Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Pile penetration into scour protection with DEM model

I. Terribile*, E. Nicolini, A. K. El Haj
Cathie Group, Nanterre, France

* *ivan.terribile@cathiegroup.com*

ABSTRACT: The long-term performance of offshore foundations frequently relies on the protection against scour. To avoid erosion of the seabed, a coarse granular crushed rock layer is placed around the foundation. This layer is frequently set over the seabed before the foundation is installed, to optimise the construction of the offshore windfarm. In the case of monopiles, suction caissons, or anchors, the rock cobbles forming the scour protection layer may have a significant size and could be at the origin of initial damages and permanent deformations of the steel wall at the base, potentially affecting the continuation and completion of the installation to target depth. Additionally, the scour protection could initially bear the pile self-weight even in case of relatively soft seabeds, which exposes the pile to free falling once the driving installation is started. For the above cases, numerical analyses carried out with the Finite Element Method (FEM) based on continuous material model fail to capture some of the essential features of the problem, that is the interaction between the pile steel wall and the coarse granular hard rock cobbles. The Discrete Element Method (DEM) modelling carried out by the Authors provides a reliable estimate of such interaction, also taking into account a calibrated modelling of the seabed sands within the same DEM, which allow for truly large displacements to be taken into account in the analyses. Comparison with a field measure of a real pile do reinforce the reliability of the predictions obtained by the modelling technique.

Keywords: monopile; scour protection; discrete element method (DEM), self-weight penetration.

1 INTRODUCTION

A scour protection layer, consisting of coarse to very coarse aggregates, is installed on the seabed around the offshore foundation where, based on the seabed soil characteristics and meteocean conditions, a potential erosion of the seabed is recognized.

In case of monopile foundations, to optimize the installation sequence and reduce both time and costs, the complete scour protection layer is sometimes installed before the foundation, which may lead to installation challenges.

The presence of the scour protection could be at the origin of initial damage at pile tip, which could then propagate during impact driving installation, potentially affecting the completion of the installation to target depth. In addition, in some cases, the scour protection could provide the required resistance to bear the monopile's self-weight even in presence of a relatively soft seabed, exposing the monopile to the risk of punch through with consequent free falling under the hammer's weight or when impact driving starts.

This paper focuses on the use of numerical analyses for modelling the penetration behaviour of a monopile through the scour protection layer.

The study is carried out adopting the Discrete Element Method (DEM) method, that is well-suited for problems involving large displacements and large rigid bodies, like boulders and cobbles.

Two different case studies are presented in this paper:

- Case Study 1: simulation of a real monopile penetration through a 2-layers scour protection, consisting of an armour layer overlying a filter layer. The two scour protection layers are modelled with DEM while a continuum approach is used in this case to model the seabed soil.
- Case Study 2: Simulation of a larger monopile penetrating through a filter layer. In this case, both the scour protection and seabed sand were modelled with DEM.

2 CASE STUDY 1 – DEM SCOUR PROTECTION

2.1 Geotechnical conditions

The first study was focused on the simulation of the monopile self-weight penetration through a 2-layers scour protection, composed by an armour layer overlying a filter layer. The two scour protection layers were characterized by an angle of internal friction (φ') of 45°. This value was selected based on experimental data obtained from large Casagrande shear box testing (Bernard et al., 2016), performed on very coarse aggregates of similar characteristics of the material adopted in the offshore industry for the scour protection layers; properties of the latter are summarized in Table 1.

The scour protection was installed above a sandy seabed; this layer is modelled as elastic, characterized by a Young's modulus (E) of 50MPa and Poisson's ratio (ν) of 0.3.

The real monopile has an outer diameter (D) of 6.5m with D/t=90 (t is the pile wall thickness), which was used in the numerical simulation.

Table 1. Case Study 1 - Scour protection layers properties

Layer (-)	Grading (-)	Thickness (m)	φ' (°)	ρ (kg/m^3)
Armour	LMA 10-60	0.75	45	3140
Filter	1"-5"	0.75	45	2700

2.2 Numerical model

The adopted model for the numerical analysis of the monopile self-weight penetration is a coupled finite-difference (FDM) / distinct-element (DEM) model. In particular, the discrete element software PFC3D (Particle Flow Code) and FLAC3D from Itasca (Itasca, 2021) were used.

The armour layer is modelled in PFC3D with polyhedral blocks where 6 block geometries were used as shown in Figure 1, with size distribution comprised within 200mm and 360mm. The filter layer is modelled in PFC3D with rigid spherical elements, with size distribution limited between 40 and 110mm.

