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Determination of the peak vertical punch-through foundation capacity of jack-up vessels in a multi-layered seabed

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ABSTRACT: Wind turbine installation vessels (WTIVs) are extensively utilized in the offshore industry for their mobility, versatility, and cost-efficiency. In multi-layered soil profiles, where a strong layer overlays a weaker one, rapid leg penetration or punch-through can occur during preloading. This failure mechanism can cause substantial structural damage and result in significant downtime for the vessel. To determine the peak punch-through capacity of spudcan foundations in sand-over-clay profiles within a multi-layered seabed, the industry traditionally relies on the load-spread method as provided in ISO 19905-1:2023. An accurate determination of the load-spread factor is crucial as it can define whether the punch-through is predicted to occur or not during installation which can affect the planning and operational timing of WTIV installations and potential leg reserve issues. This study has investigated the peak punch-through capacity for a typical WTIV using 2D axisymmetric wished-in-place Finite Element Analysis (FEA) in comparison with the load spread method in ISO19905-1:2023 and a more recent approach published in SNAME Bulletin 5-7 J-REG JIP. Throughout the study the main variables affecting the peak punch-through capacity have been identified and a parametric study has been carried out to evaluate the impact of each variable. The study compares the abovementioned methodologies with real site data and illustrates which methods can potentially overestimate the onset of punch-through capacity.

Keywords: Punch-through; Peak capacity; Finite Element Analysis; Hang-up

1 INTRODUCTION

Decades of research and engineering have been spent in trying to accurately estimate the penetration response of jack-up structure's spudcans into the seabed. The importance of realistic predictions of the spudcan penetrations has direct consequences on assessing installation risks and potential mitigation measures, the operability of such structures when fully installed and in elevated conditions and finally on their demobilisation and departure from the location. The knowledge derived from numerous research and engineering developments carried out on this topic for variety of seabed conditions in combination with rich field experience from thousands of installation experiences globally has resulted in the jack-up industry to follow standards such as ISO 19905-1:2023 or SNAME Bulletin 5-7 J-REG JIP. The standards in-use provide multiple calculation methods for different seabed conditions and also, they allow engineering to be carried out by using more sophisticated methods such as Finite Element Analysis (FEA). The purpose of this paper is to assess one specific issue regarding spudcan penetration response (Punch-Through Peak Capacity) with comparing the analytical methodologies provided in the above-mentioned standards along with 2D FEA approach in a parametric study focusing on major variables affecting the foundation failure mechanism. To validate the parametric study, actual penetration records across multiple offshore windfarms in the North Sea have been utilised to shed light on the degree of accuracy and suitability of each method.

The issue of punch-through failure mechanism has been extensively studied with the focus on peak capacity resulting in hang-up scenario (shallow penetrations supported by the top strong layer in a punch-through profile), the rapid penetration phase and potential inclination of the structure and damage to the legs and finally the ultimate penetration depth including any potential soil-plug as presented in publications such as Hosseini-Kamal et al., 2023, Hu et al., 2014, 2015a, 2015b. The focus of the current study is for Wind Turbine Installation Vessels (WTIV) which rely heavily on optimising the applied preload to minimise unnecessary wear and tear and save installation time for increasingly challenging schedules. Therefore, it is critical to estimate the peak punch-through capacity as accurately as possible so such preload optimisation activities can be performed.

2 METHODOLOGY

The current parametric study investigated the following variables in relation to punch-through peak capacity following three different methods, namely the load-spread method using a load spread factor of 4 as outlined in ISO 19905-1:2023, the peak resistance in sand overlying clay method outlined in Appendix 10 – Section 2.2.1 of SNAME 5-7 J-REG JIP and finally 2D axisymmetric FEA wished-in place analyses using PLAXIS software as outlined in Hosseini-Kamal et al., 2023. The variables considered are top sand thickness as a ratio of the spudcan diameter, top sand layer's strength, clay layer's strength, diameter of the spudcan and tip shape of the spudcan. Linear elastic, perfectly plastic soil model is used for all soil layers with model boundary conditions approximately 8 times the spudcan radius and assuming rough contact between the spudcan and the soil layers. Approximately 2500 15-noded triangular elements are adopted for the FEA models.

