INVESTIGATING SOIL-PLUG FORMATION FOR A SPUDCAN PENETRATING A MULTI-LAYERED SEABED; ANALYTICAL METHODS & 2D FINITE ELEMENT ANALYSIS VS FIELD OBSERVATIONS

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ABSTRACT

Conservatism inherent in current punch-through calculation methods outlined in ISO 19905-1, with exclusion of soil-plug formation in the failure mechanism, would result in inaccuracy in predicting the onset of the punch-through as well as the final penetration depths. Both the potential for punch-through and expected penetration depths would significantly impact the operability of Wind Turbine Installation Vessels (WTIVs) in the ever more challenging Offshore Windfarms (OWFs) environments. The current study investigates two alternative solutions to ISO load spread method, namely load spread with soil plug inclusion and 2D Finite Element Analysis (FEA) including soil-plug. The accuracy of the predictions from the alternative methods and ISO load spread method is compared with actual measured penetrations across 6 OWFs in the North Sea. The study concludes that significant improvement in modelling PT locations can be achieved by using the alternative methods outlined in this paper.

KEY WORDS: Offshore Windfarms (OWFs), Punch-Through (PT), Load spread, Soil-plug, Finite Element Analysis (FEA)

INTRODUCTION

The punch-through (PT) risk is predominantly defined as uncontrolled and rapid penetration of one leg during the installation, or at elevated conditions, which would result in structural damage to the legs and/or total loss of stability. Given that such risk is critical for statically determinate 3-legged structures, the focus of the industry using such structures has been predominantly predicting the potential for a punch-through event with the aim to mitigate the risk [1] & [2]. Therefore, most methods available are derived to predict the onset of the punch-through failure mechanism, namely predicting the load level at which the spudcans penetrate rapidly by mobilising the capacity of the underlying soft clay layer. By predicting the point of punch-through one could mitigate against the risk with cautious preloading with the minimum possible airgap, using relevant safety factor against PT, increased preloading level and holding time or with seabed mitigation measures [7].

Although rapid penetration response is not desirable for indeterminate 4-legged (or 6-legged) structures, given the structural redundancy in the legs and load distribution during the predriving exercise, such an event is more manageable compared to 3-legged structures. What is however more critical for such vessels is the accurate prediction of the spudcan penetration depths which would define the available leg reserve for the vessel operations and provide a better estimation of jacking times and associated geotechnical risks for the vessel owner. With Wind Turbine Installation Vessels (WTIV) working in ever deeper waters, accurate prediction of the final penetration depths becomes more important. Soil-plug formation and its impact on the penetration behaviour and depth has been studied extensively using numerical and model testing [3], [4], [5] & [6] and its importance has been highlighted in practical examples by several authors in the past [8] & [9].

There are three main variables which would affect the accuracy of leg penetration analysis (LPAs); appropriate estimation of the soil properties (in particular, strength properties); capturing the soil layers lateral variability beneath each spudcan; and modelling the failure mechanism correctly. It is widely accepted practice to use low and high estimates for the soil properties given the wide variability in such data. One can of course improve the soil properties estimation by back calculating the properties based on historical spudcan penetration data. The soil lateral variability would manifest itself mostly in differences in experienced penetrations at each leg location and away from the geotechnical borehole or CPT. High resolution geophysical data can be used to improve the considered soil layering variation for each leg location.

In the current study the main objective is to investigate soil-plug formation and its impact on penetration predictions independent from the soil properties and variations in soil layering. As such, a blind testing approach was considered with the soil data across 6 different sites in the North Sea are provided by the rig operator to the consultant for the LPA derivation before sharing the actual penetration records after completion of the predictions. In this sense, the consultant could not calibrate their LPA curves and final penetrations by back calculating the soil conditions. Two methods are considered to derive the spudcan penetration curves in comparison with the load-spread method given in ISO 19905-1: the ISO load spread method adjusted to include the soil-plug used for low estimate (LE), best estimate (BE) and high estimate (HE) soil conditions; and wished-in-place 2D FEA with soil plug considering the best estimate (BE) soil properties. On completion of the penetration analysis, the penetration records were compared with the predictions with the accuracy of the estimates measured against the real data.

METHODOLOGY

SITE DATA

Soil data were provided for 20 locations across 6 different OWFs in the North Sea. The soil data consisted of CPT logs and in some cases laboratory strength test results. Soil data provided for the study were anonymised so no general knowledge of the sites could impact the choice of design parameters. The design soil parameters were solely derived based on the available measured data and the judgment of the consultant engineers performing the assessment. An example of derived soil profile is presented in **Figure 1**.

