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Estimation of spudcan penetration using a probabilistic Eulerian finite element analysis

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ABSTRACT: The probabilistic approach was employed to consider the uncertainties in prediction of spudcan penetration in clay. The Latin Hypercube Sampling method was used to generate 300 sample sets of input parameters based on the laboratory and field data. Each set of input parameters was used in conducting Coupled Eulerian Lagrangian finite element analysis. The probabilistic density function of the penetration depth under the maximum applied preload was obtained. The comparison of the results to the measured data showed that the introduced method can produce reasonable prediction of spudcan penetration considering the uncertainties involved in this problem.

1 INTRODUCTION

Uncertainty and risk are dominant characteristics in geotechnical and geological engineering practice. The soil profiles by their nature are very complex and inhomogeneous. Current design approaches and numerical simulations are based on models that do not completely reflect the complexity of the soil behaviour under different loading conditions. Furthermore, the interpretation of input parameters for these models can be a great challenge for the engineers while having a great impact on the accuracy of the design parameters in geotechnical engineering problems such as estimation of load-penetration curve in spudcan penetration (Quiros et al. 2008). Shortcomings in sampling methods and measurements analyses procedures are other sources of uncertainty in the engineering designs. The current practice generally relies on the experience and judgment of the Geotechnical Engineer, choosing conservative approaches or employing experimental methods. In order to generate more realistic results, it is useful to consider the influence of uncertainty in selecting material properties on the result of the analysis. In recent years, probabilistic methods have found wide application in geotechnical engineering (Bienen et al. 2011, Cassidy et al. 2013. Griffiths & Fenton 2004, Houlsby 2010, Lacasse & Nadim 2007).

This paper outlines the probabilistic approach in predicting the spudcan penetration under the maximum applied load. The probabilistic Eulerian Finite Element Analysis for spudcan penetration was simulated using ABAQUS/Explicit (Dassault Systémes, 2013) and MATLAB toolbox for sensitivity analysis, Eikos (Ekström 2005). The Latin Hypercube Sampling (LHS) algorithm was used to generate a 300 sample of input data for parametric Finite Element model in Abaqus/Explicit. The results showed a wide range of estimation for penetration depth, which underlines the importance of considering the uncertainty. The results of probabilistic analysis were compared to measured field data and other prediction methods.

2 METHODOLOGY

Initially, the field and experimental data was assessed in order to decide on the material model and input parameters that will be used in the simulations. It was decided to use the Tresca Constitutive model, which is commonly used for undrained analysis of clay. The variation of undrained shear strength, s_u, of the soil with depth was taken into account by diving the soil domain into 5 layers and assigning different input parameters for s_u in each layer. The statistical distribution of each input parameter was determined according to the field and laboratory test results. Then, the Latin Hypercube Sampling (LHS) method was used to produce 100 sets of input parameters for the numerical analyses.

Then, a parametric Coupled Eulerian Lagrangian (CEL) finite element model was built in which input parameters were variable and could therefore be changed throughout the probabilistic analyses. This model was conducted with generated input parameters and the results were saved for post-processing. The sensitivity analysis (SA) was performed and it was shown that a 100 sample was not enough to produce the complete distribution of outputs in the numerical model (mainly estimated penetration depth). As a result, the probabilistic analyses were repeated by

considering 300 samples. In this paper, the results of the 300 sample simulation are presented.

2.1 *Coupled Eulerian Lagrangian analysis*

Because of the numerical difficulties associated with performing large deformation analyses, early work on finite element analysis of spudcans assumed the foundations to be wished-in-place and the stress field around the pile was defined by making some simplifying assumptions. Recent developments in finite element analyses allow large deformation such as spudcan installation to be modelled.

