SPUDCAN PENETRATION ASSESSMENT WITH A TRAPPED SOIL PLUG

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ABSTRACT
An initial assessment of the suitability of a jack up drilling rig for any offshore location relies on a consideration of the required leg length based on estimates of air gap, water depth and leg penetration. This site-specific assessment provides an evaluation of the strength of the rig at a given site, the characteristics of the supporting foundation, and the interaction between the two. For locations where the seabed soils are layered, and stronger layers overlie weaker layers, the risk of rapid leg penetration or punch-through must be considered. Industry guidance documents identify three methods for predicting punching failure of stronger soil over weaker soil; load spread, punching-shear and a trapped soil plug. It is common industry practise to use the punching-shear method but this often results in doubt as to whether the site is suitable for jack up operations. This paper presents several examples of how the trapped plug method has been applied for recent jack up deployments and the benefits this gives in assessing site suitability. Some ideas for further development of the soil plug method are also offered.

KEY WORDS: jack-up, punch-through, soil plug

INTRODUCTION

A leg penetration analysis for a three-leg jack-up considers the change in spudcan penetration as the leg load increases from the initial leg self-weight of the leg to one-third of the total rig self-weight when the preload tanks are full. During these operations the hull is at a minimum airgap above mean sea level for safety reasons and the correct assessment of leg behaviour has a significant effect on the time it takes to install the rig, and therefore the cost.

Methods that may be used to predict spudcan penetration are documented in ISO 19905-1 /1/. For locations where the seabed soils are layered, and stronger layers overlie weaker layers, the risk of rapid leg penetration or punch-through must be considered. Rapid leg penetration is the primary cause in many incidents of rig damage and so, when it is predicted, mitigation measures also need to be developed. Classical mitigations include leg-by-leg preloading and/or hull partial submergence, that may make the rig placement operations very weather sensitive. Unfortunately, the results from the leg penetration analysis methods recommended in /1/ may differ considerably and it is common industry practise to use the punching-shear method - but this often results in doubt as to whether the site is suitable for jack up operations and it difficult to determine if the “mudline” risk or the “metocean” risk requires the most consideration.

The ISO document identifies three methods for predicting punching failure of stronger soil over weaker soil; load spread, punching-shear and consideration of a trapped soil plug. The purpose of this paper is to illustrate how the trapped plug method may be applied and the advantages of doing this.

ALTERNATIVE METHODS FOR THE PREDICTION OF PUNCHING FAILURE

Section A.9 of the ISO document sets out three methods for predicting punching failure of a strong over a weak layer. These are:

- Load Spread: This involves consideration of a larger fictitious footing at the base of the strong material The Insafe JIP /2/ recommends caution when applying this method because it has no theoretical basis and we have not used the approach in this paper.

- Punching-shear: Methods by Hanna & Meyerhof /3/ (sand-over-clay) and Brown and Meyerhof /4/ (layered clay) are based on the strength of the underlying weaker material with an added component of capacity developed by the shearing capacity of a soil plug in the stronger crust. The methods assume the boundary between the units is maintained, with the plug thickness being gradually eroded as the spudcan penetrates: essentially the footing is "wished-in-place" at successively deeper penetrations. When the spudcan reaches the base of the crust its capacity is calculated purely from the strength at the top of the clay.

- Trapped Soil Plug: This is similar the punching-shear methods but the soil plug acts a rigid body, moving with the spudcan as it penetrates. The penetration resistance increases as the plug penetrates the ground and there is a continuing significant contribution from shear against the sides of the plug (and spudcan).

The crucial difference between the wished-in-place and trapped soil plug is illustrated in Figures 1&2. Figure 1 is common to both and shows initial penetration. Figure 2 shows the situation for successively deeper penetrations in the layered soil profile. The wished-in-place situation is shown on the left hand side, the trapped plug on the right hand side.

TRAPPED PLUG ANALYSIS METHOD

Soil resistance for the trapped soil plug situation was assessed for successive spudcan penetrations. Bearing capacity was based on the methods for all-sand or all-clay given in /1/. The frictional shear on the circumference of a rigid soil plug was assessed using the methods given by the American Petroleum Institute and ISO:19902 /5&6/ and added to the bearing capacities.

