IMPROVING PREDICTIONS OF SPUDCAN PERFORMANCE DURING JACK-UP INSTALLATIONS

Can Mollaibrahimoglu	Cadeler A.S.	Lottie Sharp	Vattenfall
Angelo van Tongeren	Jan De Nul	Okky Purwana*	Geo Oceanics (formerly CORE at NUS)

** corresponding author: okky.purwana@geo-oceanics.com*

ABSTRACT

As part of J-REG joint industry-funded project, a study has been attempted to provide more definitive guidance related to improving predictions of spudcan performance during installation of offshore wind farm jack-ups. In the study, a simplified framework is developed by adapting the state-of-the-art predictive methods and other recent research findings on spudcan penetration mechanisms in multi-layered soils. While the framework involves the integration and simplifications of the mechanism-based methods, the general approach in predicting spudcan bearing capacity for a given penetration depth still follows the procedure described in ISO 19905-1. The proposed framework has been validated using a total of 31 detailed jacking data supplied for the study and 143 centrifuge tests data in the public domain. Large deformation finite element simulations using CEL method were also performed to back-analyse selected site data, to investigate sand plug formation and to assess performance of available constitutive models for realistic modelling of spudcan penetration.

The paper describes the approach for developing the guidance and the performance of the proposed framework for improving predictions of the spudcan penetration in multi-layered soil profiles.

KEY WORDS: offshore wind farm, jack-up, spudcan, penetration prediction, punch-through

1. INTRODUCTION

Despite the considerable number of jack-up installations being undertaken on a daily basis, the reliability of spudcan performance predictions still need improving. There is a tendency for analysts to address the uncertainties in the prediction performance by increasing the prediction bounds rather than its reliability. While research endeavour on revealing the mechanism of spudcan penetration behaviour have been ongoing in the past two decades, the state of practice still embraces simplified methods. The available framework in ISO 19905-1 (Ref. /1/) provides basic formulations for single and two-layered soils with a general guidance for handling multi-layered systems. When dealing with actual seabed conditions which typically consists of multi-layered soils, the wished-in-place bearing capacity equations for two-layered systems are normally somewhat adapted by analysts to suit the multi-layered system based on their judgement and experience.

Despite the simplifications, the current framework is able to predict the final penetration depth reasonably well in many cases. However, the reliability of the present methods for spudcan penetration prediction involving punch-through failure remains uncertain. In addition, the actual trajectory of continuous spudcan penetration may not be consistent with the predicted trend. Relatively wide prediction bounds often conceal the drawback of a spudcan penetration prediction and make it challenging to identify the actual mechanism occurring during real installation.

From extensive research in this subject, several new approaches have been proposed by several studies based on centrifuge tests and numerical simulations. Compared to the existing methods in ISO 19905-1, the new approaches proposed by the recent studies generally predict higher spudcan penetration resistances for the same soil shear strength profile and spudcan bearing pressure. Figure 1a shows the performance of ISO 19905-1 for predicting peak resistance in sand over clay compared to the measured data from centrifuge tests as reported in Zheng et al. (Ref. /2/). The tendency for the underprediction of the peak resistance using ISO 19905-1 method is also observed from the study of Hu et al. (Ref. /3/) based on recorded data from a total of 37 offshore sites as shown in Figure 1b.

For spudcan penetrations in multi-layered soil profiles involving alternating sand and clay layers or stiff clay over soft clay layers, soil plug potentially forms below the spudcan if the applied predrive footing reaction exceeds the bearing resistance of the strong over weak soils. The soil plug influences the post-peak bearing response of the spudcan when advancing further. The mechanism of sand plug development in sand over clay profiles observed from both centrifuge tests and numerical modelling has been revealed by numerous recent studies. The methods described in ISO 19905-1 for predicting spudcan bearing capacity in punch-through soil formations however do not explicitly put a consideration for incorporating sand plug formation post-peak resistance. This can result in an underprediction of spudcan penetration resistance (or overestimation of the predicted leg penetration depth) in multi-layered soils.

While lower predicted resistance derived in a desktop study may be deemed conservative, uncertainties arise as to the leg length availability of a jack-up unit for jacking operation at a site in question. The over-conservatism in the spudcan penetration estimation poses challenges to increasing deployment of offshore wind farm jack-ups at deeper water and frontier regions. An overcautious installation approach may also be taken as a result of the over-conservatism taken in the desktop study. In addition, this situation can also lead to uncertainty in terms of safety margin to the true punch-through resistance if the spudcan hangs up during the actual installation and deviating from the predicted “pushed through” situation.

In the following section, the development of a new framework for improving performance of the spudcan penetration prediction in multi-layered soils is described. The basis for key elements of the proposed framework is discussed. Details of the framework can be found in SNAME TR&B 5-7 and will not be repeated here.

2. OVERVIEW OF PROPOSED FRAMEWORK

In order to improve the performance of spudcan penetration predictions in multi-layered soil, a simplified procedure is introduced by adapting the available methods for predicting punch-through resistance. The key elements of the modified method are derived based on recent research findings in published literatures. Figure 2 describes the key elements of the proposed framework for predicting the peak resistance and post-peak response of spudcan penetration in multi-layered sand-clay soil profiles.

The proposed framework adopts a hybrid method with the combination of bottom-up approach for the first phase and the top-down approach for the second phase. The first phase aims to derive an equivalent soil strength at each soil layer interface to allow the consideration of the effect of successive layers below the foundation base in Phase 2 analysis. In the second phase, the net ultimate bearing capacity is calculated using the criteria for two-layer systems starting from the top layer and the side resistance of any soil plug is included. Despite the simplifications, the proposed framework is expected to capture the essential mechanism of the bearing capacity failure at critical points, e.g., at punch-through depths and at soil layer interfaces, and implementable with a spreadsheet tool.

2.1 Punch through resistance

The mechanism-based method for predicting punch-through resistance in sand over clay is adopted for the proposed framework. The method, which was originally proposed by Okamura et al. (Ref. /4/), Teh (Ref. /5/) and Lee et al. (Ref. /6/), accounts for the stress-dependent behaviour of the shear resistance along the surface of a sand frustum developed below the spudcan until the peak resistance is achieved (occurrence of punch-through). The bearing capacity mechanism proposed by Lee et al. (in Figure 3a) was further developed by Hu et al. (Ref. /7/) with a larger database of numerical simulation and centrifuge test results. It was subsequently refined by Zheng et al. (Ref. /2/) to better fit the centrifuge tests data which was not considered in Hu et al combined with additional numerical simulation results.

