A NOVEL PARTICLE-BASED NUMERICAL APPROACH FOR SPUDCAN PENETRATION ANALYSIS

K. Caucis*, M. Alessandrini
GLOBAL MARITIME CONSULTANCY Ltd.

Tien V. Nguyen, Ha H. Bui
MONASH UNIVERSITY, AUSTRALIA

C. Coskun, S. Brown
CADELER

**corresponding author karlis.caucis@globalmaritime.com*

ABSTRACT
Jack-up vessel spudcan penetration is traditionally estimated using analytical methods developed from extensive offshore experience. While effective in simple, homogeneous soils, these methods face limitations in complex conditions involving irregular seabed geometries, previous footprints, or gravel berms. Numerical analyses provide better capability to capture such complex soil-structure interactions. However, conventional mesh-based methods are not readily suited to large deformations due to mesh distortion, requiring computationally intensive formulations (ALE) that are prone to numerical artifacts and rely on incremental modeling steps. This paper introduces GeoXPM, a novel particle-based numerical platform employing a mesh-free framework that inherently avoids mesh distortion, enabling seamless simulation of large deformations, material separation, and evolving contact conditions. Unlike ALE methods, GeoXPM supports fully 3D spudcan penetration simulation in a single analysis and integrates advanced constitutive models for offshore geotechnical applications. Validation against analytical solutions, finite element models, and field data from an offshore wind farm, including Cadeler O-Class penetration records, demonstrates GeoXPM's potential to advance seabed–spudcan interaction analysis.

KEY WORDS: Jack-up, spudcan, geotechnical, numerical analysis, GeoXPM

INTRODUCTION

In practice, spudcan penetrations are most frequently analysed using analytical techniques based on bearing capacity formulations. ISO 19905-1:2023 [1] provides a framework for such analyses (referred to as 'ISO' in this paper) and is widely employed and specified for jack-up vessel spudcan penetration assessments. However, these methods have inherent limitations, particularly in complex, multi-layered ground conditions where ultimate failure mechanisms are governed by the interaction of multiple soil strata. This complexity is especially critical in cases with significant variations in soil strength, such as transitions from stiff to soft clays, which may lead to punch-through or squeezing failure mechanisms.

In such scenarios, engineering judgement is required to select the most appropriate failure mechanism and corresponding analytical method. This often results in conservative designs, as analytical models may lack the capacity to confirm the governing failure mechanism through closed form solutions, prompting engineers to adopt the most conservative option.

Analytical methods also typically rely on simplified one-dimensional (1D) ground models, which preclude the inclusion of lateral soil variations and seabed slopes. These limitations are significant when evaluating jack-up operations in non-uniform seabed conditions such as spudcan placements near previous jack-up footprints, on sloped seabed, or adjacent to other seabed features which can result in complex spudcan-soil interactions.

To address these challenges, the Finite Element Method (FEM) is often employed. However, conventional FEM approaches are limited in their ability to simulate large deformations. Standard FEM analyses rely on "wished-in-place" modelling, where the spudcan is assumed to be incrementally inserted into the soil at discrete depths [2]. This approach does not accurately capture soil flow or evolving geometry during penetration, again requiring considerable engineering interpretation about the soil flow and plug formation, particularly in heterogeneous soil conditions.

To mitigate mesh distortion, techniques such as the Arbitrary Lagrangian-Eulerian (ALE) formulation have been introduced [3] & [4]. While ALE improves mesh handling by decoupling mesh motion from material deformation, it is computationally demanding, susceptible to numerical artifacts, and limited in simulating material separation, soil flow, and dynamic contact interfaces. As a result, conventional mesh-based approaches often require simplifications and staged modelling to simulate a single penetration event compromising both efficiency and fidelity.

This paper presents an alternative approach based on GeoXPM, a novel continuum particle-based numerical platform [5], [6] & [7]. GeoXPM utilizes a mesh-free computational framework, inherently avoiding mesh distortion and eliminating the need for remeshing or smoothing. This enables seamless simulation of large deformation processes and complex soil-structure interface interactions. In contrast to ALE, which still depends on mesh connectivity, GeoXPM's particle-based approach naturally accommodates material separation, multi-phase flow, and evolving contact conditions without introducing significant numerical instabilities.