- In sand, shear stress on the plug circumference depends on the normal stress and friction angle. The normal stress was determined from cone penetration test results by determining the most likely yield stress ratio (YSR) and relative density (D_r) of the soil. These were then used to assign an appropriate ratio of horizontal to vertical stress (K) and combining this with the vertical effective stress.

- In clay, shear stress on the plug circumference was determined from its undrained shear strength (s_u) and a cohesion factor (α).

K can vary from about 0.33 to 3 (from active to passive failure conditions). In normally consolidated soil it is equal to 1-sin(φ), i.e. $K \approx 0.5$, and K increases with YSR. The wished-in-place method /3/ yield points have an implied K value of about 1.5 and would be typically suited to a dense North Sea silica sand.

JACK-UP SITES

Application of the trapped soil plug method is illustrated in this paper with three jack up sites, two from the North Sea and one from the Mediterranean. At each site the spudcan tip penetration depths (z) have been normalised using the spudcan diameter (B) and the undrained shear strengths of the clays normalised with the spudcan bearing pressure at full pre-load (q_b).

SITE 1

The soil profile for this site is summarised in Figure 3. Unit I forms a competent crust of dense sand and hard clay overlying the weaker material of Units II & III, with the strength of Unit II being crucial in the analysis of spudcan penetration. The hard clay of Unit Ib is about three times the strength of Unit II and twice the strength of Unit III. The shear strength of Unit Ib is constant with depth, the strength of Unit II increases linearly with penetration and the strength of Unit III is also constant with depth.

The prediction results are shown in Figure 4. Analyses were run for both a fully backfilled hole and an 11m deep open hole. For the rigid soil plug analyses at this site the shear resistance was considered to act against only the part of the plug still in Unit I in case the soil flow around the spudcan in Units II and III prevents the simultaneous development of shear on the plug sides. An upper-bound line is also given for the open-hole situation for shear against the plug in Units II and III.

A loaded spudcan creates a pressure bulb in the soil that supports it. Figure 5 shows a typical pressure distribution below a circular footing in a uniform elastic material. Figure 6 shows the pressure distribution profile under the centreline of the footing taken from the contours in Figure 5.

In Figure 4 the rig's stillwater and preload forces are shown as constants. The preload is also shown decreasing with depth below the footing, in accordance with the stress profile in Figure 6, to represent the situation prior to the plug's shear resistance being fully mobilized. The factored line represents the situation when the plug resistance is fully mobilised and it is acting as part of the footing, transmitting the full preload, minus the shear component, to the base of the plug.

The trapped plug analyses predict the spudcans will remain close to the seabed with no risk of punch-through occurring. The punching-shear analyses predict a significant punch-through risk at full preload unless some dissipation of the spudcan pressure with depth is included in the assessment. The actual footing penetrations are plotted on Figure 4 and were 0.07B at 90% max preload.

SITE 2

The soil profile for this site is summarised in Figure 7. The Unit I sand is very dense, while Unit II s_u increases linearly with depth at a gradient of 3*z (in kPa and metres). The soils below 1.6B are competent in regards to jack up support and are represented as a hard base in the analyses.

The prediction results are shown in Figure 8. The same range of analyses run for Site 1 were used here with the addition that the rigid plug shear resistance was calculated for principal stress ratios (horizontal/vertical) of both 1.0 and 2.0 to illustrate the effect of YSR and D_r on the results.

Both methods predict the initiation of plug failure at the same load levels but the combination of the increasing strength with depth in Unit II and the presence of Unit III prevent the development of a punch-through for the trapped plug analysis. The punching-shear analyses predict a significant risk of punch-through because of the "disappearance" of the plug unless some dissipation of the spudcan pressure with depth is included in the assessment.

We predicted that the spudcans would remain close to the seabed under full preload with penetration being between 0.03B & 0.065B and no risk of punch-through. At loads greater than full preload we expected the actual load-penetration capacity to lie between the dashed and solid blue lines, representing a partially backfilled hole. The actual footing penetrations are shown in Figure 8 and were 0.04B at full preload.