Zheng et al. (Ref. /2/) reveals that the Hu et al. method tends to predict considerably high peak resistance for underlying clay of high strength. This could be attributed to the database used for back analysis of the distribution factor which mainly consists of soft clay layer underlying the top sand. The distribution factor D_F refers to the ratio between the normal stress acting on the shear plane and the mean vertical effective stress along the sand frustum. The D_F formula proposed by Zheng et al. (Ref. /2/) is expressed by Eq. (1) as a function of sand thickness over spudcan diameter ratio and normalised soil strength.

$$D_F = 0.642\left[\left(\frac{(0.1\gamma_c' + \rho)B}{s_{u,int}}\right)^{-0.5}\left(\frac{H_s}{B}\right)\right]^{-0.4} \leq 1.8 \;\left(\text{for } 0.16 \leq \frac{H_s}{B} \leq 1.0\right) \qquad \text{Eq. (1)}$$

During the benchmarking, closer agreement between the predicted and recorded peak resistance from the supplied jacking data and published centrifuge model results was observed if the empirical coefficients for the D_F factor expression is further adjusted as given in Eq. (2). As shown in Figure 3b, the modified D_F factor resembles the "average bound" of the data scatters used in Zheng et al (Ref. /2/). The modification adopted in the proposed framework can also minimise the potential overprediction of the peak resistance as discussed in more detail in Section 3.3.

$$D_F = 0.55\left[\left(\frac{(0.1\gamma_c' + \rho)B}{s_{u,int}}\right)^{-0.5}\left(\frac{H_s}{B}\right)\right]^{-0.45} \leq 1.8 \quad 0.16 \leq \frac{H_s}{B} \leq 1.0 \qquad \text{Eq. (2)}$$

2.2 Sand plug height

Height of sand-plug formed at the post-peak stage is one of the crucial parameters which considerably affect the predicted subsequent response of spudcan penetration and the final spudcan penetration at the applied footing reaction during predriving. The sand plug height H_{plug} is normally grossly measured from the spudcan base to the sand plug bottom. Hu et al. (Ref. /8/) found the best-fit sand-plug thickness $H_{plug} = 0.9H_s$ based on centrifuge tests for various spudcan shapes in medium dense to dense sand as can be seen in Figure 5(a). Numerical simulations using CEL technique were conducted in the study to investigate the effect of sand layer thickness over spudcan diameter ratio H_s/B and relative density D_R that potentially influence sand plug height in generic sand overlying clay profiles. The sand plug development was also assessed in the numerical back-simulation of nine site data. As plotted in Figure 5(b) the CEL simulations of the generic cases and the site data suggests that the nominal sand plug height of 0.8-0.9 H_s recommended by several studies appears to remain generally valid for various soil profiles. For practical applications, sand plug height can be assumed to be $0.9H_s$ for very dense sands and $0.8H_s$ for loose sands. Alternatively, a minimum sand plug height of $0.8H_s$ may be used.

The presence of interbedded sand layers in clay does not seem to necessarily lead to an accumulation of sand plug. As the spudcan advances, the sand plug formed by the top sand layer may "break" and push away the successive sand layer particularly if it is relatively thin. Such a complex behaviour may be specific to soil profiles and a generalisation of such findings cannot be made from a limited number of simulations.

2.3 Bearing capacity factor of composite foundation

If the applied predrive reaction is larger than the first peak resistance, punch-through will occur and the spudcan including the trapped sand plug (composite foundation) will advance to the successive layers until it is equilibrated with the soil resistance at deeper depths as shown Figure 4a. The bearing capacity factor of the composite foundation is expected to differ from that for the spudcan alone.

The back-analysed bearing capacity factor from finite element simulation for uniform clay as reported in Lee (Ref. /9/) was modified by isolating it from the side friction along the height of the sand plug, which for simplicity is assumed to be cylindrical. The bearing capacity factor is applicable when the composite foundation has fully penetrated the underlying clay layer. By imposing a limiting value of N_c=11.3, the bearing capacity factor profile with depth is consistent with centrifuge tests data reported in Hossain & Randolph (Ref. /10/) for homogeneous clay.

2.4 Effect of multiple successive layer

The majority of existing analytical predictive formulae were developed for idealised two soil layers. For the implementations of such methods in more complex multi-layered soil profiles involving more than two-layered soils, modifications to the existing framework are required. The effect of layered soils on the spudcan penetration behaviour should be accounted for to enable reasonable predictions of post-peak resistance and final penetration depth. The aspects that need to be considered for predicting post-peak resistance of the composite foundation include the foundation influence zone below the base of the composite foundation, equivalent soil shear strength of the subsequent layers and foundation resistance in two-layered soils.

In the event that two soil layers are detected within the influence zone, the average shear strength between the foundation base and the interface with the subsequent layer is determined and used to represent the shear strength of the top clay layer $s_{ut,ave}$. The shear strength of the bottom layer, $s_{ub,eq}$, is taken as the equivalent strength of the layer calculated in the previous calculation stage using the bottom-up approach. This enables the bearing capacity calculation to be performed using bearing capacity equations for two-layered systems.

3. PERFORMANCE OF PROPOSED FRAMEWORK

Performance of the proposed framework was benchmarked against site data supplied by the JIP participants for this study and published centrifuge tests data. The objective of the validation is to achieve not only consistent and sensible prediction of peak resistance but also the final penetration depth and the overall spudcan penetration behavior compared to the recorded data. In total, 31 sets of actual penetration records from offshore wind farm sites have been supplied used for the benchmarking. The supplied site data covers various spudcan shapes, i.e., rectangular, semi-circular and hexagonal, with the nominal predriving bearing pressure ranging from 520 kPa to 920 kPa. The soil profiles at the sites vary from a simple sand over clay profile to a complex multi-layered sand-clay system.

A total of 143 centrifuge tests data on sand over clay were also collected for the validation. The prototype spudcan diameter used for in the centrifuge tests ranges from 0.8m to 20m and with a ratio of H_s/B = 0.16-1.6. The sand relative density D_R varies from 25% to 98%. The footing bearing pressure measured in the centrifuge tests is up to 1,200 kPa which should cover the highest predrive bearing pressure of the modern offshore wind-farm jack-ups.

3.1 Comparison with recorded site data

Example validations of the proposed framework using the recorded site data at various levels of complexity of sand-clay soil profiles and for different spudcan shapes are shown in Figure 7. The corresponding predictions using ISO 19905-1 method without inclusion of sand plug are also included in the figure. In general, using the proposed framework the predicted spudcan load-penetration responses are consistent with the actual detailed jacking data. For locations without detailed load penetration data, the proposed framework can provide a reasonable estimate of final spudcan tip penetration depth with the incorporation of sand plug. On the other hand, using the ISO 19905-1 framework and without sand plug consideration, the peak resistance tends to be underestimated while the final penetration depth appears to be overpredicted partly due to the absence of sand plug effect in the computation. There are several sites where the predictions somewhat deviate from the actual spudcan penetration behaviour. Due to the limited number of boreholes and the distance between the borehole and the spudcan location, the potential lateral soil variation between the spudcan positions could not be captured in the analysis. Nevertheless, the predicted trend of the load-penetration response shows good agreement with the recorded data.

3.2 Comparison with published centrifuge and numerical data

Using the same input parameters reported in the public domain, the predicted peak resistance and overall spudcan load-penetration responses from the proposed framework are consistent with the measurement from the centrifuge modelling and the reported numerical simulation results. The effect of sand relative density and sand layer thickness are well captured by the proposed framework as shown in Figure 8. The performance of the various predictive methods against the centrifuge tests data is also investigated. In Figure 9, scatter plots of calculated versus measured peak resistance are shown. It is evident that the performance of Zheng et al. (Ref. /3/) method with the use of modified D_F proposed in the new framework is superior to the other predictive methods. Hu et al. (Ref. /7/) method is observed to somewhat overestimate the peak resistance. On the other hand, based on these datasets the tendency for underpredicted peak resistance is observed from the ISO 19901-5 recommended methods. The latter finding should be verified further with a larger database from either site data or centrifuge tests.