There are two approaches which can be adopted, the Lagrangian approach and the Eulerian approach. The difference between the approaches is illustrated in Figure 1. In the traditional Lagrangian approach, shown in Figure 1(a), the elements are filled with material and they deform as the material deforms. In the Eulerian approach, the elements are fixed and the material flows through the elements as shown in Figure 1(b). As a result, there is no mesh distortion in the Eulerian approach.

When performing large deformation problems such as spudcan penetration excessive mesh distortions may lead to difficulty with convergence or inaccurate results during numerical modelling. To overcome these problems, different techniques have been introduced such as Arbitrary Lagrangian-Eulerian (ALE) and Coupled Eulerian Lagrangian (CEL) techniques. The ALE technique aims to reduce the distortions by remeshing the domain at a certain frequency. The field values are interpolated and transferred from the old mesh to a new improved mesh. In this method, the number of elements and the connectivity of the nodes do not change during the remeshing process. Instead the nodes are moved to find a new position in order to reduce the distortion of elements. The Coupled Eulerian Lagrangian (CEL) method provides an environment in which both Lagrangian and Eulerian materials can be used. This method of analysis avoids excessive mesh distortions although it has limitation on defining the material boundaries. As shown in Figure 2(b), multiple materials can exist in an Eulerian element. Since the boundaries between the materials
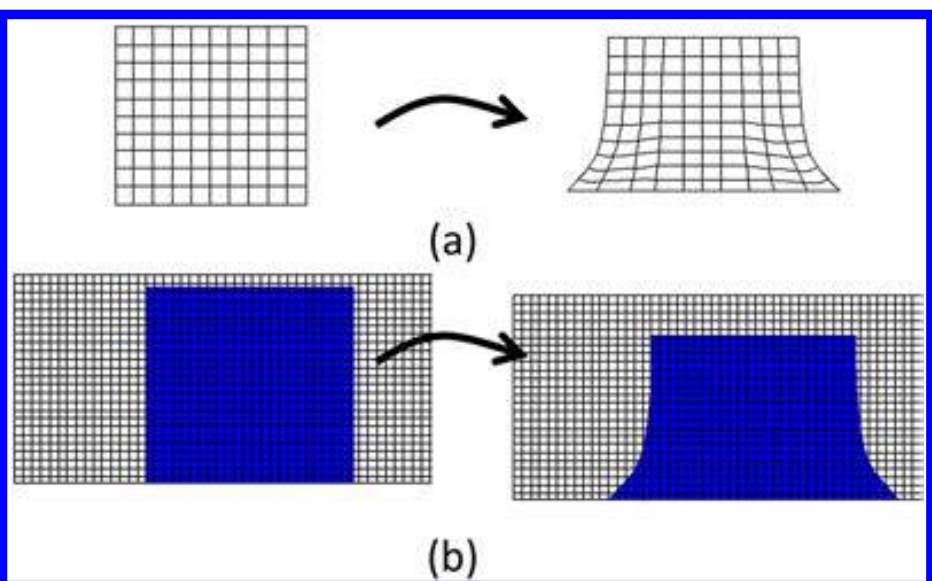
are approximate, the boundary surface is discontinuous in this approach. In this study the CEL method is adopted.

The large deformation finite element analysis of spudcans has been addressed in the recent studies (Hossain & Randolph 2010, Hossain et al. 2005, Kellezi & Stromann 2003, Zhou et al. 2009). Previous work on large deformation finite element analysis of spudcans has been performed by Qiu et al. (2011) who investigated the capabilities of the CEL method by performing benchmark tests on strip foundation. Two case studies considered in the analyses showed very good agreement with analytical solutions. The application of CEL for simulating pile installation and the effects of a ship running aground were also considered. Tho et al. (2012) performed three-dimensional Eulerian analyses to investigate the effect of spudcan penetration on adjacent piles. The results were compared to experimental data from a centrifuge and good agreement was obtained. Tho et al. (2013) performed a three dimensional Eulerian analysis to investigate the effect of spudcan penetration on adjacent piles. The results were compared to centrifuge experimental data and a good agreement is obtained. Hu et al. (2014) used CEL method to assess the risk of punch-through failure of spudcan penetrating sand overlying clay. A new expression was proposed to estimate the spudcan resistance and the values validated against centrifuge tests. Hamann et al. (2015) used CEL method in order to investigate the behaviour of the soil in pile installation problem under partially drained condition. A user material subroutine in Abaqus/Explicit was used in order to simulate the as a two phase medium considering hypoplastic constitutive model to describe the solid skeleton response. All the above studies suggest that the CEL technique is a reliable approach to solve large deformation problems such as spudcan installation. The next section describes the details of the finite element model used in this study.