Critically, GeoXPM enables full 3D simulation of spudcan penetration in a single continuous analysis without incremental staging or geometrical simplification, thereby addressing many of the shortcomings of both analytical and conventional FEM techniques.

To evaluate GeoXPM's performance in spudcan penetration analysis, a two-stage study was conducted. First, GeoXPM was benchmarked against ISO-based analytical methods in uniform soil profiles. Second, its performance was assessed in real-world ground conditions and compared to ISO analytical formulations, FEM outputs, and actual field penetration data. In the first phase, an idealized spudcan geometry was used, while the second phase utilized the geometry of the Cadeler O-Class jack-up vessel's spudcan to ensure practical relevance.

NUMERICAL VERIFICATION IN UNIFORM SOIL CONDITIONS

To facilitate a controlled comparison between the ISO analytical framework and GeoXPM, a series of simulations were performed in uniform soil profiles comprising idealised sand and clay layers. The use of homogenous soil conditions eliminates variability in ground response and removes the necessity to assume specific failure mechanisms in the ISO analytical method. This provides a neutral baseline for evaluating the performance and predictive accuracy of GeoXPM relative to conventional analytical approaches.

For this analysis, a representative spudcan geometry was employed, featuring an equivalent circular diameter of 12 metres and a tip length of 1.5 metres. The spudcan cross section is shown in Figure 1. This configuration is not based on a specific jack-up unit but serves as a generic shape suitable for benchmarking purposes.

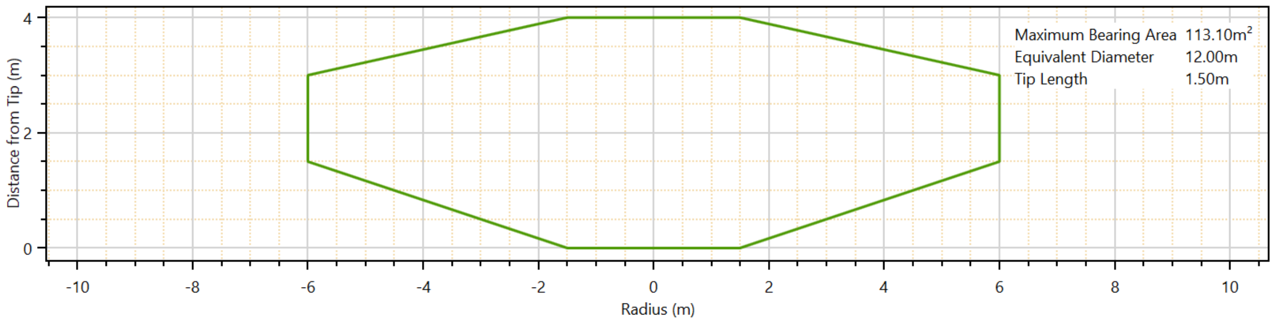


Figure 1 - Spudcan geometry used for verification analysis

For the analysis a uniform sand and clay profiles was adopted with the unit weight and strength characteristics summarised in Table 1 and Table 2 below. The parameters were selected such that a range of penetrations depths including full penetrations are achieved. No adhesion was considered for the sand.

Table 1 – Geotechnical properties for uniform sand profiles

MATERIAL	Unit weight, kN/m^3	Friction angle, degrees		
		LOW	MED	HIGH
SAND	10	20	25	30

Table 2 - Geotechnical properties for uniform clay profiles

MATERIAL	Unit weight, kN/m^3	Undrained shear strength		
		LOW	MED	HIGH
CLAY	10	100	120	140

The ISO analysis was completed assuming general shear failure mechanisms given the uniform soil profiles. Additionally, for clay profile, sensitivity to backfilling assumptions was checked and results with full and no backfill have been presented.