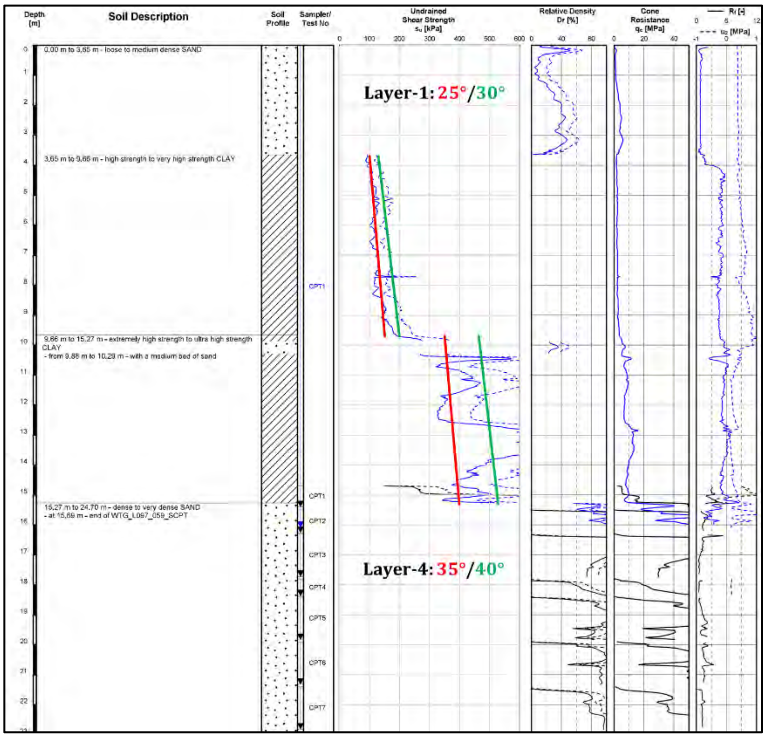

Figure 1 Example soil profile with LE and HE design parameters.

WTIV

The penetration records provided for the current study are for a WTIV with 6 truss legs and spudcan geometry with equivalent diameter of 11m and tip length of 1m. The applied preload varied for each of the locations due to preload optimisation specific for each site. The predictions for all considered methods were based on the applied preload corresponding to the measured penetration depths.

FAILURE MECHANISM; ISO LOAD SPREAD

The load spread method considered in the current study is outlined in ISO 19905-1 as presented in **Figure 2**. For sand over clay cases, ISO suggests a load spread factor, n_s to be between 3 and 5. The load spread factor would impact the point of PT but will not directly impact the predicted penetration should the PT occurs. In the current study load spread factor of 4 was considered. It should also be noted that following the completion of this study, original predictions based on ISO load spread method from the consultancy primarily working on these projects been shared for the comparison with the results in this study. The choice of soil profiles and parameters from the original study were not shared and hence the uncertainty in design soil parameters is inherent in the work of both consultancies following the same analysis methodology.

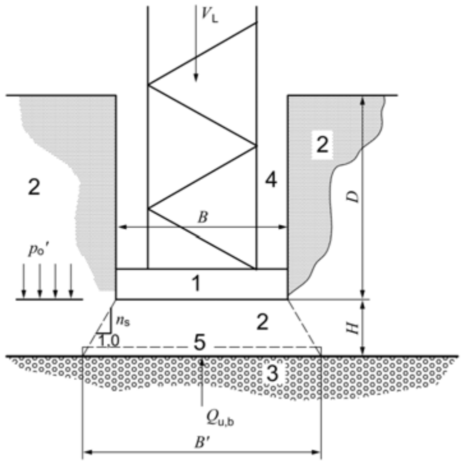

Figure 2 ISO 19905-1 load spread method: schematic failure mechanism.

FAILURE MECHANISM; SOIL-PLUG

The second approach considered in the current study was adjusting the ISO load spread method to include the soil-plug formation with including a certain thickness of the top strong layer as part of the foundation and calculating the vertical bearing capacity at the plug depth. The thickness of the plug has been reported to be 0.9 of the topsoil layer according to the study carried out at University of Western Australia [4]. Based on the experience of current authors, topsoil thickness of 60%, 75% and 90% were considered for the LE, BE and HE soil strengths respectively to provide a reasonable range of expected penetrations. It should be noted that the soil-plug thickness is dependent on the surficial thickness and strength of the strong layer and further parametric studies are required to capture the effect of surficial soil thickness on the plug geometry. **Figure 3** shows a schematic arrangement for the plug approach.