2.1.1 *Finite element model*

Three dimensional finite element models were developed to simulate the continuous penetration of the spudcan. Considering the symmetry of the problem, only a quarter of the domain was modelled. The soil domain was chosen as 10 spudcan diameters, D in the horizontal direction and 10 to the bottom boundary. Given the concentration of large deformations, the Tresca constitutive model was adopted for the

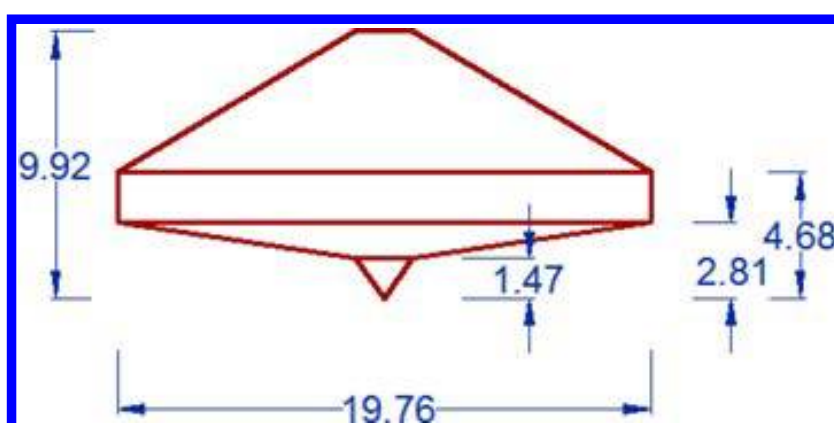Figure 1.   Lagrangian vs. Eulerian technique.

Figure 2.   Spudcan dimensions in meters.

soil. The flow of the material for normal to boundary planes was restricted by applying velocity boundary conditions to the planes. During installation, a large volume of soil is displaced to accommodate the spudcan. This will cause heave at the seafloor level. In order to allow the material to move upward, a void layer was defined above the seafloor level. The initial stress field is defined using the submerged unit weight of the soil.

The analyses were undertaken assuming undrained conditions. The soil was assumed to have a Poisson's ratio equal to 0.495, friction angle equal to zero and the dilation angle equal to zero. The steel leg was not considered in these analyses as it has been shown to have a relatively small influence on the results. The spudcan was modeled as Lagrangian rigid element. The soil stiffness E, undrained shear strength of the soil s_u, submerged unit weight γ' and the soil-structure interface friction coefficient α are specified based on the field and laboratory experiments as explained in Table 1.

2.2 Sensitivity analysis

Sensitivity analysis (SA) is the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of uncertainty input parameters (Saltelli et al. 2007). The goal of the SA in this study was to determine the uncertainty in the estimated penetration depth of spudcan arose from the uncertainty in input parameters of the model such as material properties (e.g. Young's modulus, Friction, Density, etc.). Characterisation of the uncertainty in the input variables was required in order to conduct the sensitivity analyses. The field and laboratory data was studied and different distributions were assigned to uncertain inputs as summarised in Table 1. Many different methods are available to perform uncertainty analysis including Monte Carlo simulation, differential analysis, a response surface methodology, the Fourier amplitude sensitivity test (FAST) and the closely related Sobol' variance decomposition, and fast probability integration. According to Helton and Davis (2003), a Monte Carlo simulation with Latin Hypercube Sampling (LHS) is the most broadly applicable approach to the propagation and analysis of uncertainty and often the only approach that is needed. In this study, Eikos (Ekström 2005) toolbox in MATLAB was coupled to Abaqus in order to perform probabilistic analysis using LHS method.