To provide a direct comparison, the GeoXPM analysis used identical soil parameters and a 3D spudcan geometry, applying a linear ramp load from 10 to 15,000 tonnes over 30 seconds. A Mohr-Coulomb material constitutive model was used to capture loading path effects, with Young's modulus E = 20MPa and zero dilatancy angle. Drained conditions were assumed for sand, and undrained conditions for clay (Poisson's ratio = 0.49).

SAND RESULTS

Figure 2 presents the results of the parallel analysis in uniform sand using both the ISO approach and GeoXPM with a Mohr-Coulomb. The results show that GeoXPM predicts deeper penetrations, indicating that it is more conservative than ISO method if the same friction angle is used. This is not unexpected given that friction angles used in analytical spudcan penetration analysis reflect the operational friction angles and account for spudcan shape and are therefore not always equal to the friction angle of the soil [8].

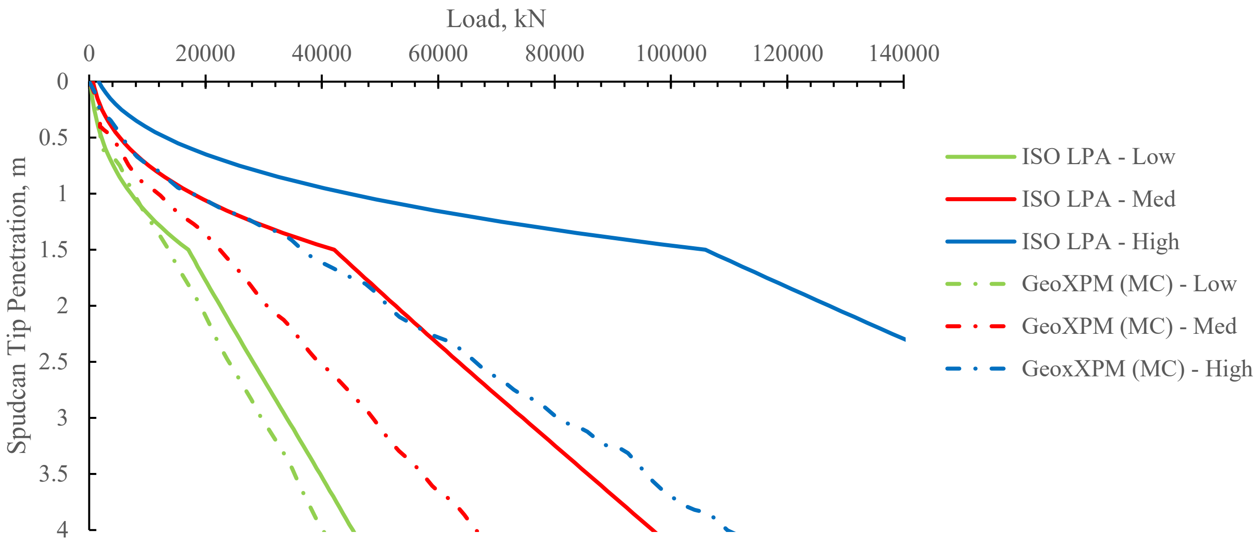


Figure 2 – Comparison of Load-Penetration curves for uniform sand profiles (Mohr-Coulomb constitutive model)

Additional analysis using Drucker-Prager constitutive model were also undertaken showing a higher spudcan reaction forces and closer alignment with the ISO-based analysis, without any adjustment to the friction angles. The results of these additional analyses are presented in Figure 3.