3.3 Model factor

The performance of the various predictive methods against the 143 centrifuge tests data is evaluated in terms model factor (γ_M) which is defined as measured peak resistance ($Q_{peak,m}$) over calculated peak resistance ($Q_{peak,c}$). Model factor can be thought of as a simplified parameter to measure lumped uncertainties inherent in a design method which can be contributed from the uncertainty in design input parameters, model uncertainty and measurement errors. If the calculated model factor equals one ($\gamma_M = 1$), it means a perfect match between measured and calculated values. Model factor less than one ($\gamma_M < 1$) means that the calculated value is larger than the measured value (i.e., the prediction method overestimates the actual value). Model factor more than one ($\gamma_M > 1$) implies that the calculated value is smaller than the measured value (i.e., the prediction method underestimates the actual value).

As summarized in Table 1, the mean model factor for the proposed framework is 1.050 with a coefficient of variation (COV) of 0.201 while that for Zheng et al. (Ref. /3/) and Hu et al. (Ref. /5/) are 0.948 and 0.903 respectively. The statistics of the model factor implies that the Zheng et al. method (Ref. /3/) and the proposed framework can provide unbiased estimation of the punch-through capacity on sand overlying clay on average (mean ≈ 1), with a low degree of variability (COV < 0.3). From the installation and risk management perspective, a model factor slightly larger than 1.0 is desirable compared to the model factor slightly smaller than 1.0. A slight underestimation of peak resistance will enable early anticipation of rapid penetration risk during installation as compared to the overestimation case.

Table 1 Model factor of various predictive methods against 143 centrifuge tests data

Predictive Method	Mean	COV	Range
Proposed framework (with Modified D_F)	1.050	0.201	0.509 – 1.643
Zheng et al. (2022)	0.948	0.188	0.456 – 1.549
Hu et al. (2014)	0.903	0.189	0.389 – 1.410
Load spread (1h:3v)	1.786	0.309	0.672 – 3.611
Hanna & Meyerhof	1.695	0.207	0.753 – 2.547

4. NUMERICAL SIMULATIONS FOR SPUDCAN PENETRATION

In recent years, advancement in finite element methods specifically in tackling large deformation problems has made a realistic and continuous spudcan penetration simulation possible. A series of Coupled Eulerian Lagrangian (CEL) simulations were performed in the present study to further investigate the sand plug development and its sensitivity to the selected soil constitutive model besides back-simulating the recorded penetrations at six sites. The same input soil parameters used in the analytical prediction for the respective sites are adopted in the numerical simulations. Spatial migration of soil state parameters due soil flow (material tracking) and strain softening of the clay layer were incorporated for a realistic simulation of spudcan penetration response.

An example comparison of sand plug height modelled with modified Mohr-Coulomb (Ref. /11/) and sand hypoplastic models (Ref. /12/) is shown in Figure 10. In general, the CEL simulated sand plug heights with modified Mohr-Coulomb model are generally greater than that simulated using the sand hypoplastic model. This is consistently observed in various spudcan shapes, soil profiles, as well as relative densities and initial thicknesses of the top sand layer considered in the numerical analyses. The sand plug height from the sand hypoplastic model ranges from 0.8 to 1.0H_s which is comparable with the observation reported in various publications. On the other hand, the modified Mohr-Coulomb tends to produce sand plug height which is almost identical to the initial thickness sand layer. This implies that the stress-dependent deformation characteristic of the sand plug is better captured by the sand hypoplastic model.

Examples of CEL simulated spudcan load-penetration responses at two of the selected sites are shown in Figure 11a for a simple soil profile and in Figure 11b for a relatively complex stratigraphy. The CEL simulations presented in the present study demonstrate that a realistic spudcan load penetration response in multi-layered soils can be produced with proper input soil parameters. Both modified Mohr-Coulomb and sand hypoplastic models are able to reasonably capture detailed response of a penetrating spudcan. Although the bearing pressure profile can be predicted relatively well in the validation case for simple sand overlying clay profiles, the limitation of modified Mohr-Coulomb model is exacerbated in the multi-layered soil profiles. The modified Mohr-Coulomb model is observed to underpredict the peak resistance in certain soil profiles. Underestimation of the final penetration depth with modified Mohr-Coulomb model is also possible whenever the simulated sand plug is thicker than the realistic condition.

5. SUMMARY

The present study describes a simplified framework for handling spudcan penetration in multi-layered sand over clay soil profiles which has been developed by adapting the mechanism-based predictive methods and other recent research findings on spudcan penetration mechanisms in multi-layered soils. The proposed framework provides an alternative to implementation of the bearing capacity equations in ISO 19905-1 for multi-layered soils. While the framework involves the integration and simplifications of the mechanism-based methods, the general approach in predicting spudcan bearing capacity for a given penetration depth still follows the procedure described in ISO 19905-1. The proposed framework has been benchmarked against detailed records of load-penetration at various soil profiles and for different spudcan shapes as well as published centrifuge tests data. The study has also demonstrated the feasibility of advanced numerical methods for realistic simulations of spudcan penetrations including in complex soil profiles.

Despite the validations performed and the positive outcome achieved in the present study, the benchmarking exercise should be continued with more installation records and more detailed assessments of input soil parameters representative of the subject wind farm site. With a larger database, the performance of and potential improvements to ISO 19905-1 methods or alternative framework adopted by analysts can be better identified. Adequate number of borehole sampling and laboratory shear strength data is imperative for the calibration of cone factors and the reliability of design soil profile for spudcan penetration analysis or back-analysis of installation data.

6. ACKNOWLEDGEMENTS

This study forms part of the research funded by J-REG Joint Industry-funded Project. The authors acknowledge extensive supports and permission from the funding participants for publishing the work: ABS, Cadeler, DEME Group, EDF Renewables, F&G, GustoMSC, Jan De Nul, Ørsted, Scottish Power, Shell, Van Oord and Vattenfall. Detailed site and jacking data provided by Vattenfall, Jan De Nul, DEME Group, Cadeler and Ørsted for the purpose of the study are greatly acknowledged.

7. REFERENCES

[1] ISO 19905-1. (2016). Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 1: Jack-ups, 2016.

[2] Zheng, J., Chen, Y., Chen, X., Wang, D. and Jing, S. (2022). Improved Prediction of Peak Resistance for Spudcan Penetration in Sand Layer Overlying Clay. Journal of Geotechnical and Geoenvironmental Engineering 148(1): 04021174.

[3] Hu, P., Haghighi, A., Coronado, J., Leo, C., Liyanapathirana, S. and Li, Z. (2021). A comparison of jack-up spudcan penetration predictions and recorded field data, Applied Ocean Research 112.

[4] Okamura, M., Takemura, J. and Kimura, T. (1998). Bearing capacity predictions of sand overlying clay based on limit equilibrium methods, Soils Found 38(1), pp. 181–94.

[5] Teh, K.L. (2007). Punch-through of spudcan foundation in sand overlying clay, PhD thesis, National University of Singapore, Singapore.