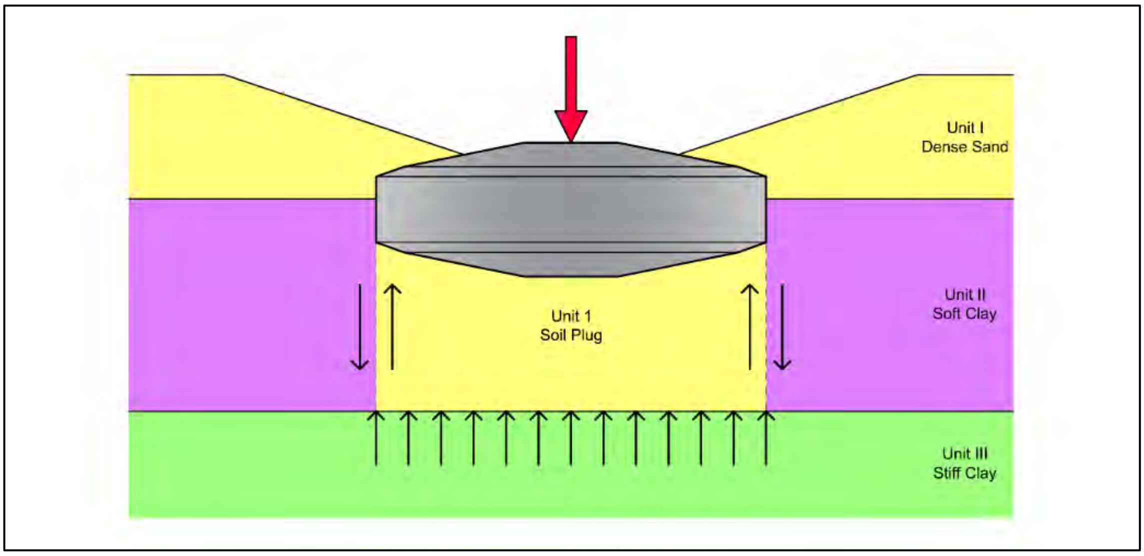

Figure 3 ISO 19905-1 load spread method including soil-plug: schematic failure mechanism.

FAILURE MECHANISM; FEA

To capture a more realistic failure mechanism and hence more accurately predicting the expected spudcan penetrations performing FEA is recommended [1] & [11] Wished-in-place 2D Finite Element Analysis (FEA) with soil plug considering the best estimate (BE) soil properties were performed using PLAXIS 2D software [10]. Axisymmetric condition with 15 noded elements and Mohr Coulomb (MC) constitutive model were considered in the current study. It should be noted that other constitutive soil models can be investigated for a more precise modelling of the soil-plug formation. The spudcan was modelled with non-porous linear elastic material using steel properties. No interface element was considered between the spudcan and surrounding soils replicating a rough footing condition.

The first stage of each analysis started at the spudcan's maximum bearing area resting on the seabed surface. Applied vertical displacement of the spudcan results in the vertical reaction force confirming the vertical bearing capacity at that particular spudcan tip penetration depth. Failure mechanism in the zone of influence was investigated by checking the displacements and shear strain contours to define if the failure was limited to the top strong layer or if the capacity of the weaker clay layer below was also mobilised. If the failure mechanism remained within the top strong layer (generally due to significant thickness of the top layer), spudcan was penetrated further into the topsoil layer without creating the soil-plug.

At the point in which failure zone beneath the spudcan reached the weak layer, the soil-plug geometry was decided according to shear strains and the plug shape was fixed for the subsequent penetration cases. Stability of the soil-plug was verified for each penetration case by checking if the shear failure was going through the plug itself. An example of the plug modelling is shown in **Figure 4** to **Figure 5**.

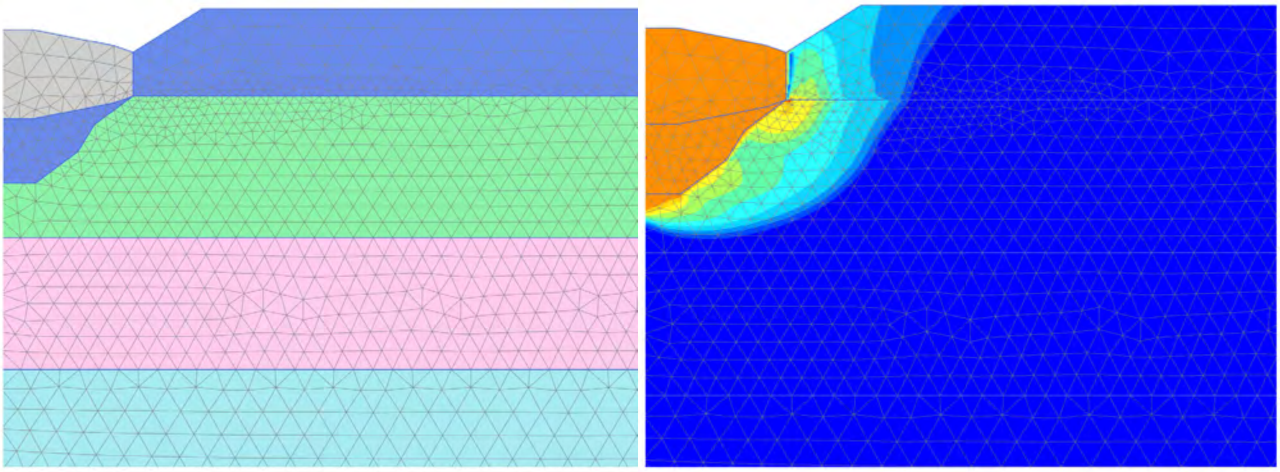

Figure 4 2D FEA model including a soil-plug; a) soil layering, b) total displacement.