3 SPUDCAN GEOMETRY

The jack-up rig operated in Site X is Le Tourneau design. Figure 2 illustrates the simplified design circular cross section was considered with diameter selected that leads to the equivalent original cross sectional area of the original design. The volume of the spudcan in both original and simplified designs was equal. The original design can be found in (Menzies & Roper 2008).

4 SOIL CONDITION AND PARAMETER SELECTION

The soil conditions for Site X located in Gulf of Mexico as reported is presented in Menzies & Roper (2008). The log present the results of standard laboratory tests such as undrained shear strength obtained from unconsolidated undrained (UU) triaxial test, remolded shear strength from Miniature Vane and Pocket Penetration test; submerged unit weights; water content and Atterberg limits. This site consists of slightly over-consolidated soft to stiff clay.

Table 1. Information of uncertain input factors.

Parameter	Symbol	Mean	Standard Deviation	Lower Bound	Upper Bound	Distribution*	Unit
Young's Modulus $E_i = E_0\, S_{ui}$	E_0	260	40	150	360	N	MPa
Undrained Shear	S_{u1} (0–6 m)	20	6	4	28	N	kPa
Strength	S_{u2} (6–12 m)	33	5	8	45	N	
	S_{u3} (12–27 m)	44	6	15	58	N	
	S_{u4} (27–45 m)	74	17	20	109	N	
	S_{u5} (>45 m)	99	9	32	113	N	
Density	γ'_i	5800	300	5200	6400	N	kN/m³
Friction Parameter	α	0.5	–	0	1	T	

*N: Normal; T: Triangle

The distributions assigned to the material properties in this study are shown Table1. The change in undrained shear strength of the soil was considered by dividing the soil domain into 5 layers and assigning the averaged. The normal distribution is assigned to each layer with the mean value, standard deviation, lower bound and upper bound derived from field and laboratory test reported in (Menzies & Roper 2008).

The value of preload was also considered to be variable since there might be errors in measurement or application of the preload to the spudcans. The normal distribution was assigned to this variable with the mean value equal to 155.9 MN and standard deviation equal to 10% of mean value.

5 RESULTS AND DISCUSSION

300 LHS simulations were performed and a set of stratified probabilistic distribution functions (PDF) of the maximum penetration depth was derived. The statistical results indicated that the estimated penetration depth was in the range between 20.7 m and 62.6 m with the mean of 37 m and the standard deviation of 6.2 m as shown in Figure 3. This figure illustrates the normal distribution of the estimated penetration depth.

The results of sensitivity analysis using PRCC method are shown in Figure 4. This figure indicates that uncertainty in measuring the applied load has the most important impact on the uncertainty of the estimated penetration depth. SA analysis showed that any error in measuring the applied preload can result in high inaccuracies in the expected penetration depth. This can be very important if the seabed profile consists of weak layers, which means there might a potential of punch-through failure mechanism. Consequently, it is important to have an accurate estimation of the maximum applied load on the spudcan in order to assure the accuracy of the estimated penetration depth and the safety of the spudcan design.

