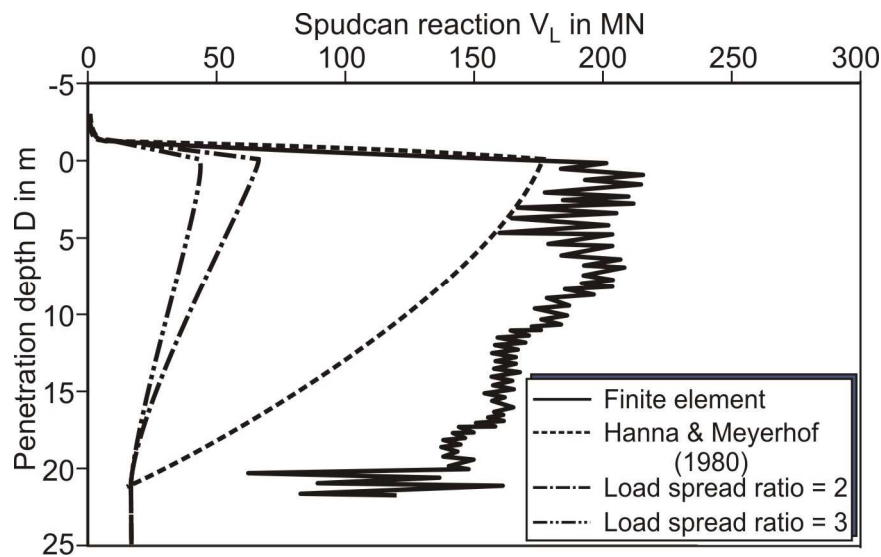


Figure 5: Comparison of finite element and analytical results; soil S2-C1 with $T/B = 1.5$

The results of the finite element simulation show a high increase of spudcan reaction up to $D = 0$ m. However, the spudcan reaction remains approximately constant up to $D = 7$ m, followed by a progressive reduction with advancing penetration depth of the spudcan. The graph in figure 5 indicates significant numerical instabilities for penetration depth $D > 19$ m, which is verified in the visualisation of the simulation, where unrealistic soil movements can be observed.

In terms of the spudcan reaction at ground surface, the method of Hanna & Meyerhof provides the best approximation of the finite element result. However, the analytical

approaches generally underestimate the spudcan reaction up to $D = 19$ m. Considering the slope of the graph at punch through failure mechanism ($0 \text{ m} < D < 19 \text{ m}$), the load spread method with a ratio of two gives the best match, although it significantly underestimates the spudcan reaction.

To investigate the influence of the soil strength of the underlying soil on the punch through mechanism the results of sandy layer (S2) overlying clay (C2) are depicted in Figure 6. The analytical calculations are based on the same methods and parameters as in the previous case. Generally, the spudcan reaction at ground surface is significantly higher, which can be associated to the higher undrained shear strength of the underlying clay (see Table 2).

In case of the analytical methods, the projected footing on the interface mobilizes a higher bearing capacity. This aspect highly affects the load spread method (larger bearing area on soil with higher strength). In contrast, the higher undrained shear strength has a lower effect on the method of Hanna & Meyerhof, which considers a projected footing of the same size and the shearing in the sand layer that does not change to the case S2-C1.

Hence, the spudcan reaction at ground surface calculated with the load spread method ($n_s = 2$) exceeds the one determined with the method of Hanna & Meyerhof. For spudcan penetration deeper than $D = 21$ m, the predicted spudcan reaction with analytical methods is the same in every approach, but on a higher magnitude than in the case S2-C1 (general shearing failure in clay with higher undrained shear strength).

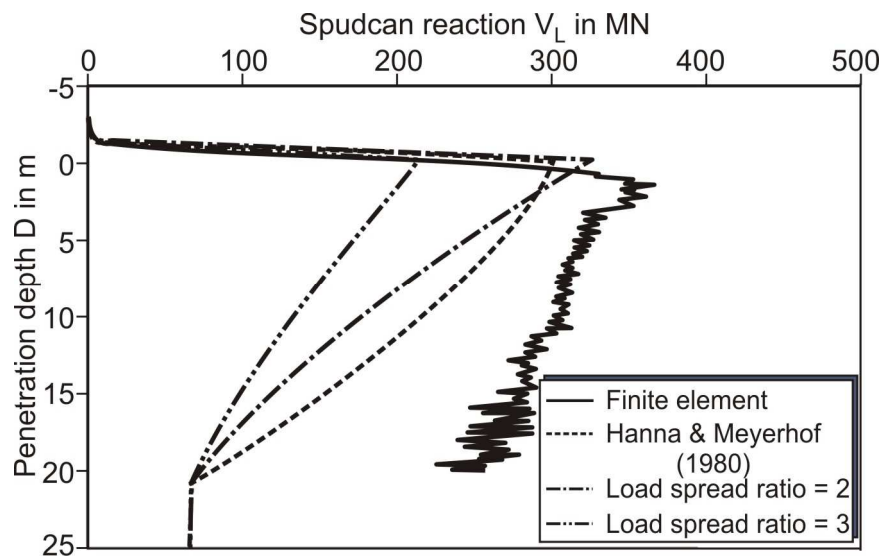


Figure 6: Comparison of finite element and analytical results; soil S2-C2 with $T/B = 1.5$