[6] Lee, K.K., Randolph, M.F. and Cassidy, M.J. (2013). Bearing capacity on sand overlying clay soils: a simplified conceptual model, Geotechnique 63, No. 15, pp. 1285–1297.

[7] Hu, P., Stanier, S.A., Cassidy, M.J. and Wang, D. (2014). Predicting peak resistance of spudcan penetrating sand overlying clay, J Geotech Geoenviron Eng 140(2): 04013009.

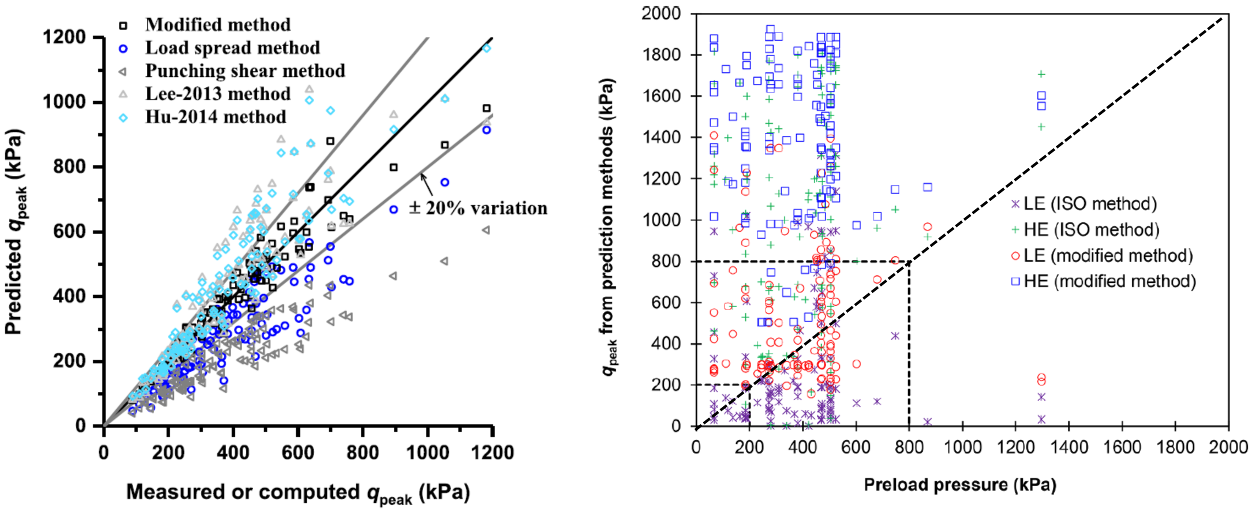
[8] Hu, P., Stanier, S.A., Wang, D. and Cassidy, M.J. (2016). Effect of footing shape on penetration in sand overlying clay, Int J Phys Model Geotech 16(3), pp. 119–33.

[9] Lee, K.K. (2009). Investigation of potential spudcan punch-through failure on sand overlying clay soils, Ph.D. thesis. Perth, Australia, University of Western Australia.

[10] Hossain, M. S., & Randolph, M. F. (2009). Effect of strain rate and strain softening on the penetration resistance of spudcan foundations on clay. International Journal of Geomechanics, 9(3), 122-132.

[11] Hu, P., Wang, D., Stanier, S.A., Cassidy, M.J. (2015). Assessing the punch-through hazard of a spudcan on sand overlying clay. Geotechnique 65(11), pp. 883–96.

[12] Herle, I. and Gudehus, G. (1999). "Determination of parameters of a hypoplastic constitutive model from properties of grain assemblies". Mechanics of Cohesive-frictional Materials: An International Journal on Experiments, Modelling and Computation of Materials and Structures, 4(5), 461-486



a) Centrifuge tests vs analytical predictions (Ref. /2/)

b) Site data vs analytical predictions (Ref. /3/)

Figure 1 Performance of ISO 19905-1 method for prediction of peak resistance in sand over clay

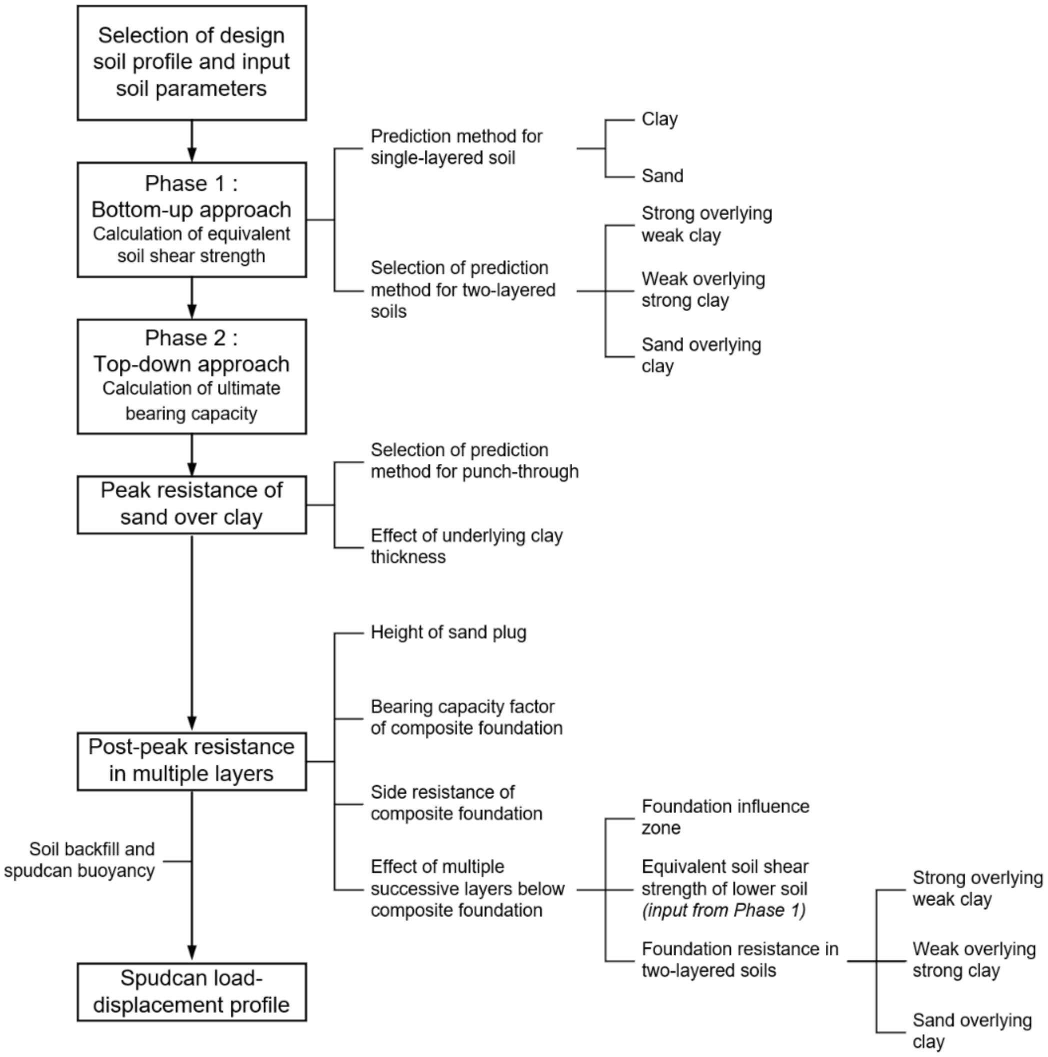
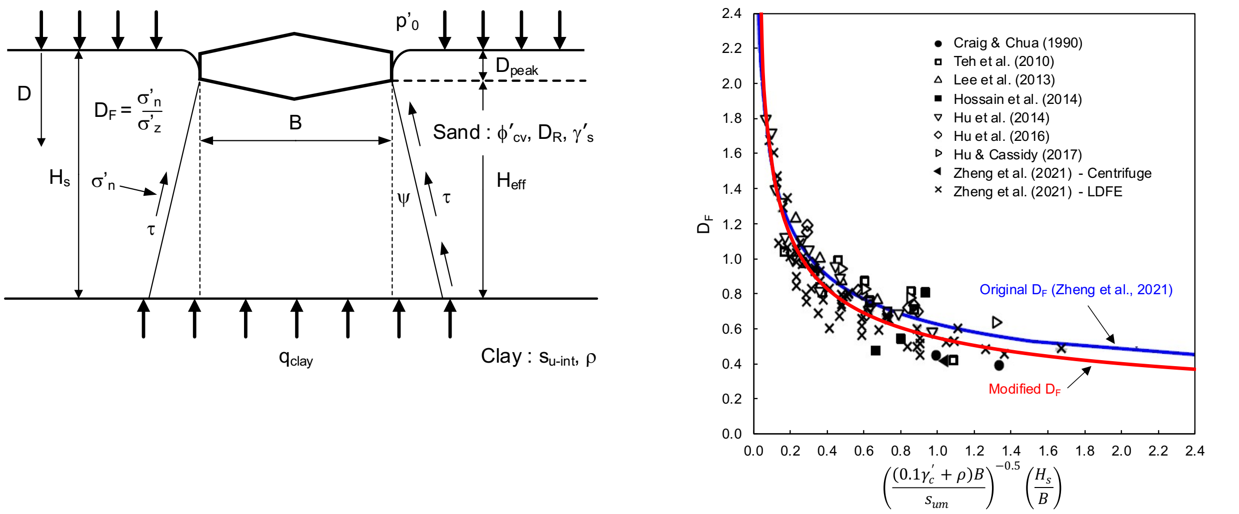