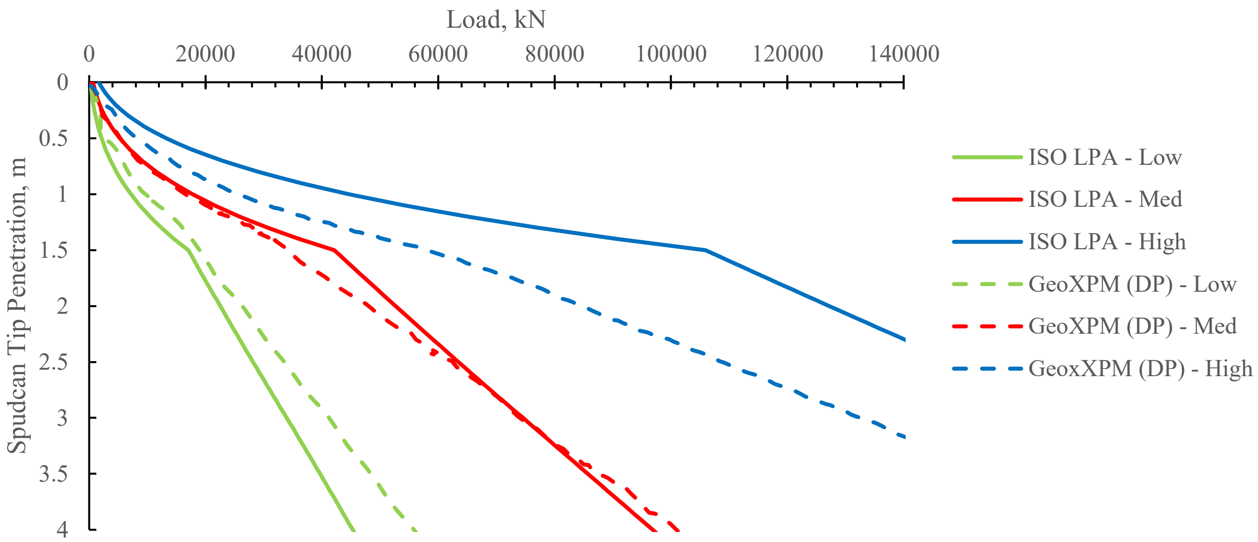


Figure 3 – Comparison of Load-Penetration curves for uniform sand profiles (Drucker-Prager constitutive model)

CLAY RESULTS

Figure 4 and Figure 5 present the results of the parallel analyses in uniform sand and clay using both the ISO and GeoXPM with a Mohr-Coulomb and Drucker-Prager constitutive models respectively. In clay, the predicted penetrations are comparable, provided the ISO backfilling assumptions align with those observed in the GeoXPM model. In this case, GeoXPM predicted no significant backfill, and the resulting load–penetration curve closely matched the ISO analysis with no backfill assumed. As noted in the ISO standard, following the approach of Hossain et. al (2005) [9] , the backfill depth is determined based on the onset of flow failure rather than wall failure. If wall failure were used as the criterion instead, the required backfill depth could be up to four times deeper [10].