2.1 Parametric Study

Two WTIVs chosen for the study with different spudcan geometries. The main analysis was performed for WTIV-A, with spudcans approximately 11m in diameter and relatively flat shape with tip length of approximately 1m. A more limited study to evaluate the effect of spudcan shape was also performed on WTIV-B with approximately 15m in diameter and more conical shape with approximately 2.5m tip length.

The analyses performed for WTIV-A, consisted of four different sand thicknesses: 0.25, 0.5, 0.75 and 1.0 times the spudcan diameter and three friction angle values of 30, 35 and 40 degrees, where dilatancy angles calculated following Bolton, 1986 assuming critical state angle of shearing as 30 degrees, representing medium dense, dense and very dense top sand layer respectively. For the clay layer, constant undrained shear strengths of 75, 100 and 125 kPa were considered assuming the layer is sufficiently thick to cause a punch-through.

The above combination of variables resulted in 36 cases which were considered for WTIV-A and for each of the above-mentioned methodologies.

The study performed for WTIV-B, only considered dense sand scenario with friction angle of 35 degrees resulting in 12 analysis cases and 6 additional sensitivity cases for top sand thickness and tip shape of the spudcan.

Linear interpolation was performed between each of the above cases to derive contours and surfaces representing the punch-through peak capacity for the range of variables considered. An example of results for the 2D FEA methodology and for WTIV-A is shown in Figure 1 where x axis represents the top sand thickness normalized with spudcan diameter, y axis represents the sand density (friction angle) and z axis represents undrained shear strength of the clay layer. The surfaces created for different punch-through peak capacity values ranging between 5500 to 10500 tonnes.

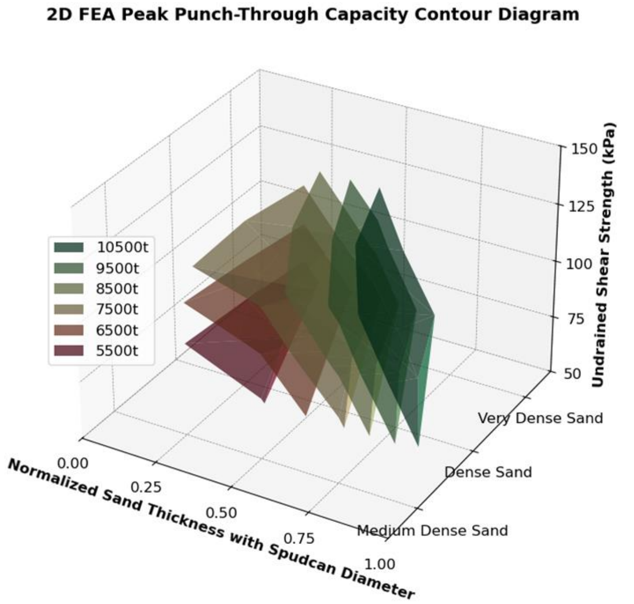

Figure 1. Peak punch-through capacity surfaces for WTIV-A following 2D FEA approach and for the range of top sand thickness & strength and clay strength

2.2 Validation

The validation of the above parametric study was carried out by comparing the results from each of the methodologies outlined above with actual penetration records of WTIV-A across multiple offshore windfarms in the North Sea. To evaluate the punch-through peak capacity, only those penetration records could have been used which showed deep penetrations with no hang-up scenario for the applied preload. Subsequently the applied preload was compared with the punch-through peak capacity of different methods to evaluate the likelihood of a method predicting a hang-up scenario compared to actual penetration response.

3 RESULTS

3.1 Top Sand Thickness

The study showed that there is a significant relationship between the top sand thickness and punch-through peak capacity for all three methods considered with highest dependency evident for the 2D FEA approach as shown in Figure 2. Unlike the two analytical methods which show a linear relationship between the punch-through peak capacity and top sand thickness, the 2D FEA shows a more realistic relationship with thinner sand layer conditions being affected more by the mobilised clay strength compared to thicker sand layers which are less affected by the underlying clay layer within the zone of influence of the spudcan. It should be noted that, a sensitivity analysis is performed for different load spread factors suggested in ISO 19905-1:2023, 3 and 5, but the results were not consequential, and it did not affect the overall observed relationship presented here for the load spread factor of 4.