SITE 3

The soil profile for this site is summarised in Figure 9. It has medium dense sand layers that interrupt a thick clay unit that has an s_u increasing linearly with depth from mudline. The clay Units I & IIIa are of limited thickness, compared to the footing diameter, and their bearing capacity has been calculated using the squeezing failure method given by Meyerhof & Chaplin /7/. A lower bound capacity has also been considered using the method given by Davis & Booker /8/.

The punching-shear analysis prediction results are presented in Figure 10a and the trapped plug results in Figure 10b. The upper-bound prediction in both graphs is derived from the soil strength profile in Figure

9, the lower-bound prediction is obtained by deleting Unit IIIb, making Units IIIa and IIIc contiguous. The trapped plug prediction is for the hole above the spudcan to remain open but a dashed line is shown representing the hole backfilling if the spudcan were to penetrate below 45%B.

The actual footing penetrations were 0.35B at 80 to 90% max preload and these are plotted on the graphs. Furthermore the rig was stable throughout its 5-month deployment. In Figure 10a the spudcan preload is again shown both as a constant and as it might decrease with depth below the footing and a significant risk of punch-through is predicted in both scenarios. It would be difficult to accept the rig at this site based on this prediction and the actual penetrations recorded. In contrast, although the trapped soil plug analyses (Figure 10b) predict the soil plug resistance will be fully mobilized during preloading the strength gradient in Unit III is sufficiently large to prevent this developing unto an uncontrolled leg-run and the good agreement between prediction and actual outcome meant the rig could be accepted with confidence.

FURTHER WORK

The trapped plug analyses in this paper uses K values based on the assessed site stress histories. However, it is possible that up to the point that the plug's shear resistance is fully mobilized the spudcan pressure locally increases the horizontal pressure and therefore the frictional resistance. But, once the plug's resistance is fully mobilized this enhanced stress might no longer apply, giving a sudden reduction in soil support as the spudcan load is transferred to the base of the plug. This would produce a higher peak resistance followed by an actual cut-back, reproducing the shape of the classic punch-through curve.

Because the trapped plug analyses includes realistic K values rather than the implied ones of the punching-shear methods it means that if the prediction is based on the latter methods then a punch-through could happen earlier than expected in loose sand, but only at much higher values in dense sand.

CONCLUSIONS

The punching-shear method, routinely used by the industry to assess sites with layered soil profiles, often results in doubt as to whether sites are suitable for jack up operations. The trapped soil-plug method can resolve this doubt and should be used routinely for jack up penetration predictions.

When compared to a wished-in-place analysis, the results of a soil-plug assessment may show a substantially different risk profile for the planned location. This will allow a more balanced understanding of the metocean and mudline risks.

RECOMMENDATION

That research into the lateral stresses exerted on a soil mass under the influence of a spudcan's bearing pressure be carried out. The soil profile in question should be a competent soil crust overlying weaker soil. The results should examine the stress fields across the plug's shear surface both before and after the mobilisation of the plug's shear capacity.

ACKNOWLEDGEMENTS

Whilst the examples presented in this paper are intentionally unattributed, the authors acknowledge the depth and breadth of the technical discussions held with the owners of the three jack-ups.

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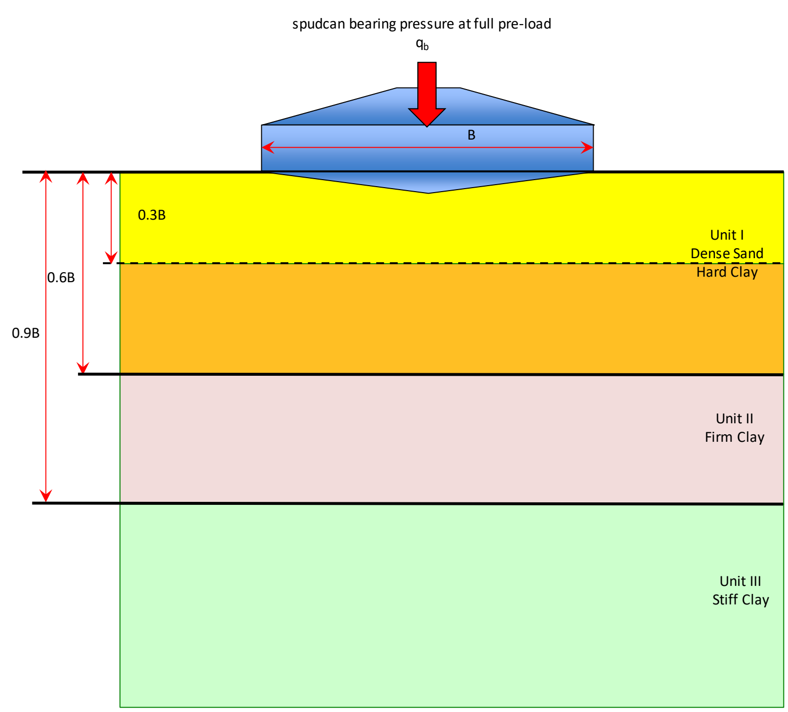