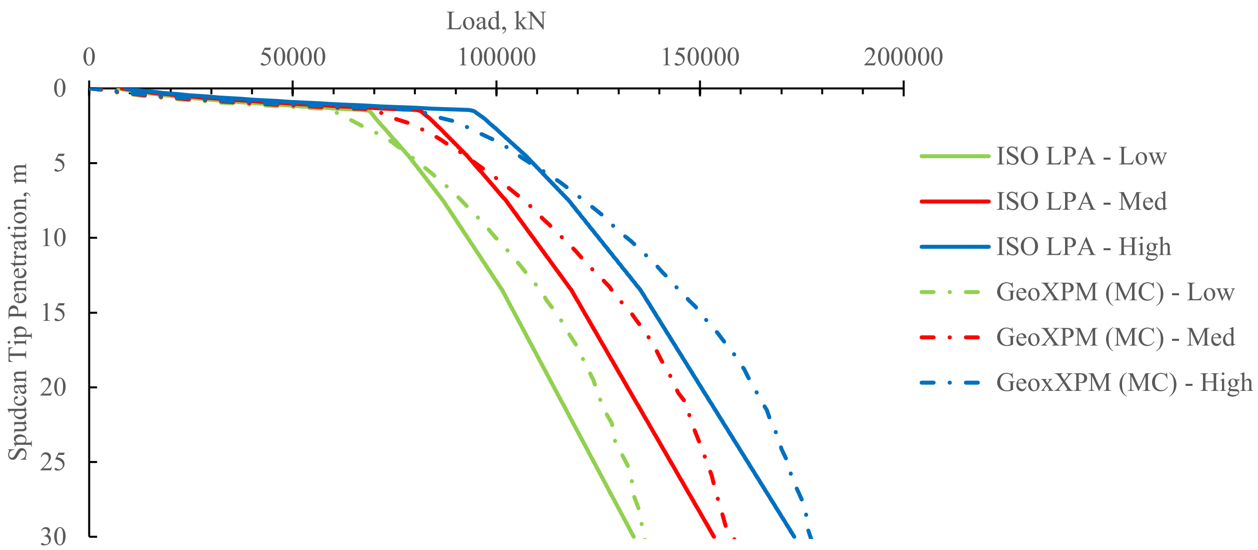


Figure 4 – Comparison of Load-Penetration curves for uniform clay profiles (Mohr-Coulomb constitutive model)

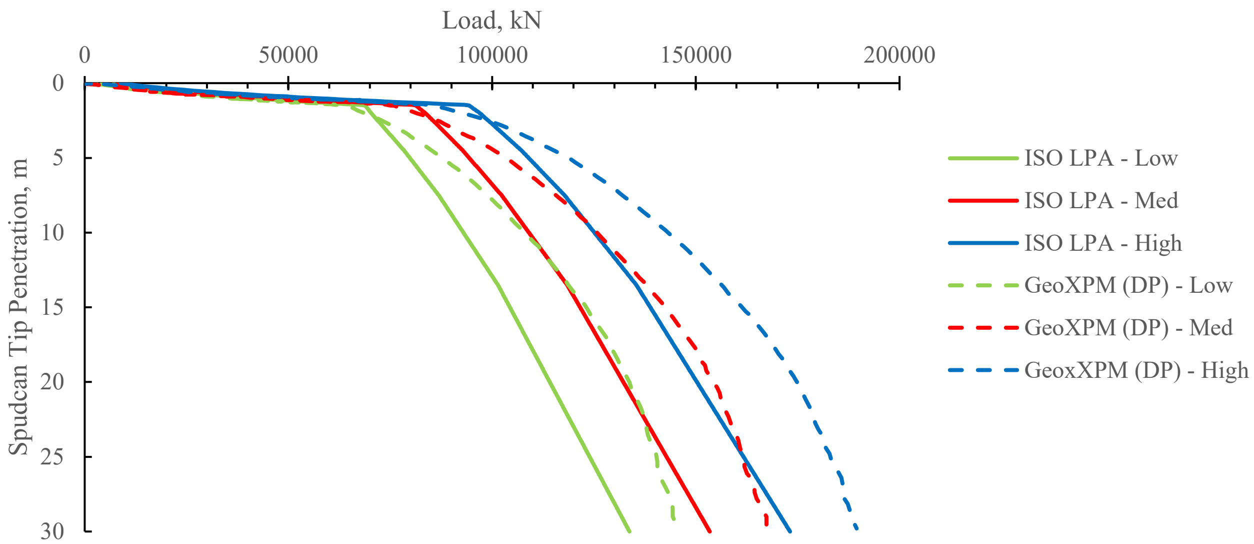
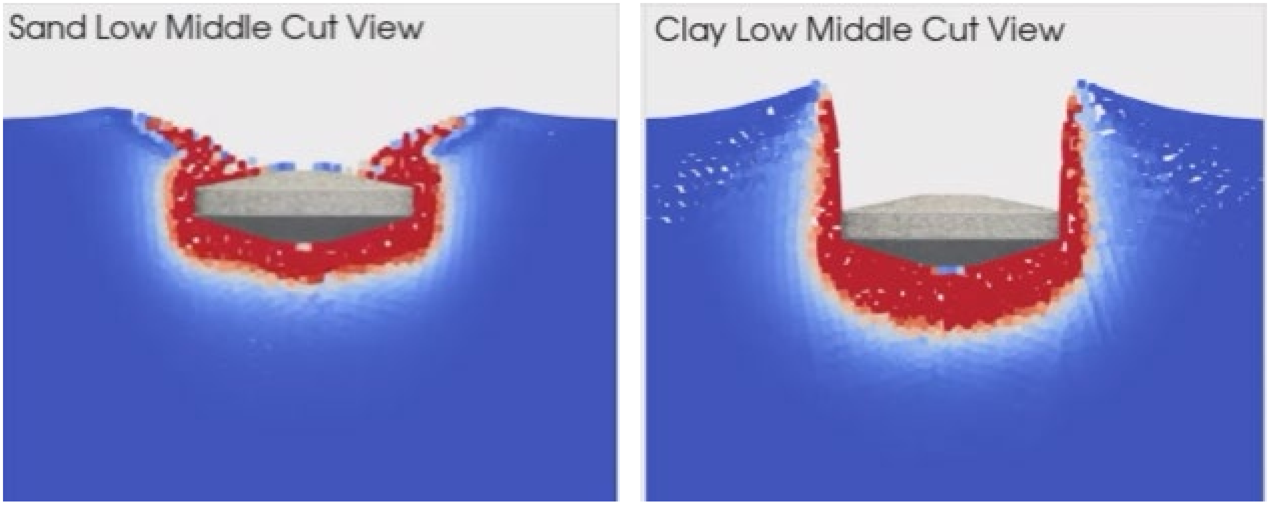