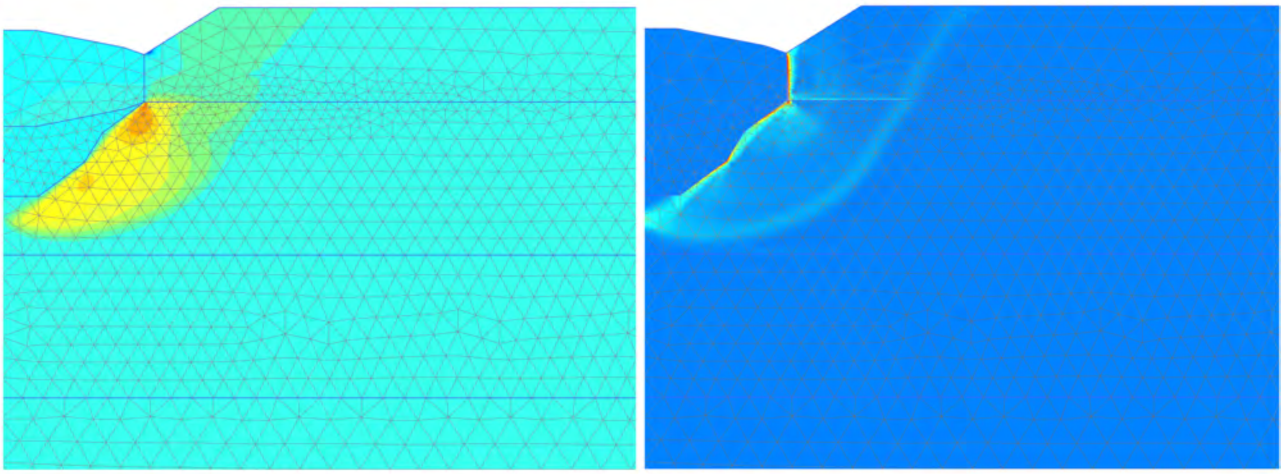

Figure 5 2D FEA model including a soil-plug; a) horizontal displacement, b) shear strain.

The failure mechanism observed in the FEA results varied depending on the soil layer thickness and strength properties. As evident in examples shown above, general shear with punch-through failure mechanism with a degree of clay squeezing was experienced for this particular location. This is an advantage of using FEA which a complex failure mechanism including PT and squeezing and the impact on the capacity and penetrations can be more accurately captured.

An example LPA chart showing the ISO load spread method without soil-plug effect and measured penetrations is shown in **Figure 6** and example LPA chart including the load spread with sand-plug and FEA is shown in **Figure 7** for the same soil profile as presented in **Table 1**.

Table 1 LE and HE soil properties used in the example LPA (Figure 6 & Figure 7).

#	Depth From (m)	Depth To (m)	Soil Type	γ' (kN/m³)	Low Estimate			High Estimate		
					Su Top (kPa)	Su Bottom (kPa)	φ' (°)	Su Top (kPa)	Su Bottom (kPa)	φ' (°)
1	0	3.7	Sand	9.5			30			35
2	3.7	8.5	Sand	9.5			20			25
3	8.5	23.6	Clay	9.5	45	55		70	80	
4	23.6	26.7	Clay	9.5	150	150		200	200	
5	26.7	30	Sand	9.5			25			30

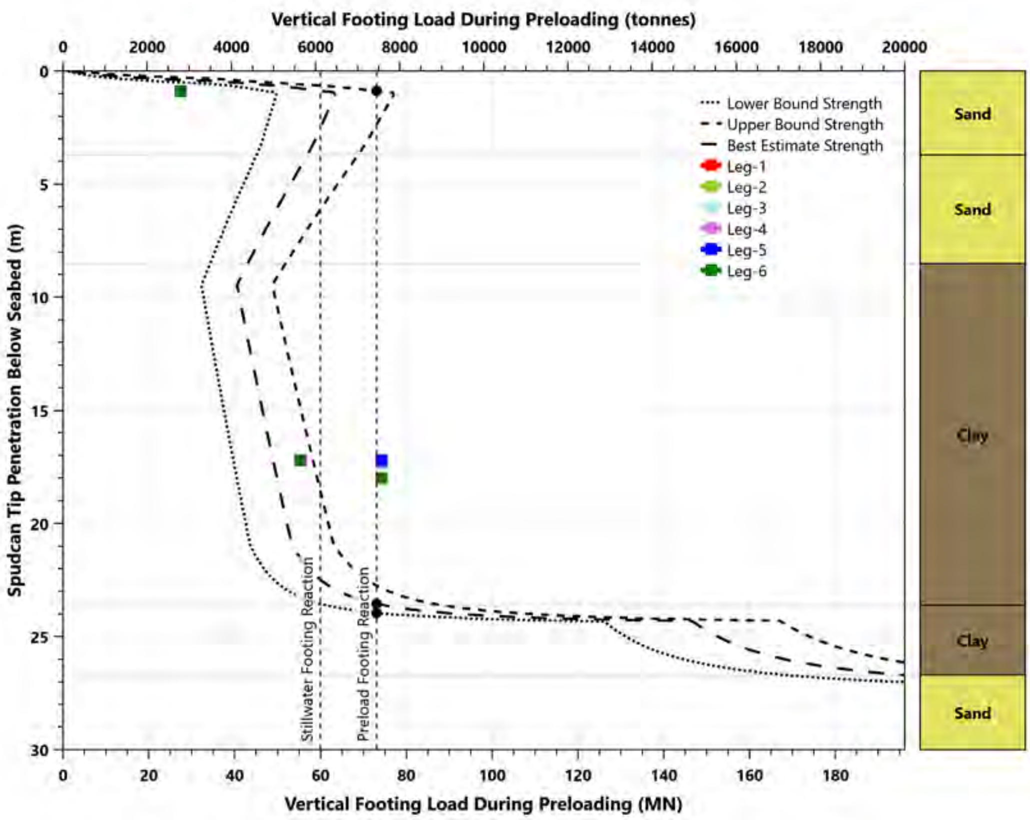

Figure 6 LPA chart with ISO load spread method and measured penetrations (Data points are blocking each other).