Figure 1 Initial Leg Penetration on a layered soil

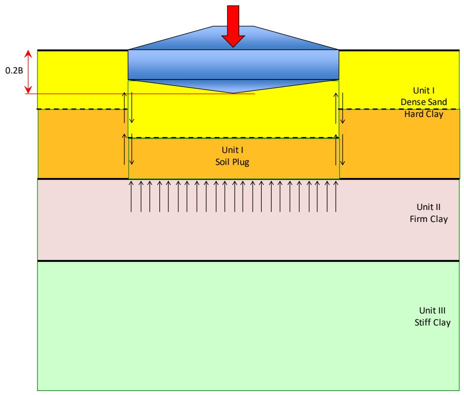
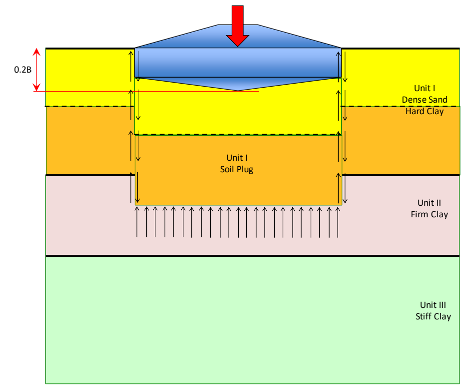
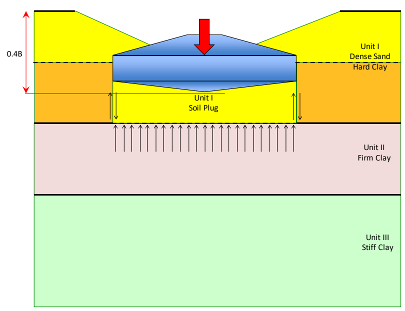
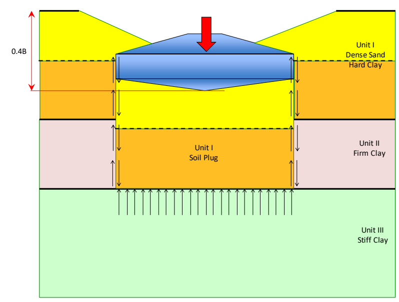
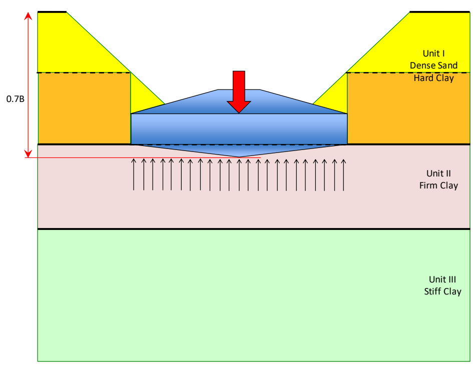
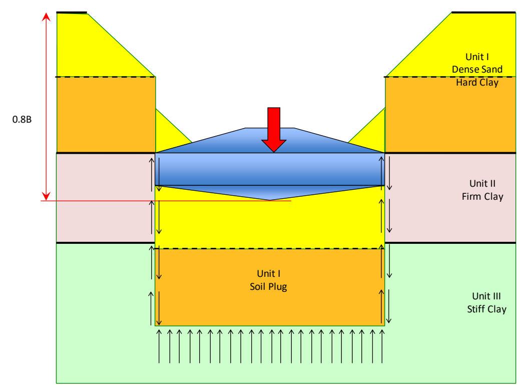
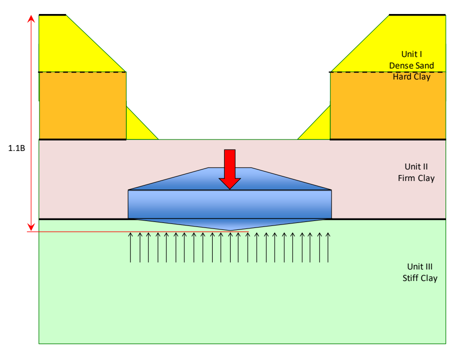
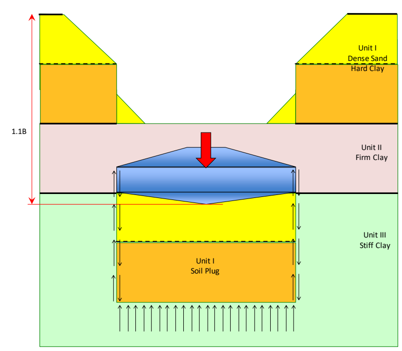
	Wished-in-place	Trapped plug
a		
b		
c		
d		