Figure 5 – Comparison of Load-Penetration curves for uniform clay profiles (Drucker-Prager constitutive model)

These uniform profile results suggest that while some differences between GeoXPM and ISO are expected, particularly in sand, GeoXPM provides an accurate framework for modelling spudcan penetration. In sandy soils, special attention may be needed in practice such as adjusting the friction angle in GeoXPM if close alignment with ISO predictions is required.

In addition to the predictions of the penetration depth, the results output from GeoXPM provides valuable insight into the disturbed soil zone around the spudcan and deflections that may be experienced at seabed (Figure 6). Moreover, the SPH-based framework inherently captures large deformation, progressive failure, and soil flow mechanisms without mesh distortion, features that are particularly advantageous in simulating spudcan extraction, footprint collapse, and soft-soil punching. The continuous stress field and velocity data also enable realistic evaluation of post-penetration soil behavior and can inform design decisions for installation sequence or spudcan reinstallation at the same location. These are not achievable from conventional LPA analysis and provide valuable insights for interaction analysis with adjacent infrastructure or potential future spudcan interaction with the footprints.



(a) (b)

Figure 6 – Figures from GeoXPM analysis showing strain and cavity development in (a) sand soil and (b) clay soil

CASE STUDY OF REAL-WORLD CONDITIONS

Following the verification study, the GeoXPM modelling approach was applied to a real-world scenario involving the spudcan of the Cadeler O-Class wind turbine installation vessel. Borehole data and achieved penetration records were obtained from an offshore wind farm site. Due to confidentiality agreements, details regarding the specific site location, spudcan geometry, and preload magnitude are withheld from this paper.

The interpreted soil profile is presented in Table 3, with both Lower Bound and Upper Bound soil parameters derived to reflect standard practice in Load Penetration Analysis (LPA). These parameters were developed from borehole logs and downhole Cone Penetration Test (CPT) data. Site-specific N_{kt} values were used to estimate undrained shear strength in cohesive layers, while the soil friction angle in granular layers was derived from the relative density recorded in the CPTs.

Table 3 – Soil profile and geotechnical parameters for real-world case study

#	Depth From (m)	Depth To (m)	Soil Type	γ' (kN/m³)	Lower Bound			Upper Bound		
					S_u Top (kPa)	S_u Bottom (kPa)	φ' (°)	S_u Top (kPa)	S_u Bottom (kPa)	φ' (°)
1	0	1	Sand	9.1			30			35
2	1	2.9	Sand	9.4			30			35
3	2.9	6.3	Clay	8.9	8	25		15	35	
4	6.3	8.3	Clay	11.7	50	190		75	300	
5	8.3	18.3	Clay	11.1	210	250		330	380	

The ISO analysis was completed using the soil profile above and given the presence of competent sand layer over soft clay, a punch-through mechanism for the sand was applied. To provide a range of potential outcomes, the development of a sand-plug was assumed in the analysis assuming 60, 75 and 90 percent of plug thickness for the Lower Bound, Best Estimate and Upper Bound respectively [11].