The finite element results, depicted in Figure 6, exhibit a high increase of spudcan reaction up to $D = 1.50$ m, which remains approximately constant up to $D = 3$ m. As the spudcan penetration exceeds this depth, the underlying clay becomes progressively more affected by the penetration process and thus, the spudcan reaction reduces as the sand is forced downwards instead of mobilising resistance against the penetrating spudcan. Subsequent to this rapid decrease, the spudcan reaction reduces steadily with advancing penetration depth.

Comparing the results of the finite element method with the ones of the analytical calculations shows that the approach of Hanna & Meyerhof as well as the load spread method ($n_s = 2$) give a good approximation of the highest spudcan reaction of the finite element result. The slope of the graph during punch through calculated with the method of Hanna & Meyerhof matches well with the finite element graph up to $D \approx 10$ m, whereas the load spread ratio of $n_s = 2$ owes a too high decrease of spudcan reaction with depth. The load spread ratio of $n_s = 3$ represents a similar slope like the finite element graph, but significantly underestimates the spudcan reaction at ground surface and in the underlying soil.

Figure 7 provides a comparison of multiple thicknesses of the sand layer S2 above clay C2, which are represented for depth (D) normalised by the diameter of the spudcan (B). The penetration depths (D) is normalised by the layer thickness (T). The graph of $T/B = 1.5$ is depicted up to $D/T = 0.71$ to exclude the numerical instabilities that occur for penetration depth $D > 15$ m. Figure 6 shows that the thicker the overlying layer, the higher is the initial spudcan reaction at ground surface, because a thicker sand layer is able to resist a higher load and thus prevents effects of the underlying clay. For $T/B \geq 1$, the clay becomes affected after the resistance of the sand layer is exceeded (peak value) and the sand is forced downwards. For a normalised layer thickness of $T/B < 1$, no punch through failure is observed. Nevertheless, an increase of the layer thickness causes a higher spudcan reaction.

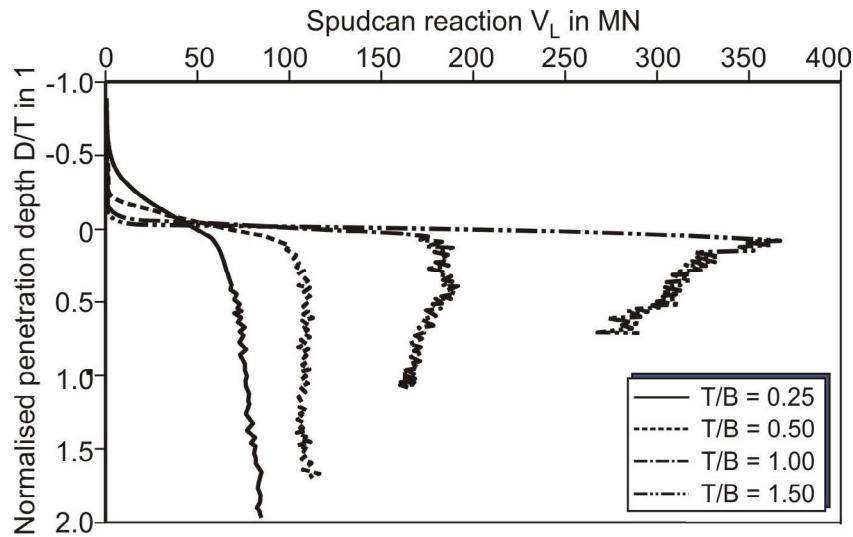


Figure 7: Effect of the layer thickness on the punch through of sand; soil S2-C2

For $T/B < 1$, the underlying soil is almost immediately affected by the spudcan penetration and thus the spudcan reaction results mainly of the underlying clay augmented by the resistance of the sand surrounding the penetrating spudcan. While the spudcan penetrates in the sand, a soil plug is formed beneath and moves progressively downwards together with the spudcan. The most typical punch through failure is represented in $T/B = 1.5$, where a high spudcan reaction is followed by a major reduction of spudcan reaction. A residual spudcan reaction subsequent to the punch through cannot be observed, but is expected to occur at a deeper penetration.

5 CONCLUSIONS

A numerical study was performed that aimed at comparing analytical and finite element results for multiple cases and investigated the effects or mechanisms that occur as the spudcan penetrates in layered soil. An essential aspect is the application of the Coupled Eulerian-Lagrangian method in the numerical model, which is suitable for analysis of large deformation problems.

In case of homogeneous sandy soil the analytical methods applied in practice to estimate the spudcan penetration depth generally match well with finite element results and it was observed that the analytical results mostly underestimated the results from the FE model by homogeneous clay.