Figure 2 Leg Penetration Sequences

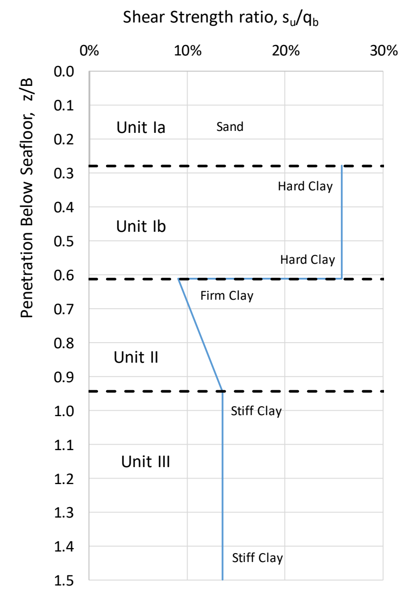


Figure 3 Soil Profile Example 1

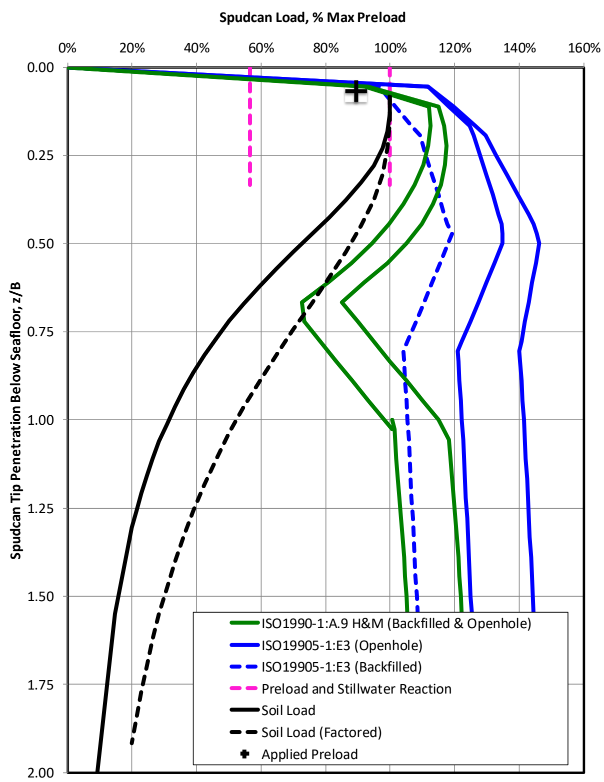


Figure 4 Example 1 Spudcan Penetration Predictions & Actual

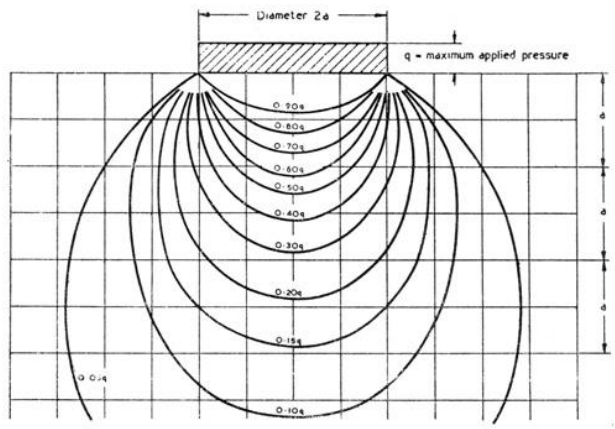