The Best Estimate parameters were also modelled in FEM using Plaxis 2D software, adopting a “wished-in-place” methodology. Sand friction angle was increased compared to analytical results by 5 degrees, to account for the angles stated above being operational friction angles. The formed plug shape was estimated from the FEM results with further modifications made based on the failure planes determined in the initial models. To obtain a better match with the site results, the analysis showed that a smaller plug thickness than that assumed for Best Estimate in the ISO analysis is required, with even a 60% plug thickness overpredicting the site behaviour and the GeoXPM behaviour once at preload.

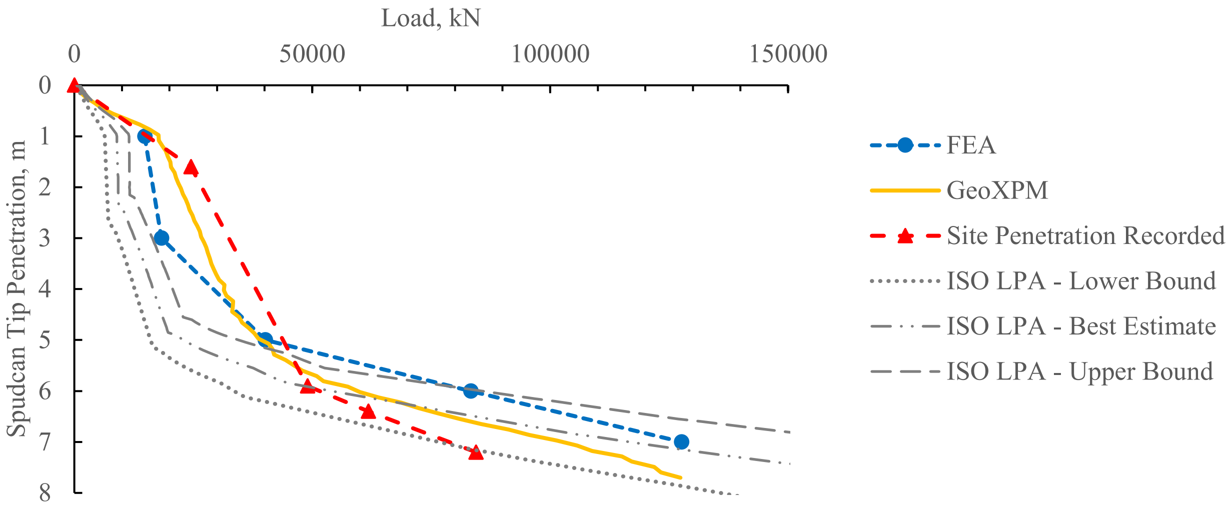


Figure 7 – Comparison of Load-Penetration curves for the real-world case study

GeoXPM simulation employed the Mohr-Coulomb model, assuming drained conditions for sand and undrained conditions for clay, with a constant spudcan penetration velocity of 0.3 m/s. Leveraging the fully dynamic nature of the SPH-based method, GeoXPM captures the evolution of failure mechanisms directly from the governing physics, without the need for predefined assumptions or failure criteria.

The results from the set of the analysis shows that although all of the methods achieved a relatively accurate prediction of the actual penetration curve, GeoXPM was able to provide the most accurate estimate of the initial part of the penetration.

CONCLUSIONS

As part of the study, the performance of the GeoXPM software has been assessed against the analytical calculations following ISO standards as well as FEM analysis methods and real-world leg penetration readings. The results have shown that GeoXPM is capable of analysing spudcan penetrations in sand and clay profiles, with the potential to extract valuable insights on soil flow, cavity side wall stability. Using the appropriate constitutive models, the performance in clay profiles provided a very close match to the analytical solutions. The results in sand also show a good alignment, but identify that particular user consideration is required for selection of sand strength properties.