If the soil is layered, it was observed that the results of the applied analytical methods mostly underestimated the results from the FE model. Hanna & Meyerhof method gives the best estimate of spudcan penetration resistance compared to FE-analyses. Load spread ratio results depend on the shear strength of the underlying clay layer, so it gives better results for the max. penetration force in case of underlying clay layer with high cohesion value beneath the upper sandy layer.

To improve the reliability of the relatively novel CEL method for use in geotechnical applications, further studies comparing model tests and in-situ data with such simulation are highly useful. The continual verification of FE results with model tests, as well as a better understanding and consequently prevention of numerical instabilities will greatly improve the applicability of finite element methods to investigate and analyze the spudcan penetration process.

REFERENCES

- [1] Cassidy, M. J. & Houlsby, G. T., 2002. Vertical bearing capacity factors for conical footings on sand. *Géotechnique*, 52(9), pp. 687-692.
- [2] Craig, W. H. & Chua, K., 1990. Deep penetration of spud-can foundations on sand and clay. *Géotechnique*, 40(4), pp. 541-556.
- [3] Gao, W., Yu, L. & Hu, Y., 2012. Large deformation FE analysis of large diameter spudcan penetration into two-layer of uniform clays. *International Journal of Geotechnical Engineering*, 6(2), pp. 171-177.
- [4] Gütz, P., 2012. Finite Element Analysis of Spudcan Footing Penetration, Diploma thesis, Leibniz University of Hannover (unpublished).
- [5] Hanna, A. M. & Meyerhof, G. G., 1980. Design charts for bearing capacity of foundations on sand overlying soft clay. *Canadian Geotechnical Journal*, 17(2), pp. 300-303.
- [6] Hossain, M. S., Hu, Y., Randolph, M. F. & White, D. J., 2005. Limiting cavity depth for spudcan foundations penetrating clay. *Géotechnique*, 55(9), pp. 679-690.
- [7] Hossain, M. S. & Randolph, M. F., 2010b. Deep-penetrating spudcan foundations on layered clays: numerical analysis. *Géotechnique*, 60(3), pp. 171-184.

- [8] Houlsby, G. T. & Cassidy, M. J., 2011. A simplified mechanically based model for predicting partially drained behavior of penetrometers and shallow foundations. *Géotechnique Letters*, 1(3), pp. 65-69.
- [9] ISO 19901-4:2003, 2003. *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 4: Geotechnical and foundation design considerations*, s.l.: International Organization for Standardization.
- [10] ISO 19905-1:2011, 2011. *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 1: Jack-ups*, s.l.: International Organization for Standardization.
- [11] Kellezi, L. & Stromann, H., 2003. *FEM analysis of jack-up spudcan penetration for multi-layered critical soil conditions*. Dundee, BGA International Conference on Foundations, pp. 411-420.
- [12] Martin, C. M., 2004. *User Guide for ABC – Analysis of Bearing Capacity*, University of Oxford: Department of Engineering Science.
- [13] Qiu, G. & Henke, S., 2011. Controlled installation of spudcan foundations on loose sand overlying weak clay. *Marine Structures*, Band 24, pp. 528-550.
- [14] Qiu, G., Henke, S. & Grabe, J., 2011a. *3D FE analysis of the installation process of spudcan foundations*. London, 2nd International Symposium on Frontiers in Offshore Geotechnics.
- [15] Qiu, G., Henke, S. & Grabe, J., 2011b. Application of a Coupled Eulerian–Lagrangian approach on geomechanical problems involving large deformations. *Computers and Geotechnics*, 38(1), pp. 30-39.
- [16] Simulia, 2012. Abaqus 6.12.
- [17] Skempton, A. W., 1951. *The Bearing Capacity of Clays*. London, Building Research Congress.
- [18] SNAME, 2008. *Guidelines for Site Specific Assessment of Mobile Jack-Up Units. Technical and Research Bulletin 5-5A*, New Jersey: The Society of Naval Architects and Marine Engineers (SNAME).
- [19] Tho, K. K., Leung, C. F., Chow, Y. K. & Swaddiwudhipong, S., 2012. Eulerian Finite-Element Technique for Analysis of Jack-Up Spudcan Penetration. *International Journal of Geomechanics*, 12(1), pp. 64-73.
- [20] Tho, K. K., Leung, C. F. & Swaddiwudhipong, S., 2009. *Application of eulerian finite element technique for analysis of spudcan and pipeline penetration into the seabed*. London, 12th International Jack-up Conference
- [21] Yi, J. T. et al., 2012. Eulerian finite element analysis of excess pore pressure generated by spudcan installation into soft clay. *Computers and Geotechnics*, Band 42, pp. 157-170.
- [22] Young, A. G., Remmes, B. D. & Meyer, B. J., 1984. Foundation Performance of Offshore Jack-Up Drilling Rigs. *Journal of Geotechnical Engineering*, Vol. 110, No. (7), pp. 841-859.