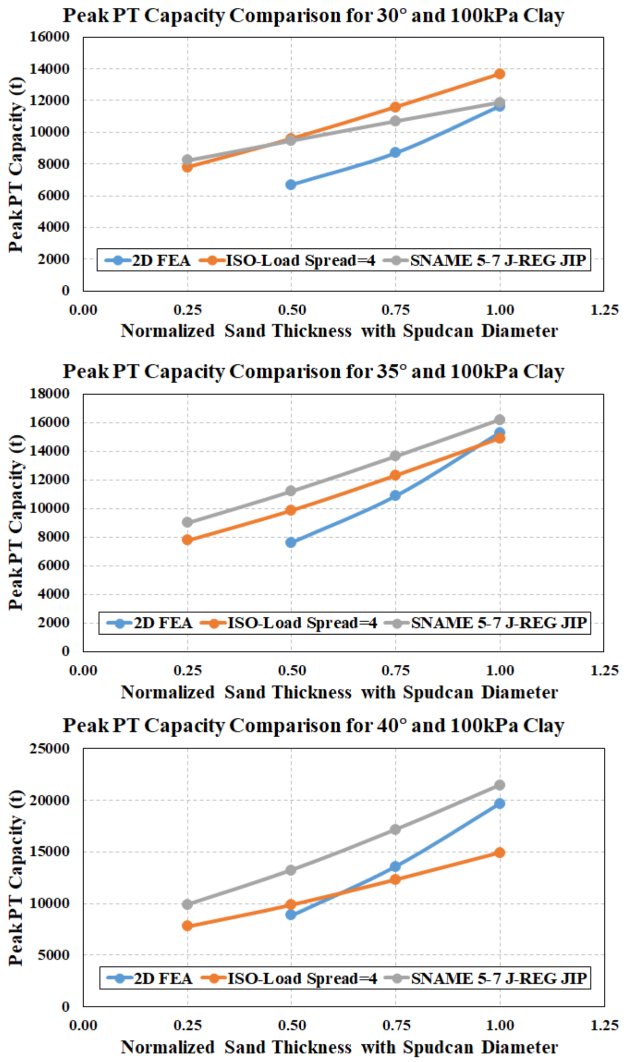

Figure 2. Effect of top sand thickness and strength on punch-through peak capacity

However, one major finding was that both ISO 19905-1:2023 load spread and SNAME 5-7 J-REG JIP methods overpredicted the punch-through peak capacity for a thin sand layer case (0.25 x spudcan diameter) by incorrectly modelling the penetration curve and allowing significant load to be carried by a thin sand layer. In 2D FEA analysis, it was observed that the failure mechanism was extended beyond the top sand layer, mobilising the shear strength of the underlying clay layer and therefore exhibiting a more gradual penetration response instead of typical punch-through response with capacity cut back from the peak followed by rapid penetration. For very dense top sand layer combined with relatively high strength underlying clay, the two analytical methods can predict a hang-up scenario for a thin sand layer overlying clay, which may not occur in real installation and therefore engineers are advised to consider potential consequences of using such methods. An example penetration response for 0.25 x spudcan diameter case is shown in Figure 3.

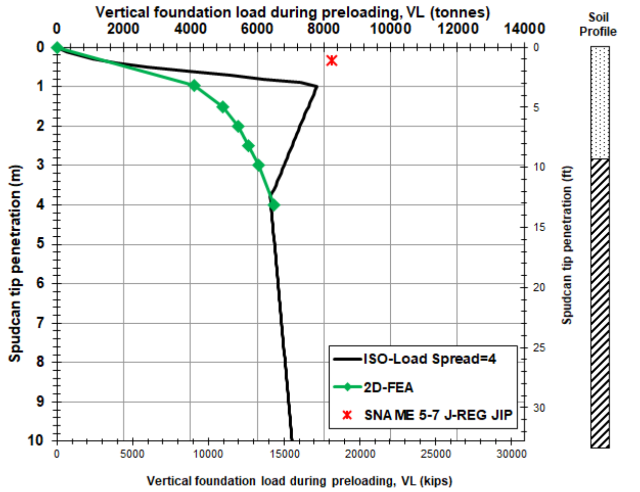

Figure 3. Gradual penetration response evident from 2D FEA analysis in comparison with overestimated punch-through peak capacity from ISO load spread and SNAME 5-7 J-REG JIP methods for thin sand layer of 0.25 x spudcan diameter

3.2 Top Sand Strength

The results that show the effect of top sand layer thickness and strength are presented in Figure 2 for clay strength case of 100 kPa.