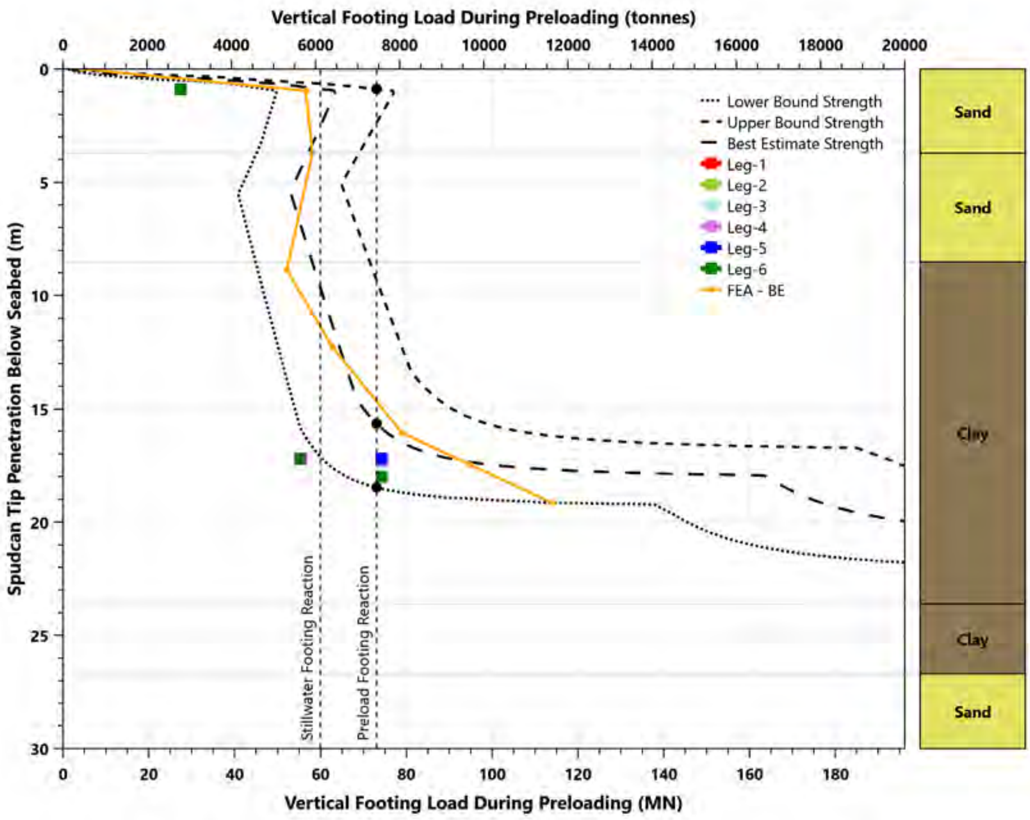

Figure 7 LPA chart with load spread soil-plug and FEA methods and measured penetrations (Data points are blocking each other).

RESULTS

The results showing the range of expected penetrations normalised by the spudcan diameter based on the LE, BE and HE soil properties following the ISO load spread method in comparison with the average measured penetrations and FEA BE predictions are shown in **Figure 8**.

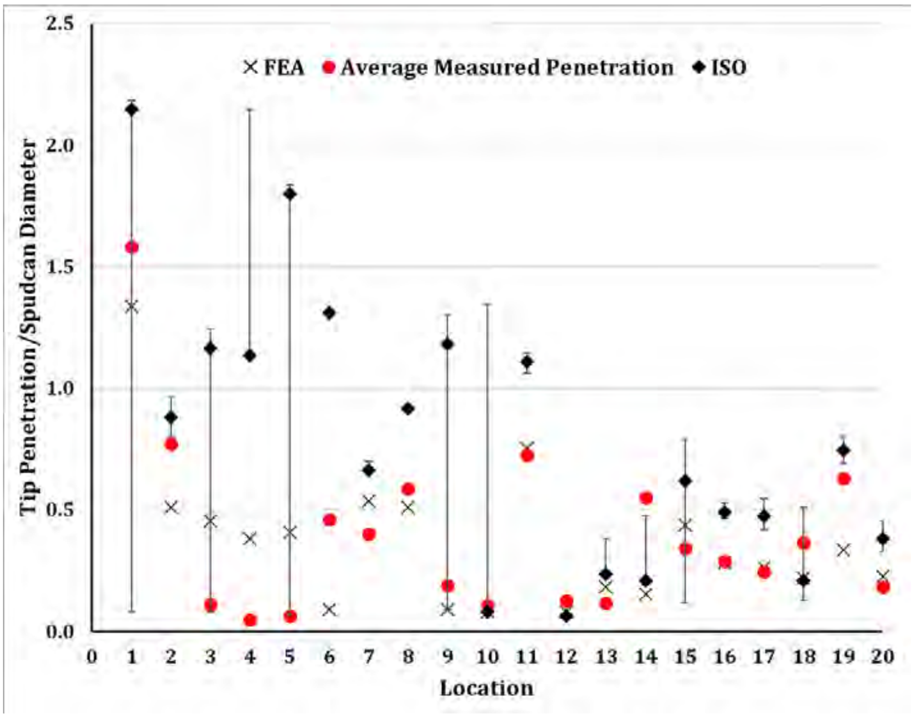

Figure 8 Normalised predicted penetrations based on ISO load spread and FEA methods.