The undrained shear strength of layer 4 (27–45 m), stiffness coefficient (E_0) and the submerged unit weight (γ'_{sub}) are other parameters that have the most
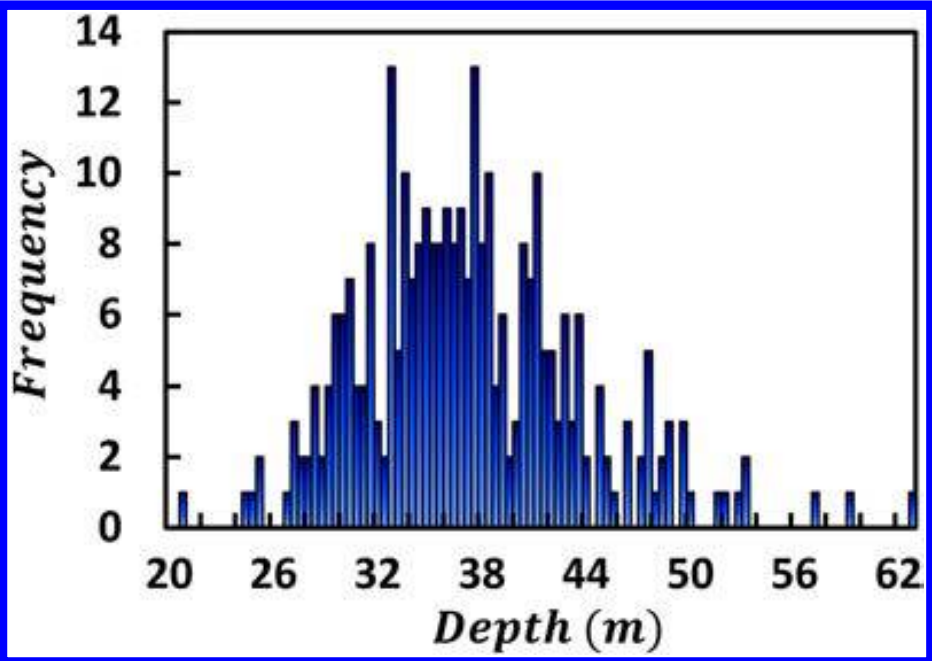
influence on the estimated penetration depth. The histogram in Figure 3 show that the spudcan penetrations under the applied load will most probably in Layer 4 (27–45 m). So it is reasonable to expect the high influence of the strength characteristics on the penetration depth of the spudcan. Furthermore, the results show that the undrained shear strength of layer 1, 2, 3 and 5 have very little influence on the penetration depth. This suggests that the spudcan penetration in the studied case, mostly involved the replacement of soil in the layer 4 and the effect of other layers were small. The stiffness coefficient (E_0), the submerged unit weight (γ'_{sub}) and the friction coefficient have small influence on the estimated penetration depth as shown in Figure 4(b).