As explained earlier, 2D FEA method do not show punch-through failure mechanism for a thin sand layer case and hence there is no value presented on the charts for the thin sand layer case of 0.25 x spudcan diameter for this method.

The results show that the method presented in SNAME 5-7 J-REG JIP overestimates the punch-through peak capacity for thin and medium sand thicknesses compared to the 2D FEA approach. However, for sand thickness of 1 x spudcan diameter the two methods tend to converge for three different friction angles considered in this study.

The SNAME 5-7 J-REG JIP approach shows similar trend as the ISO load spread method for thin to medium top sand thickness for the medium dense condition and friction angle of 30 degrees. However, the SNAME 5-7 J-REG JIP method overestimates the punch-through peak capacity compared to the ISO load spread approach for dense and very dense conditions with friction angles of 35 and 40 degrees respectively. The difference between the two methods significantly increases with the choice of friction angle chosen as the SNAME 5-7 J-REG JIP method incorporates the dilation angle of the sand and hence higher reliance on the top sand capacity compared to ISO load spread method.

The results also suggest that the ISO load spread method generally overestimates the punch-through peak capacity for thin and medium top sand thickness conditions in comparison with 2D FEA approach with the difference between the two methods most evident for lower top sand thickness and friction angles.

The differences in punch-through peak capacity between the three methods, considering the two main variables—top sand thickness and strength—raise questions about the suitability of each method. These differences highlight their limitations and potential for both conservative and non-conservative outcomes, which could have significant implications for the installation and operation of WTIVs.

3.3 Comparison with Real Penetration Data

To benchmark the above parametric study with real site installation data, the authors found 11 recent case histories in which the spudcans penetrated deeper than a hang-up scenario for the applied preload suggesting the top sand layer peak capacity in combination with the underlying clay capacity were not sufficient to cause hang-up scenarios. The limitation in dealing with the in-situ data is that the actual onset of punch-through load is not known, and only final deep penetrations are known for the full preload applied. Therefore, for comparison with the parametric study, the real data are labelled with punch-through peak capacities lower than the applied preload. Therefore, if any of the methods predict a punch-through peak capacity beyond the applied preload, it indicates that the capacity has been overpredicted and a hang-up scenario has been incorrectly assumed.

It should be noted that the differences between the predictions and actual data can be the result of variations in the actual soil conditions in the analysis where uniform soil conditions are assumed and present at the site. These variations could be affecting the choice of strength parameters for both clay and sand parameters, but the differences could also be caused by the thickness and sequence of soil layers which are not captured in the calculated methods. To account for this major unknown in the study, identical soil conditions and parameters are used for each of the three methods and a comparison with real data was then conducted. Therefore, the trends shown in Figure 4 in comparing three different methods are valid regardless of in-situ soil conditions.