The average accumulative error between the ISO BE predictions and the average measured penetrations is 3.6 times the error between FEA BE predictions and the measured penetrations. It was also noted that the average measured penetrations fall in between the ISO LE and HE predictions for 45% of the locations as shown in the **Figure 9**. It should be noted the original consultant also captured 55% of the locations with their LE and HE predictions in good agreement with the results from the current study. The similar likelihood of capturing the measured penetrations within the LE and BE range for two independent studies following ISO load spread method is suggesting a degree of confidence in consistency of the prediction results regardless of the inherent soil interpretation uncertainties common between the two independent consultancies.

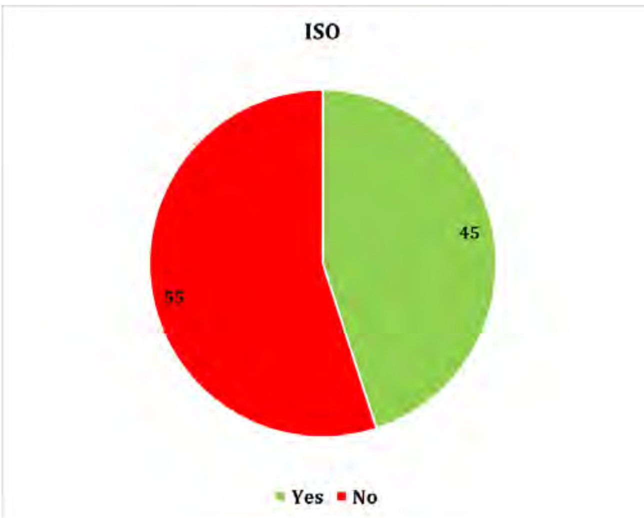

Figure 9 Percentage of the locations where average measured penetrations fall within the predicted range for the ISO load spread method.

The results showing the range of expected penetrations normalised by the spudcan diameter based on the LE, BE and HE soil properties following the soil-plug method in comparison with the average measured penetrations and FEA BE predictions are shown in **Figure 10**.

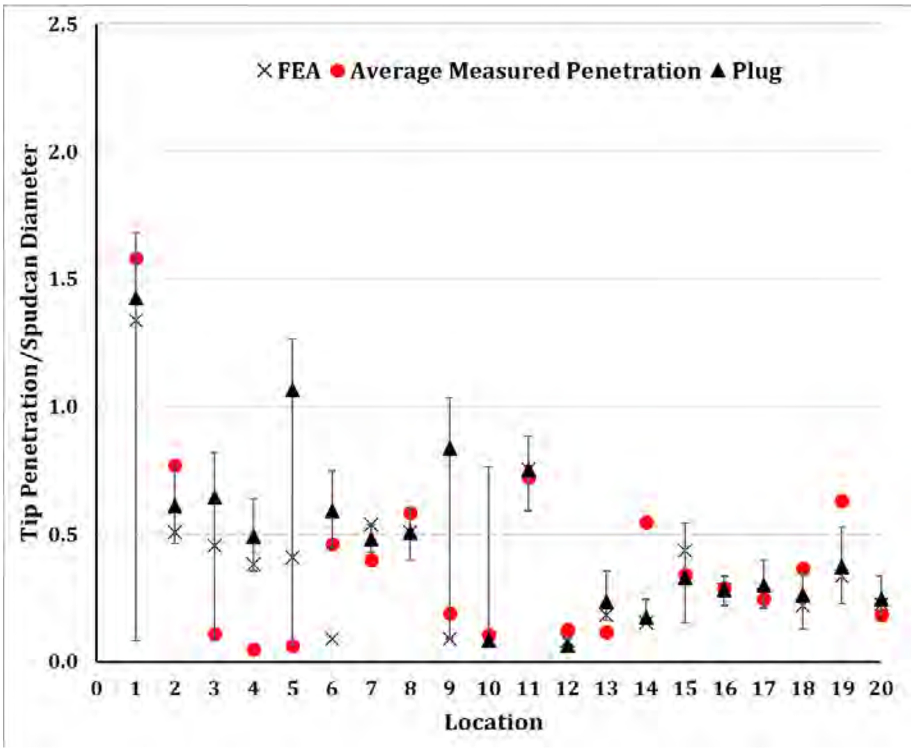

Figure 10 Normalised predicted penetrations based on soil-plug load spread and FEA methods.

The average accumulative error between the soil-plug BE predictions and the average measured penetrations is 1.8 times the error between FEA BE predictions and the measured penetrations. It was also noted that the average measured penetrations fall in between the soil-plug LE and HE predictions for 80% of the locations as shown in the **Figure 11**.