The key lessons learned from application in uniform soils profiles have been that the Drucker–Prager model may offer closer alignment with ISO-based predictions for sand, unless friction angles are adjusted when compared to the analytical analysis where operational friction angles are normally used. Furthermore, in clay, the use of undrained total stress analysis, based solely on undrained shear strength and neglecting both dilation and pore pressure dissipation, may lead to overestimation of backfill depth. This effect could be more pronounced when extraction occurs after a prolonged time period.

The multi-layered case presented in the paper shows potential for the GeoXPM application in complex ground conditions and that it can perform better than ISO analytical calculations. It is noted that the current analysis focuses on a horizontal soil profile and an axisymmetric spudcan, and does not yet utilise GeoXPM's full three-dimensional simulation capabilities. GeoXPM is parallelised with MPI and supports distributed computing across multiple nodes. For example, the simulations in this study representing 30 seconds of penetration and involving nearly 2.5 million particles were completed in under a day on a desktop equipped with an Intel i7-12700KF CPU using 8 cores. The framework also supports advanced constitutive models, spatial variability through random fields, coupled hydraulic–mechanical behaviour, and multi-stage loading scenarios.

With verification and validation established in this study, future work will extend to more complex, non-uniform soil conditions, including scenarios involving existing footprints and extraction phases. The framework also enables investigation of group effects from multiple spudcan penetrations.

REFERENCES

[1] ISO 19905-1:2023 - Oil and gas industries including lower carbon energy — Site-specific assessment of mobile offshore units, Part 1: Jack-ups: elevated at a site

[2] Engin HK, Jostad H - Finite lement analysis of spudcan – subsea template interaction during jack-up rig installation, Frontiers in Offshore Geotechnics III - 3rd International Symposium on Frontiers in Offshore Geotechnics, ISFOG 2015

[3] Nazem M, Carter JP, Airey DW - Arbitrary Lagrangian–Eulerian method for dynamic analysis of geotechnical problems, Comput. Geotech., 36 (4), 2009, pp. 549-557

[4] Jiayu W, Run L, Chao L, Hui X, Jun W - Study on ALE Method for Simulating Spudcan Penetrating Near Piles, International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers, 2018

[5] Bui HH, Fukagawa R, Sako K, Ohno S - Lagrangian mesh-free particles method (SPH) for large deformation and failure flows of geomaterial using elastic-plastic soil constitutive model, International Journal for Numerical and Analytical Methods in Geomechanics, 2008, Vol.32(12), pp.1537-1570

[6] Bui HH, Nguyen GD - Smoothed particle hydrodynamics (SPH) and its applications in geomechanics: From solid fracture to granular behaviour and multiphase flows in porous media, Computers and Geotechnics 138, 104315. 2021

[7] Bui HH, Nguyen VT, Nguyen GD - GeoXPM: Particle-based continuum solutions for extreme geoengineering, geomechanics & geophysics applications, Tutorial Manual. 2023

[8] Tolooiyan A, Gavin K, Dyson AP, Estimation of spudcan penetration in variable sand deposits with the Arbitrary Lagrangian Eulerian Finite Element Method, Ocean Engineering Volume 281, 1 August 2023, 114955

[9] Hossain MS, Hu Y, Randolph MF, White DJ, Limiting cavity depth for spudcan foundations penetrating clay, 2005 Geotechnique 55, No. 9, 679–69

[10] Yi JT, Pan YT, Huang LY, Xu SJ, Liu Y, Determination of limiting cavity depths for offshore spudcan foundations in a spatially varying seabed, Marine Structures, 2020, Volume 71, 102723

[11] Lee KK, Randolph MF, Cassidy MJ - New simplified conceptual model for spudcan foundations on sand overlying clay soils. Proc. Annu. Offshore Tech. Conf., Houston, Texas, Paper OTC 20012. 2009