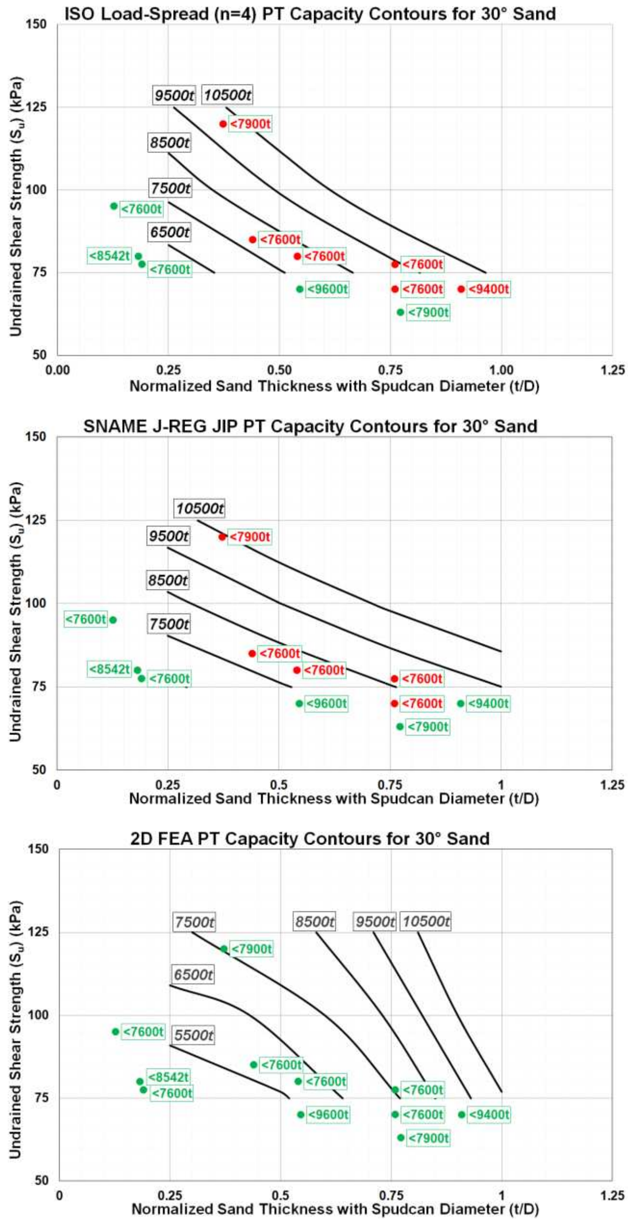

Figure 4. Comparison of real penetration data with predicted punch-through peak capacity for three different methods, green represents correct prediction and red represents overestimated capacity

The different preload values presented in Figure 4 with the solid lines are derived by calculating the peak capacities at defined soil parameters and interpolating them at certain preload levels.

The penetration records are presented relative to the punch-through peak capacity contours for each method, using a sand friction angle of 30 degrees. This value was considered an appropriate estimation of the sand strength across the locations considered in the study.

The results from the comparison with real penetration data prove the trends presented earlier in the paper. Both the SNAME 5-7 J-REG JIP and ISO 19905-1:2023 load spread methods overestimate the punch-through peak capacity for nearly 50% of the locations, while the 2D FEA approach shows 100% agreement with the real site data.

4 CONCLUSIONS

A parametric study was performed to investigate effects of different variables on punch-through peak capacity for three different calculation methods: ISO 19905-1:2023 load spread, SNAME 5-7 J-REG JIP and 2D axisymmetric wished-in-place FEA. The variables studied were top sand thickness and strength, clay strength, and spudcan shape. The results from the parametric study were compared with the real penetration records to validate the outcome and trends observed for each method. Some of the findings and the trends for certain variables are presented here with the main following conclusions:

- both analytical methods outlined in ISO 19905-1 load spread and SNAME 5-7 J-REG JIP overestimate punch-through peak capacity compared with the 2D FEA approach and the real penetration data,
- the above overprediction is more profound for thinner top sand thickness cases and for higher friction angle values,
- the punch-through peak capacity derived from SNAME 5-7 J-REG JIP is highly affected by the strength of the top sand layer resulting in significant overestimation of the capacity compared with the other two methods and for thin to medium thickness of top sand layer,
- 100% agreement was observed for the 2D FEA approach when comparing with the real penetration data, while the other two analytical methods showed 50% agreement for the same soil conditions as those used in the 2D FEA approach.

Based on the initial findings from the ongoing research presented here, it is observed that over reliance of the analytical methods on capacity of the top sand layer is the main reason for over-predicting the punch-through peak capacity. Unlike finite element analysis, these methods are not explicitly capturing the foundation capacities by incorporating the failure mechanism within the zone of influence. Based on the preliminary results of the parametric assessment, it can be concluded that adoption of finite element applications in spudcan penetration assessments in hang-up scenarios could provide more accurate estimation of the peak capacity. The focus of the current paper was to present the outline of the parametric study and share the results on some of the variables affecting the outcome. Further publications would focus on effects of spudcan shape and size, effects of undrained shear strength of the clay, and further comparisons with real penetration data and large deformation FE models.

AUTHOR CONTRIBUTION STATEMENT

R. Hosseini-Kamal: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – original draft. **M. Ilcioglu:** Data curation, Formal Analysis, Investigation, Software, Visualization, Writing – review & editing. **C. Mollaibrahimoglu:** Resources, Validation, Writing – review & editing. **V. Emren:** Resources, Validation, Writing – review & editing.

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