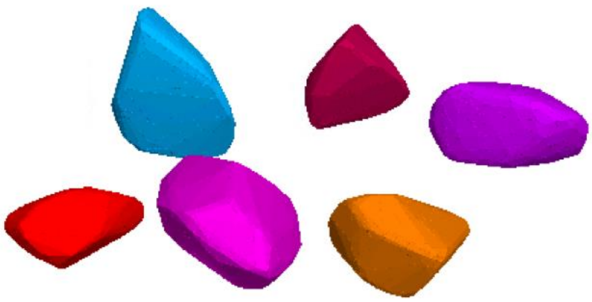

Figure 1. Shape of armour layer blocks – Polyhedral elements

The contact model used in the study was the soft-bond contact model (Itasca, 2021). This model can be used to model both unbonded and bonded systems. For the present study, the soft-bond contact model was used as unbonded. The model is able to transmit both force and moment at the contact point, with transmitted shear force, bending moment and twisting moment capped by the frictional strength parameters.

The stiffness of the model is set to use an effective microscale elastic modulus of 100MPa and a normal-to-shear stiffness ratio of 2.5. These values correspond to settings commonly adopted in DEM models, to ensure the model is run in the rigid grain limit (GDR Midi, 2024). The viscous damping normal critical ratio is set to a usual value of 0.2. Additionally, a local damping coefficient of 0.7 is used to help numerical convergence. Since the model is run in quasistatic conditions, it is not expected for these parameters to influence the results.

The contact model friction coefficient parameter controls the frictional and rolling resistance strength of the contacts and the macroscopic internal friction angles of the filter and armour assemblies. A trial-and-error procedure is required to calibrate the contact model friction to achieve the target angle of internal shear resistance. For this study, this calibration was performed simulating triaxial tests in PFC3D. Based on the results of these confined compression tests, the obtained contact model friction coefficients to achieve the target angle of internal friction (i.e. 45°) were 0.33 and 0.25 for the filter and armour layer, respectively.

The seabed sand is modelled as an elastic continuum in FLAC3D, while the monopile was modelled as an assembly of rigid blocks, rigidly connected to each other.

Taking advantage of symmetry, the numerical model was limited to 1/4th of the entire size, resulting in a reduced number of particles and, therefore, in a significant reduction of the computational time. Symmetrical boundary conditions were used, consisting in frictionless boundaries, with no rolling resistance.

2.3 Results and discussion (Case study 1)

The numerical analysis was performed in two phases:

- 1st phase: the analysis was performed by imposing a vertical displacement to the monopile, simulating the monopile stabbing phase, during which the monopile is restrained by the crane.
- 2nd phase: a load-controlled analysis was performed to simulate the hammer installation on top of the monopile, during which the monopile is not restrained and can freely accelerate under the monopile plus hammer weight.

The developed model is presented in Figure 2. Results, in terms of mobilized vertical reaction force with monopile penetration, are presented in Figure 3. The obtained curve is compared to the only experimental data available to the authors, from site measurements made on same conditions (i.e. scour protection properties and thickness, and monopile geometry and self-weight). A good correspondence between the numerical results and the only experimental data can be observed for the monopile self-weight penetration part (i.e. 1st phase). Indeed, this is a partial verification, but this highlights the good potential of the DEM modelling in simulating the monopile-scour protection interaction.

However, a limitation of the proposed modelling is represented by the boundary effects which can be identified in the last part of the resistance-penetration curve (i.e. 1m pile penetration), when the monopile tip approaches the elastic continuum boundary.

The conclusion of this initial study was that DEM modelling of the seabed soil is required to simulate the monopile penetration through the entire scour protection layer, which is treated in the second case study in the following.