Figure 5 Pressure Distribution below a Circular Footing

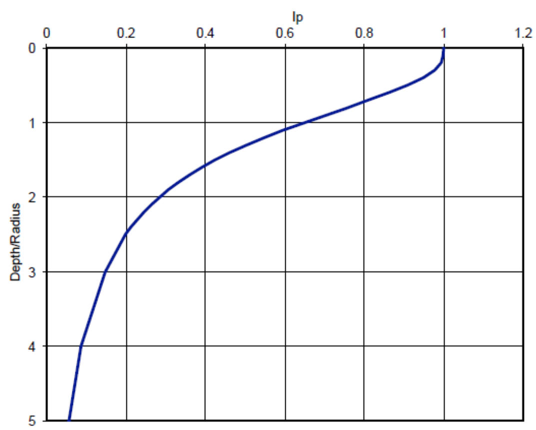


Figure 6 Pressure Profile under the Centreline of a Circular Footing

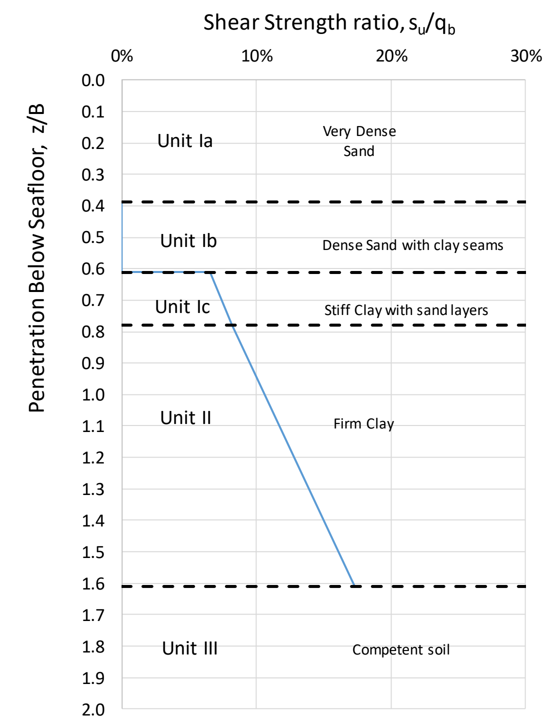


Figure 7 Soil Profile Example 2

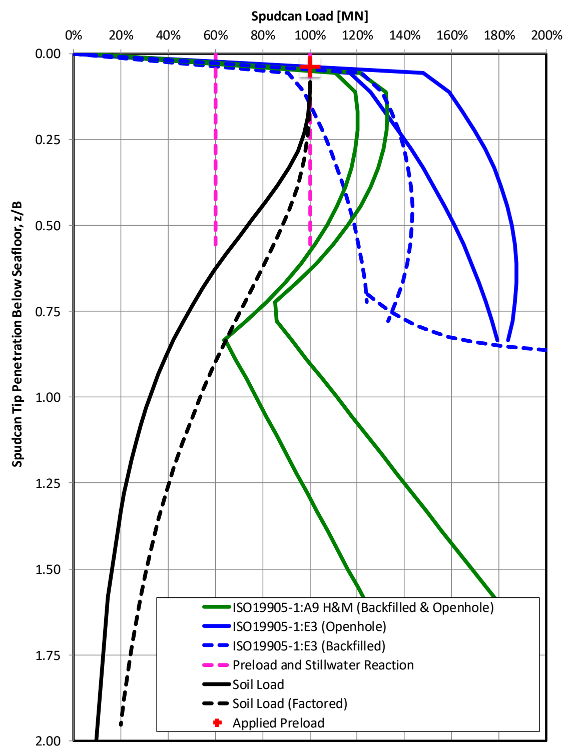