Figure 2 Simplified framework for incorporating mechanism-based method and sand plug effects in complex multi-layered soils



a) Punch-through failure mechanism (Ref. /6/)   b) Further calibrated D_F factor from (Ref. /2/)

Figure 3 Mechanism-based method for predicting punch-through resistance in sand over clay

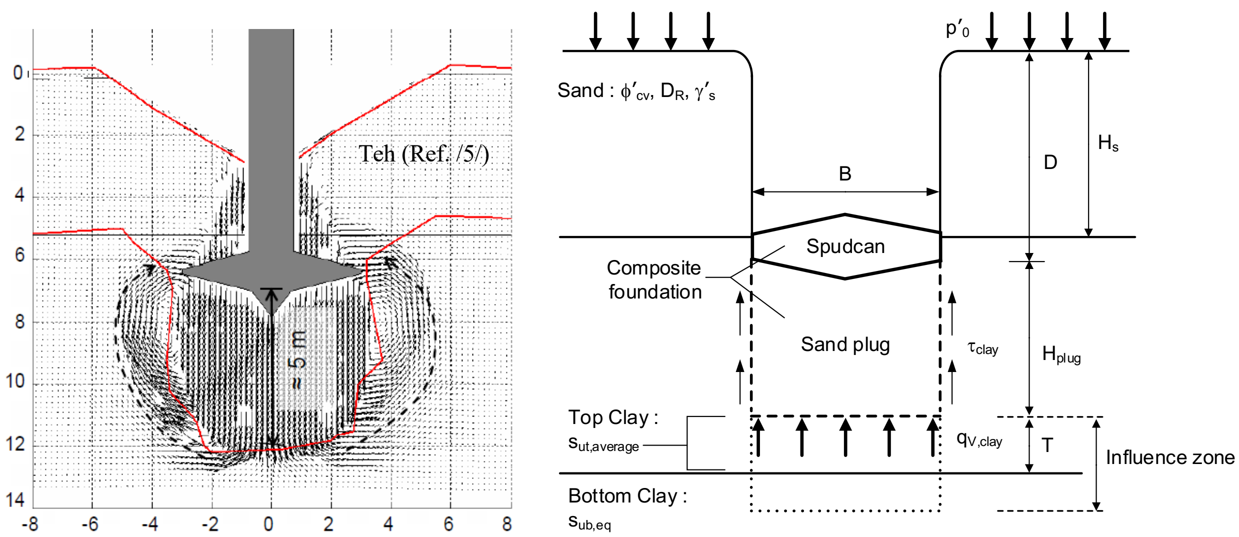
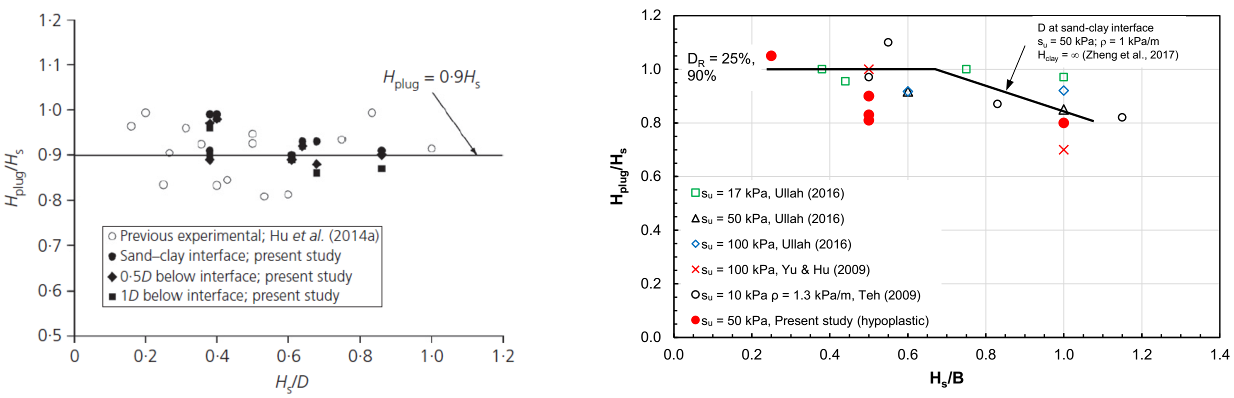


Figure 4 Proposed scheme for bearing capacity prediction in multi-layered sand over clay profiles



a) Centrifuge tests (Ref. /8/)   b) Numerical simulations

Figure 5 Measured height of sand plug from centrifuge tests and numerical simulations