Figure 5 shows the descending cumulative distribution functions (CDF) for the model. The vertical axis in this plot shows the fraction of all the generated values for estimated depth that are equal to or more than the corresponding estimated penetration depth on the x-axis. The range of predicted values is reasonable considering the uncertainty in determining material characteristics. According to Figure 5 there is a 5% probability that the spudcan penetrates more than 48.4 m and there is a 50% probability that the spudcan penetrates more than 36.5 m. The mean value of the estimated penetration depth for 300 samples was 37 m.
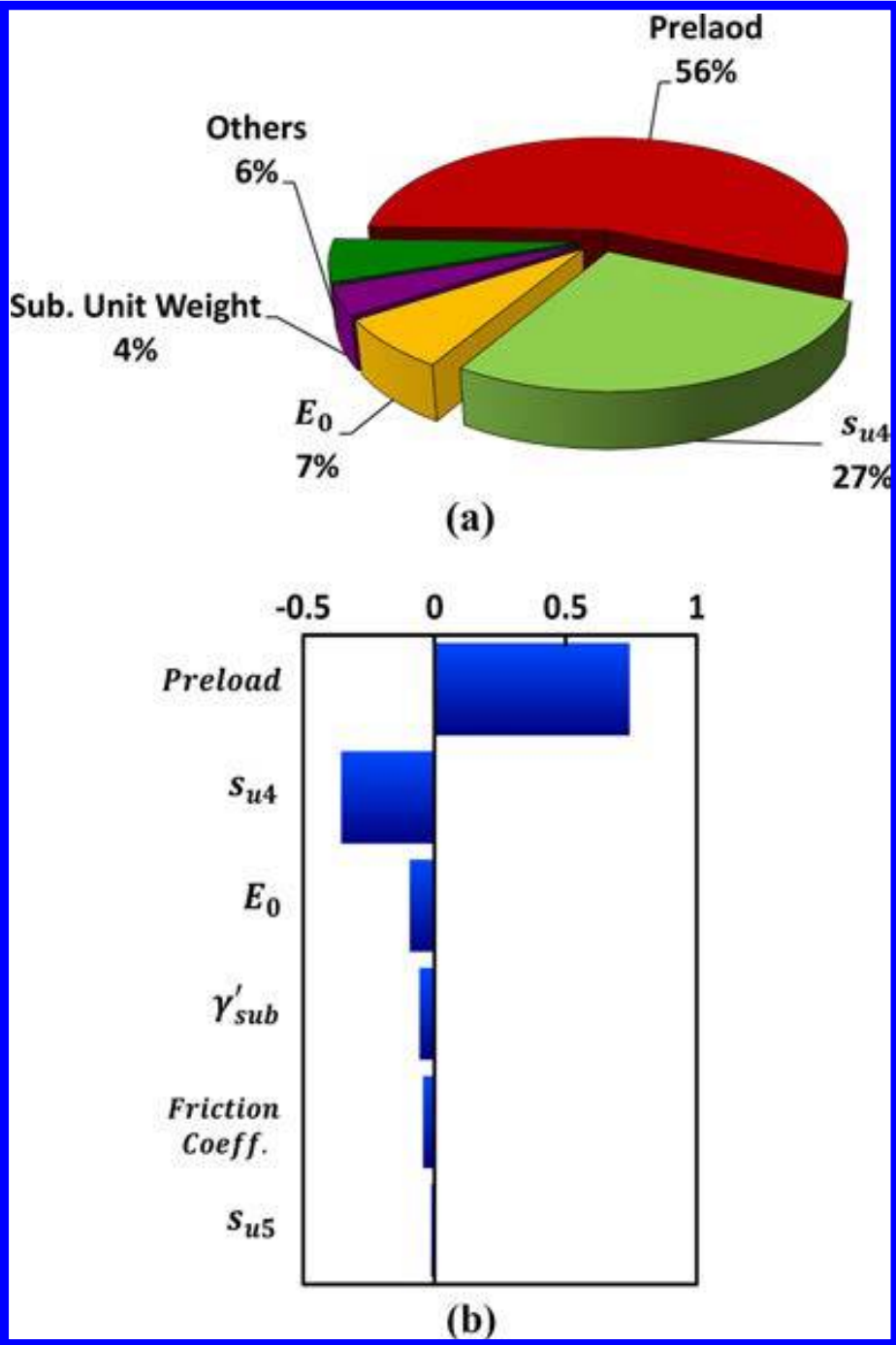

Figure 4. (a) Pie Chart, (b) Tornado graph of the result of sensitivity analysis using PRCC method.

Figure 3. Histogram over the estimated penetration depth.

6 COMPARISON TO MEASURED DATA AND OTHER ESTIMATION METHODS

In this study the estimated penetration depth from probabilistic analysis was compared to the results of SNAME (2002) guidelines, which is based on the bearing capacity methods proposed by Skempton (1951) and Hansen (1970). Inputs for these methods are undrained shear strength of the soil, submerged unit weight and spudcan dimensions.

Figure 6 shows the load-penetration curves predicted by using bearing capacity methods proposed by Skempton (1951) and Hansen (1970), results of

Probabilistic Eulerian Finite Element (PEFE) analysis conducted in this study and the measured data presented in Menzies & Roper (2008). The load-penetration curve from bearing capacity theories did not match well with the measured data and underestimated the penetration depth. The histogram obtained from PEFE analysis is also shown in Figure 6. As it can be seen in this figure, the penetration depths estimated by the PEFE analysis vary over a wide range of between 21 m and 63 m. However, the penetration depths between the range of 33 m and 41 m had the highest probability of occurring according to this study.