Figure 8 Example 2 Spudcan Penetration Predictions & Actual

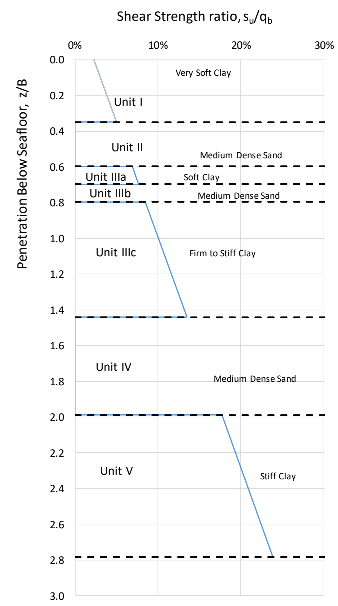
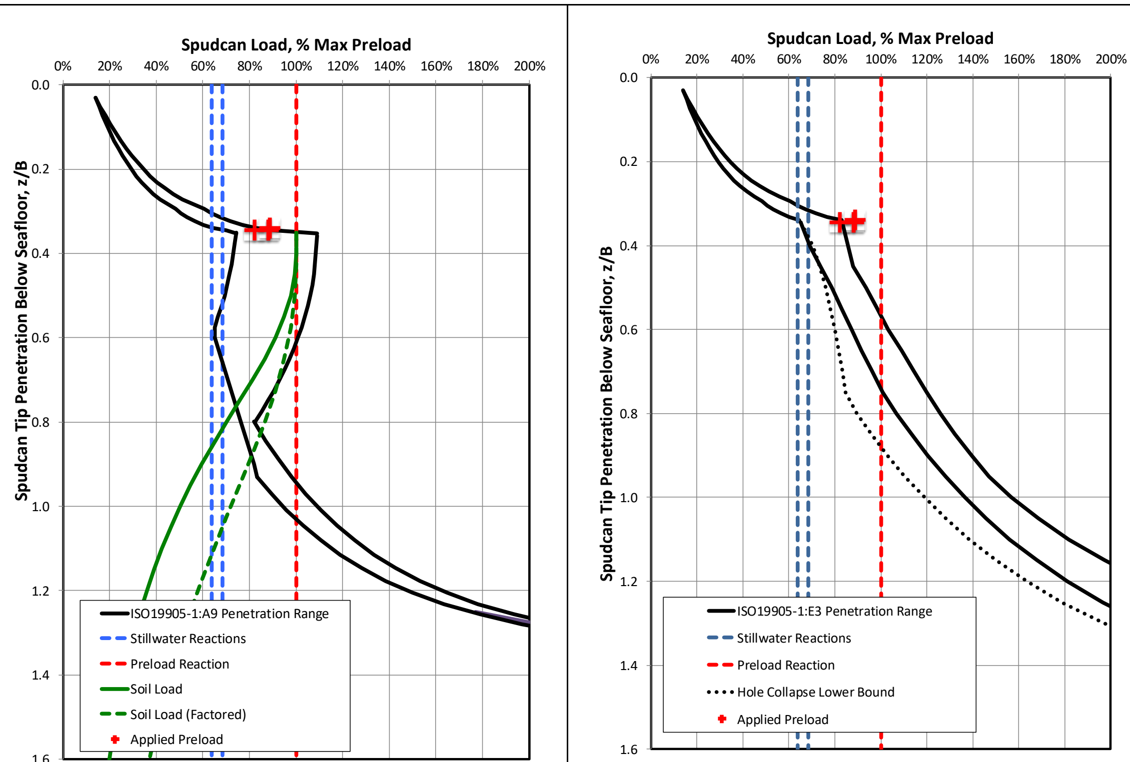


Figure 9 Soil Profile Example 3



(a) H&M

(b) Soil-plug

Figure 10 Example 3 Spudcan Penetration Predictions & Actual