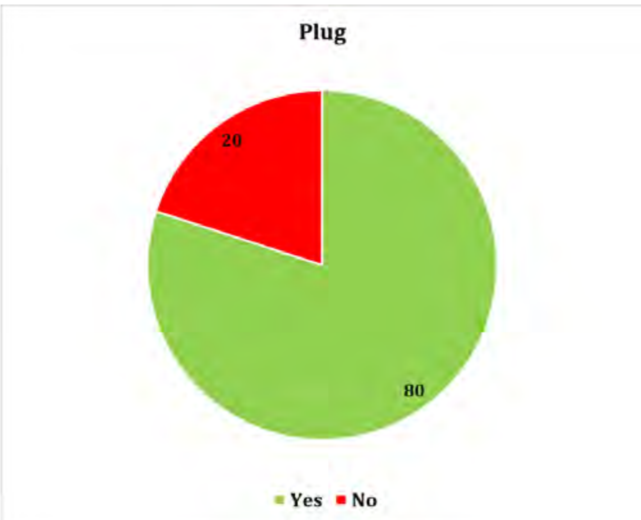

Figure 11 Percentage of the locations where average measured penetrations fall within the predicted range for the soil-plug method.

The above results highlight a clear advantage in using the soil-plug method compared to the ISO load spread method with 35% higher chance of capturing the measured penetration within the LE and HE bounds and 2 times more accuracy on BE expected penetrations when compared with the ISO load spread method. It should be noted that due to time limitations, LE and HE cases were not performed with the FEA method.

To compare the three different methods more clearly, BE predictions for each method relative to measured penetrations are presented in **Figure 12**. A clear trend can be observed with ISO load spread method deviating the most with the actual measured penetrations in comparison with FEA results which show the closest match to the actual measured penetrations. The soil-plug method is also showing a significant improvement compared with ISO load spread method.

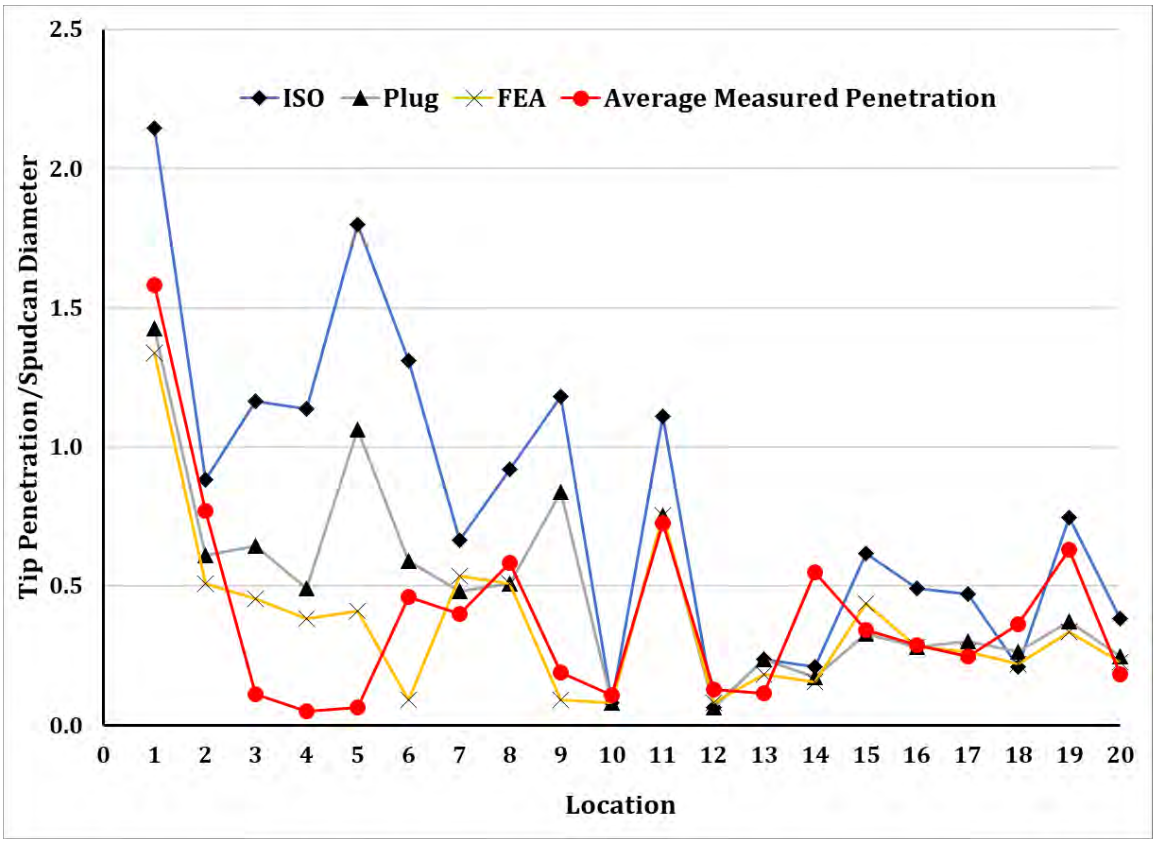

Figure 12 Normalised BE predicted penetrations based on ISO load spread, soil-plug load spread and FEA methods.