The results were compared to measured data. As reported in Menzies & Roper (2008) two penetration depths were observed under the applied load. The mean value of the distribution was 37 m, which agrees well with the observed penetration depths at site.
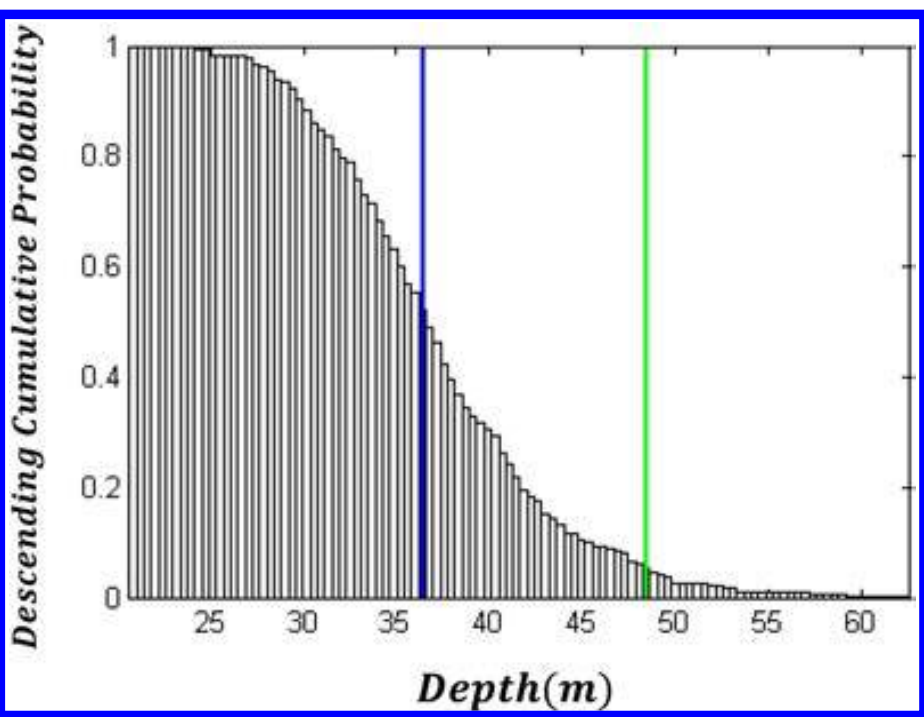