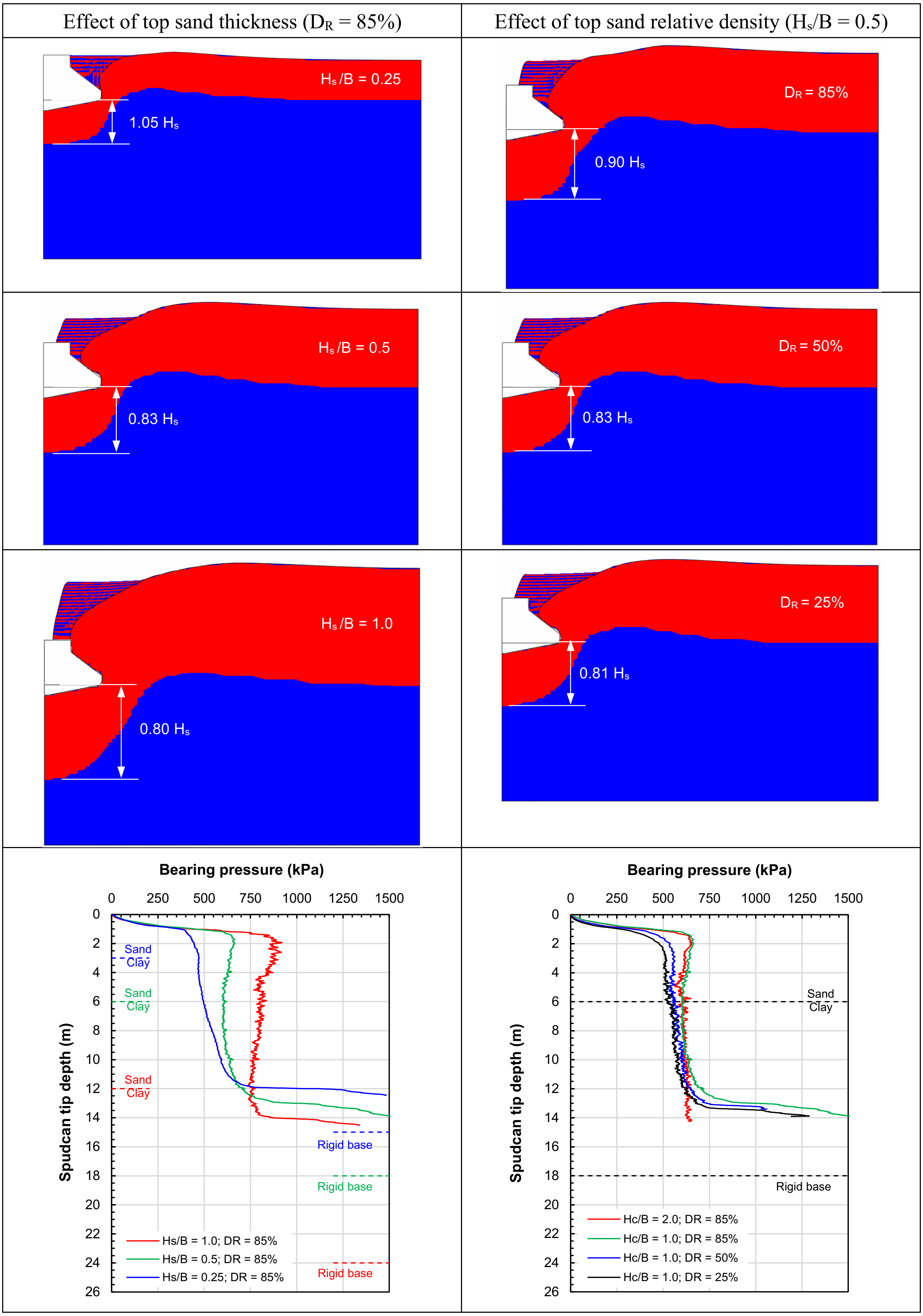
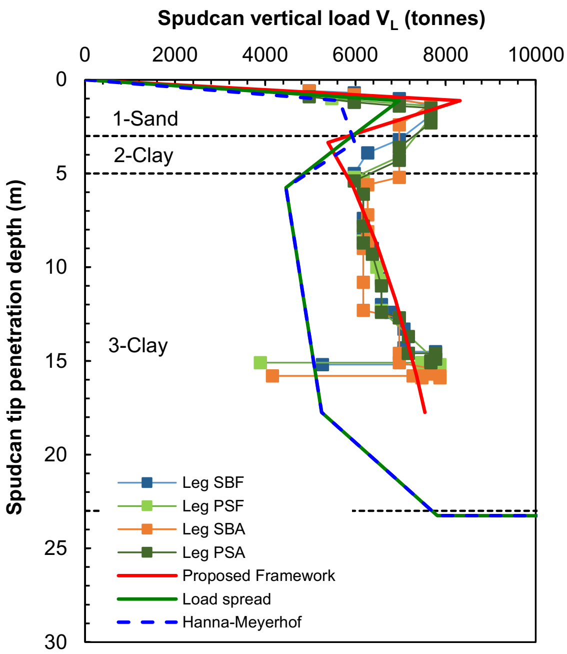
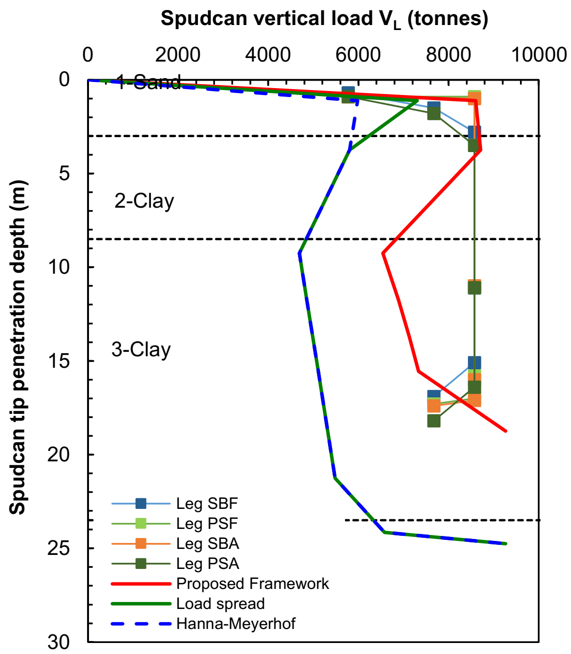


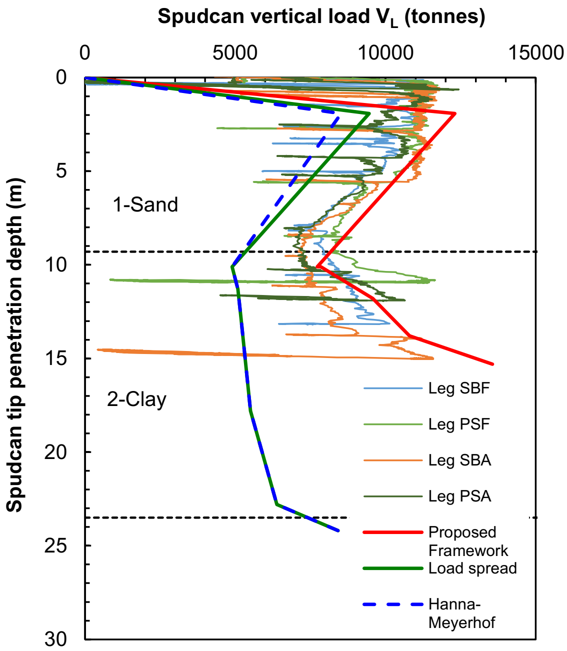
Figure 6 CEL simulation results to investigate sand plug height (Sand hypoplastic model)