The comparison between three different methods for the locations which shallow and hang-up penetrations were achieved are presented in **Figure 13**. Out of 7 locations which experienced hang-up scenario, 3 locations shown a good match between all 3 methods and achieved penetrations. However, at the other 4 locations a clear trend is evident with ISO load spread method significantly over-predicting the penetrations (not capturing the hang-up penetration for the BE case) while FEA method showing the closest prediction to the actual measured penetration depths. The soil-plug method falls in between ISO and FEA results in terms of accuracy of BE predictions.

It should be noted that 5 out of 7 hang-up locations had surficial sand thickness of between half spudcan diameter and one spudcan diameter. The other two locations with thinner surficial sand, however had stronger underlying clay layers which resulted in the hang-up scenario. A parametric study to understand the impact of sand thickness and density as well as clay thickness and strength requires further data pool which is not presently available to this study.

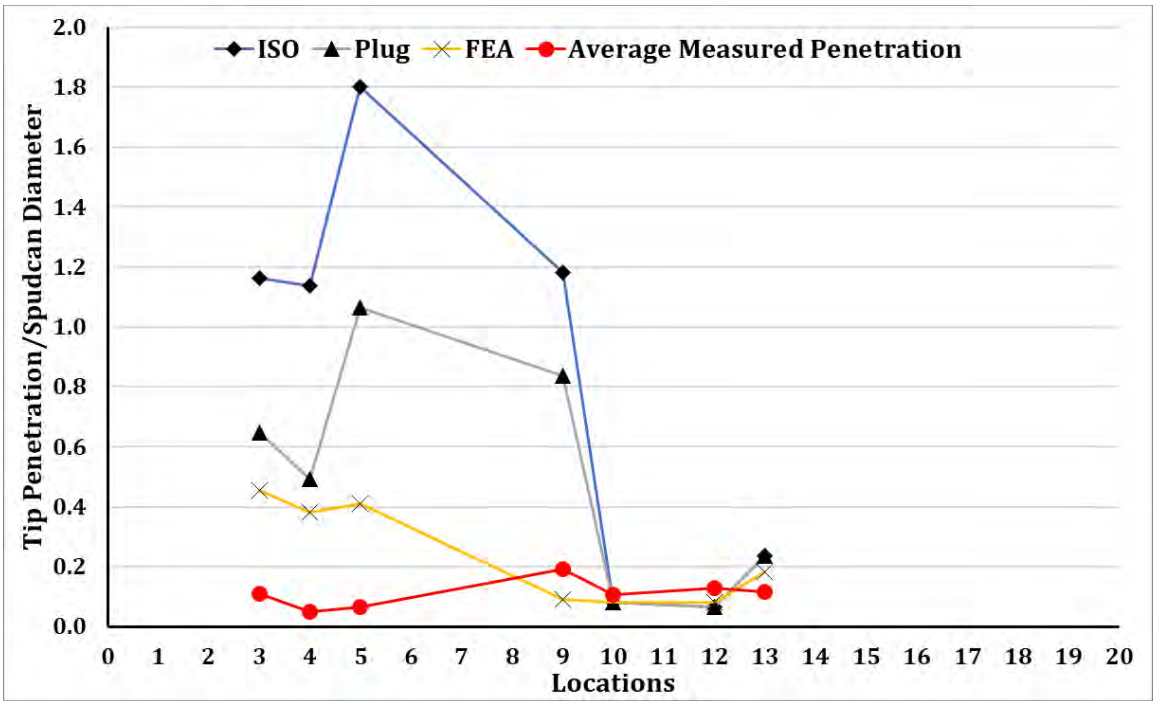

Figure 13 Normalised BE predicted penetrations based on ISO load spread, soil-plug load spread and FEA methods; hang-up locations.

DISCUSSIONS AND CONCLUSIONS

The comparison between three different methods in analysing spudcan penetration response in multi-layered soil condition and actual measured penetrations shown a clear advantage for the methods in which soil-plug is included in the failure mechanism. The current commonly used load spread method outlined in ISO 19905-1 could capture 50% of the measured penetration within the LE and HE soil conditions in comparison with 81% for the analytical method including the plug in the load spread method. The average accuracy of the analytical method including the plug was also 2 times the ISO load spread method. Based on the current study 2D FEA approach showed the closes match with the site measured penetrations for both deep and hang-up scenarios.

Based on the 2D FEA study the actual penetration response for multi-layered soil conditions could be a clear PT with rapid penetration response, squeezing failure mechanism with a gentler penetration response or a behaviour in between the two. The analytical methods both with and without soil-plug are unable to capture the penetration response and hence the advantage of using 2D FEA in deriving a more reliable penetration curve.

The authors recommend that soil-plug formation is included in the ISO load spread method as the first simple check on the penetrations. For critical locations 2D FEA is recommended to provide more certainty in the penetration response as well as on the final expected penetration depths.

The spudcan penetration response in multi-layered soil conditions is affected by multiple variables including the top strong layer thickness and strength as well as the lower weaker clay layer thickness and strength. Further parametric study with larger pool of penetration records is required to quantify the impact of these variables on the spudcan penetration response and expected penetration depths.

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