Figure 5. Descending cumulative plot of estimated penetration depth (Green and Blue lines are corresponding to the probability of 0.5 and 0.95, respectively).
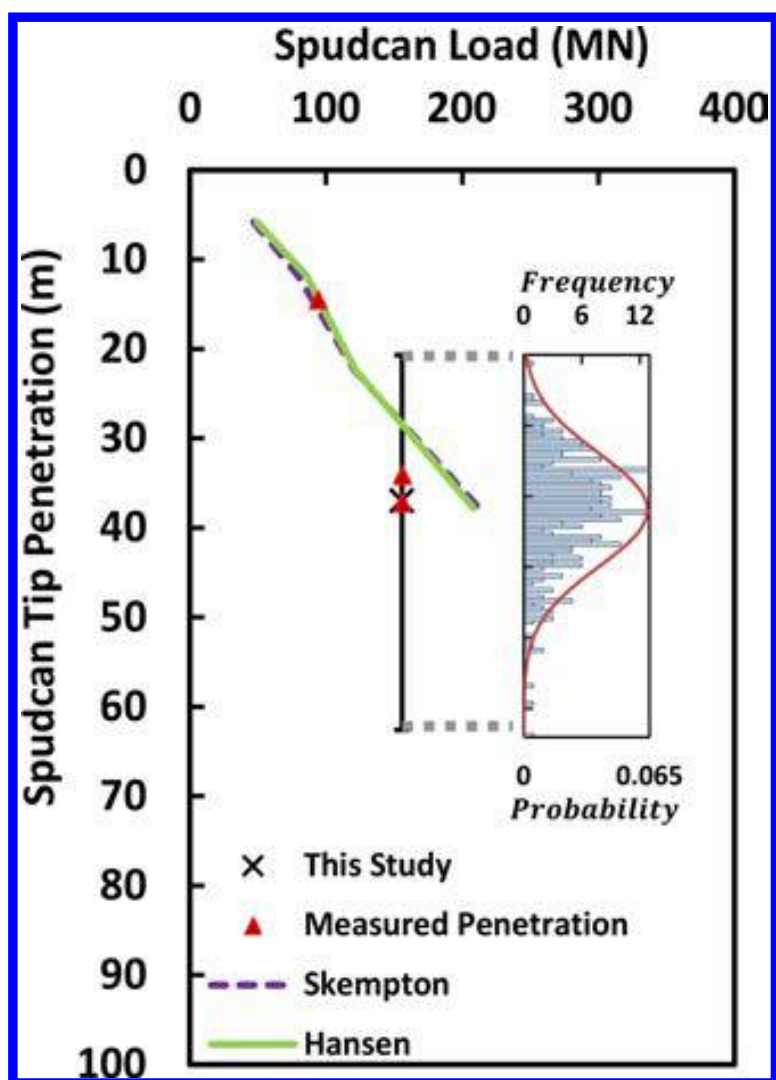

Figure 6. Comparison of the results of PEFE analysis to bearing capacity methods and measured data.

7 SUMMARY AND CONCLUSION

The uncertainty analysis described in this paper was based upon the assumption that the input parameters are statistically independent. Uncertain input parameters were identified by studying the soil condition and installation process. The soil domain was divided into five layers in order to deal with the change of undrained shear strength of the soil with depth. The maximum applied preload was also considered as an uncertain input parameter of the model due to the possible errors in measuring and process of application of the preload.

The Probabilistic Distribution Functions (PDFs) were assigned to each uncertain input parameter based on laboratory and field test results. The Eikos (Ekström 2005) toolbox was used to generate the samples and perform the sensitivity analysis. This MATLAB toolbox was coupled with Finite Element software package, Abaqus (Dassault Systémes 2013). The CEL Analysis was performed for each set of input parameters generated using Latin Hypercube Sampling method. The penetration depth under the preload was estimated using load-Penetration curve obtained from CEL analysis.

The Probabilistic Eulerian Finite Element (PEFE) analysis was first performed for 100 samples. Since the results were not satisfying, the analysis was repeated for 300 samples. The results showed that increasing the number of samples can provide better distribution of the penetration depth and can improve the correlation parameters of output-input relationships.

The histogram over the estimated penetration depth was obtained. The spudcan penetration depth varied over a range of 20.7 m and 62.6 m with the mean value equal to 37 m. The wide range of results indicates the influence of uncertainty in the analysis and underlines the importance of considering it. The mean value of the distribution matched well with the observed penetration depths at site.

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The PEFE analysis takes the uncertainty of input parameters into account and provides a range of outputs with the high probability of occurrence. Considering the uncertain nature of geotechnical engineering problems, the range of output can be much more helpful for designers compared to the estimation of only one value for output. For example, knowing the range of probable estimated spudcan penetration depth under preload can help the designer to identify the potential failure mechanisms such as punch-through. Hence, the designer can provide a safe design that assures the safety of the jack-up rig under the uncertain conditions involved in the installation process. Furthermore, the judgment of the designer in interpretation of input parameters can have a smaller influence on the output of the analysis by performing probabilistic analysis.

ACKNOWLEDGMENTS

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