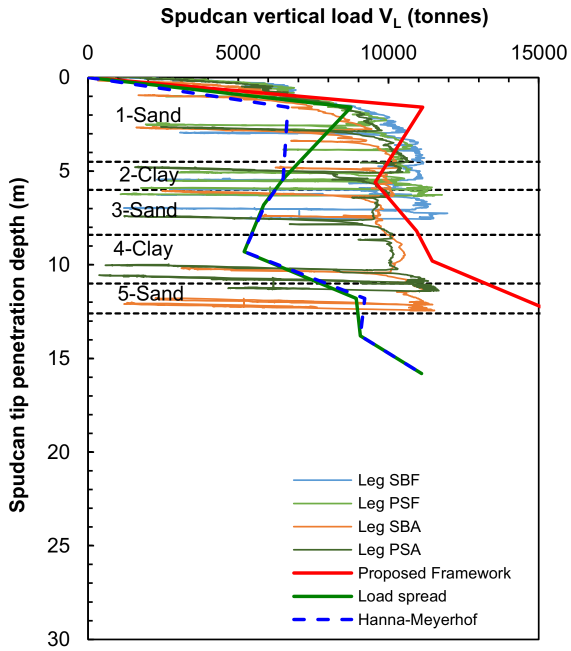
Location 1 (semi-circular spudcan)



Location 2 (semi-circular spudcan)



Location 3 (rectangular spudcan)



Location 4 (rectangular spudcan)

Figure 7 Performance of proposed framework and ISO 19905-1 method against jacking data at various sand over clay profiles

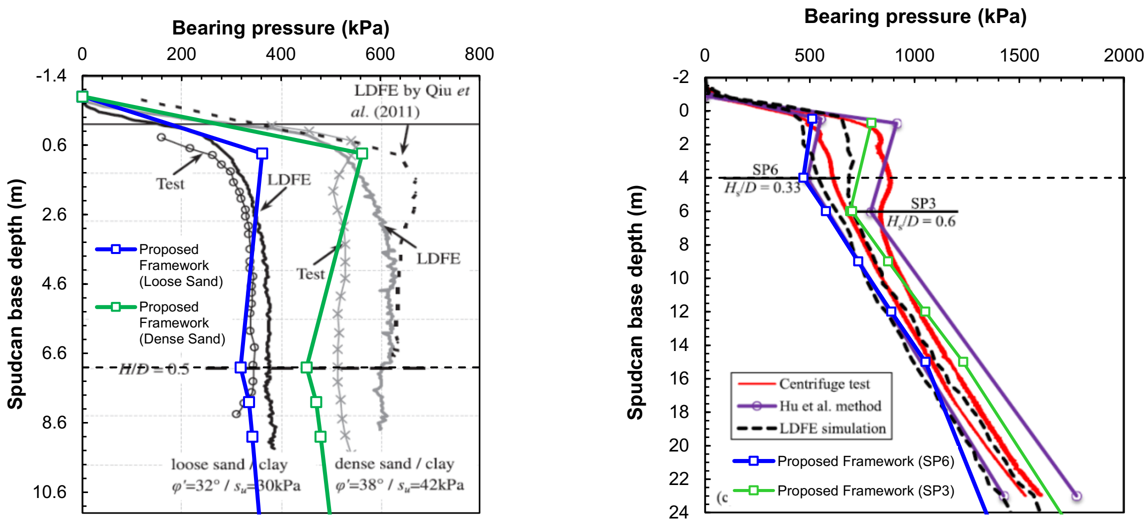
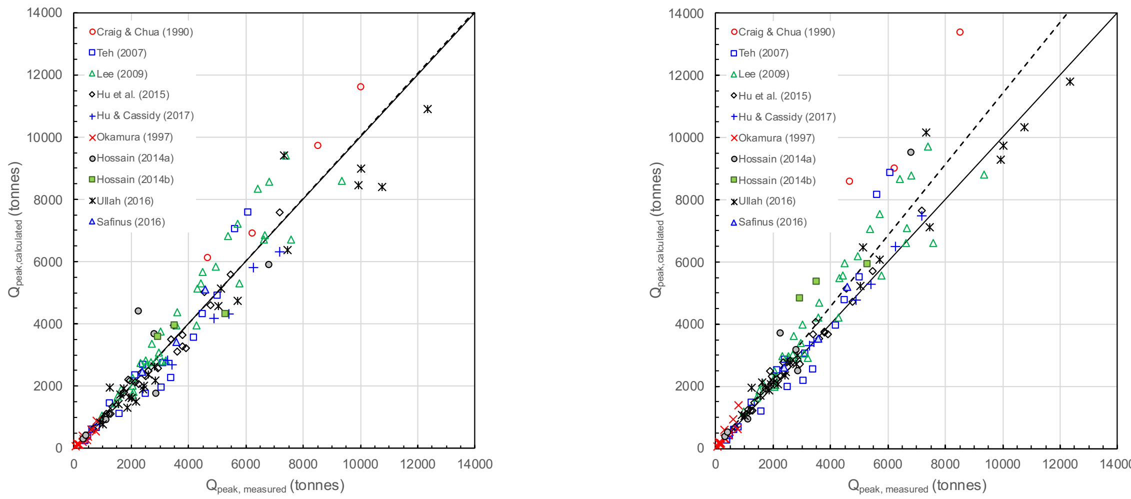
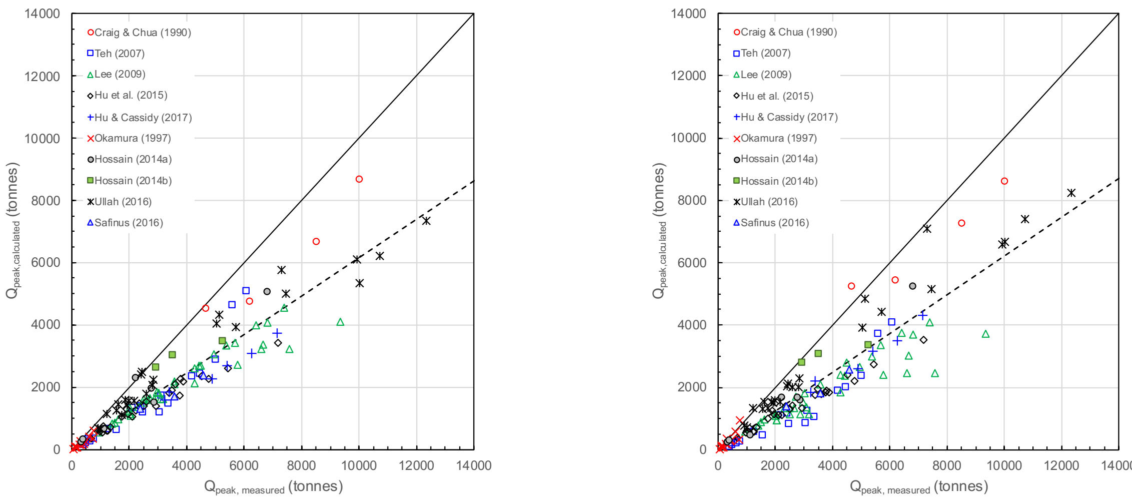


Figure 8 Performance of proposed framework against centrifuge and numerical simulations data



a) Proposed frameowk with D_F modified from Zheng et al. (Ref. /2/)

b) Hu et al. method (Ref. /5/)



c) Hanna & Meyerhof method

d) Load spread method (1h : 3v)

Figure 9 Performance of various predictive methods against centrifuge tests data in sand over clay

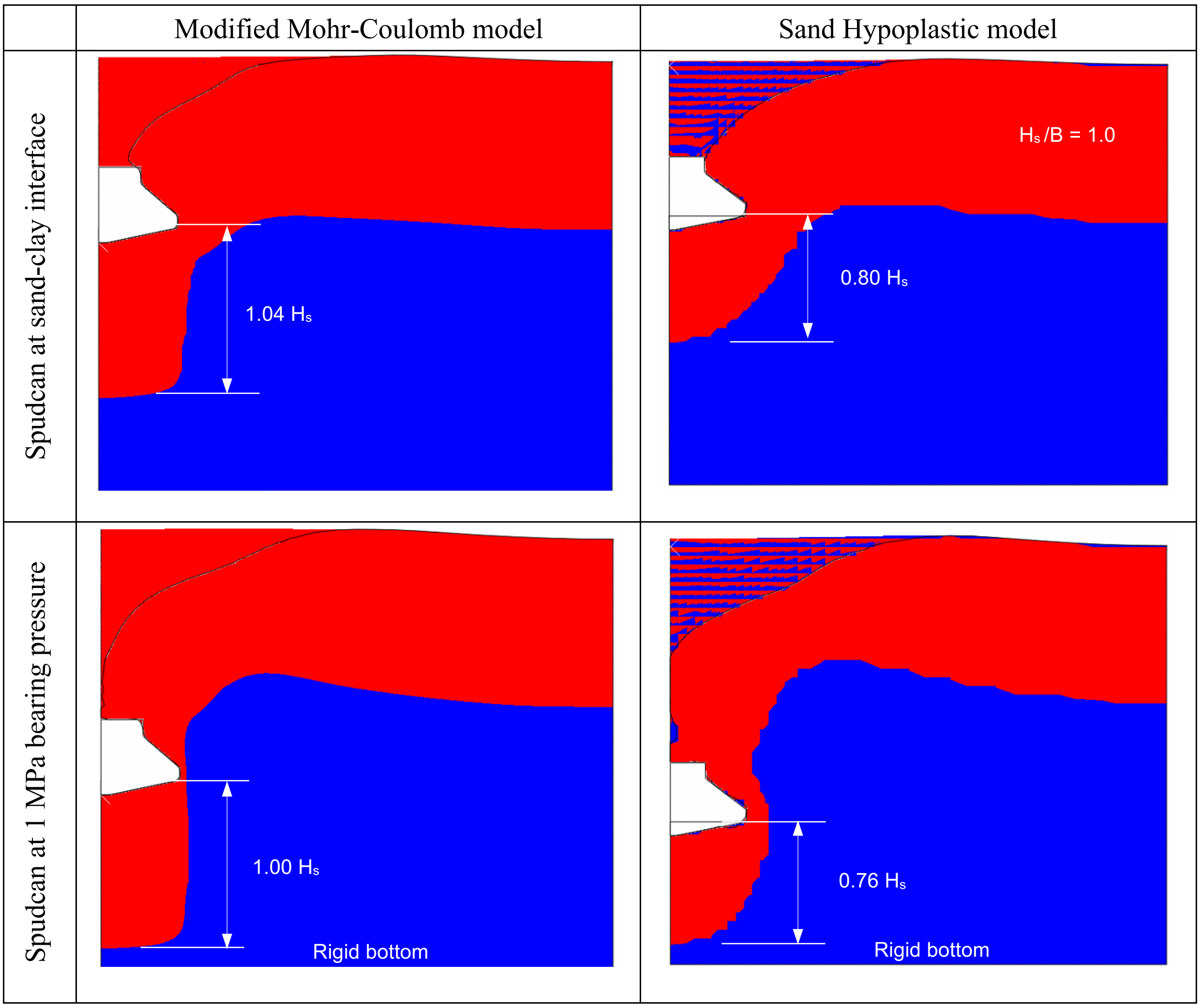
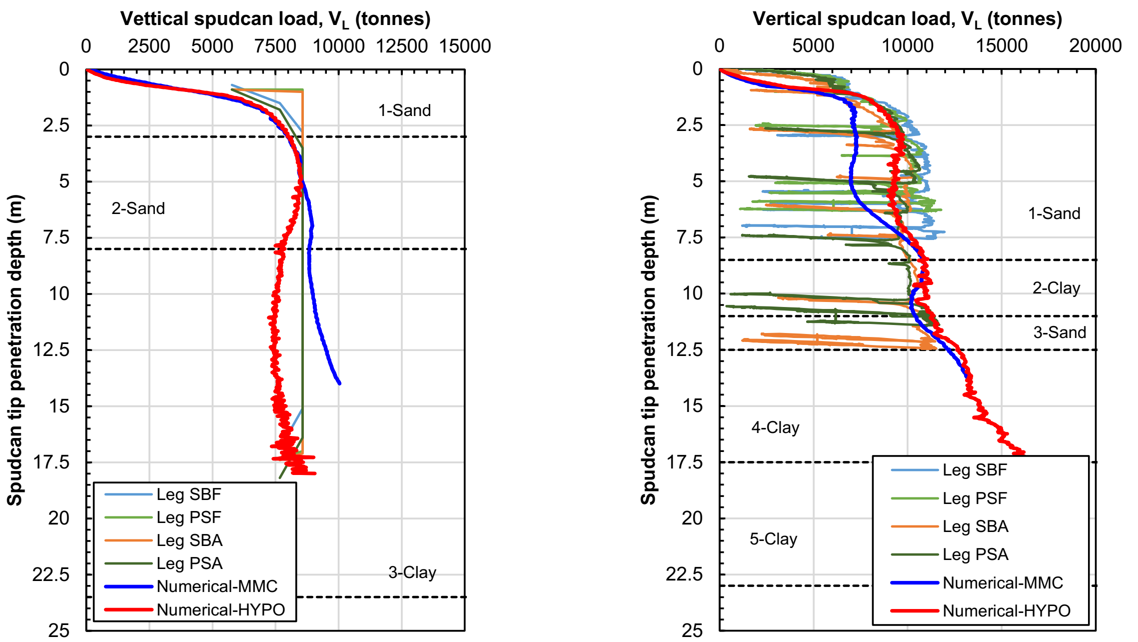


Figure 10 Comparison of sand plug development using two soil models (H_s/B = 1.0, D_R = 85%)



a) Location 5 (Semi-circular spudcan)

b) Location 6 (rectangular spudcan)

Figure 11 CEL simulations of spudcan penetration