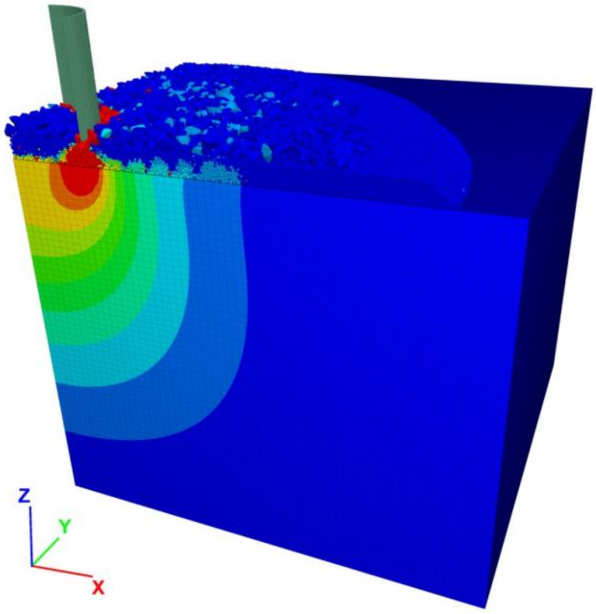

Figure 2. Case Study 1 – Model and induced displacement field

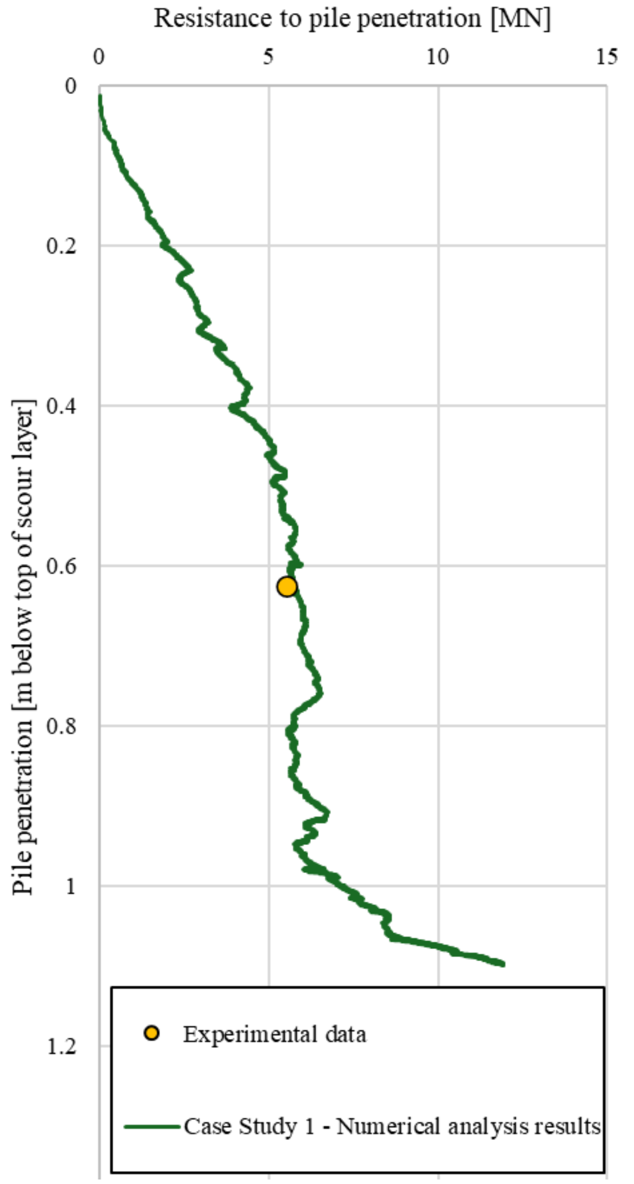

Figure 3. Case Study 1 – Resistance to penetration curve

3 CASE STUDY 2 – DEM SCOUR PROTECTION AND SEABED

3.1 Geotechnical conditions

The second study is conducted considering a unique scour protection layer overlying a sandy seabed. The scour protection consists of a filter layer, with grading 50-150mm (2-6”), while the seabed soil is characterized by two layers, with a dense sand overlying a loose sand. Geotechnical properties of the two sand layers are summarized in Table 2.

The aim of the study was to simulate a complete penetration through the scour protection layer, investigating potential pile-run (i.e. the rapid monopile self-weight penetration) in case a punching phenomenon of the dense sand layer through the loose sand occurs. For the above reason, two thicknesses of the dense sand layer were investigated with the numerical modelling: 2m and 4m. In this study, a 8.6m diameter monopile pile, with *D/t*=92, is s modelled.

Table 2. Case Study 2 - Sand layers properties

Layer (-)	γ (kN/m^3)	φ‘ (°)	E (MPa)	ν (-)
Dense Sand	18	40	100	0.3
Loose Sand	18	25	10	0.2

3.2 Numerical model

To overcome the limitation observed in the first study (i.e. Case Study 1), related to the boundary effects produced by the continuum modelling of the seabed soil below the scour protection, the latter and the in-situ sand layers are both modelled with discrete elements within this study.

The same contact model used in Case study 1 (soft-bond contact model in its unbonded solution), is adopted for both scour protection and seabed sand material.

The filter layer was modelled with rigid spherical elements in PFC3D, characterized by the same microscale parameters calibrated in Case Study 1.

The sand layers were modelled in PFC3D with rigid spherical elements, with uniformly distributed particles diameters comprised between 33mm and 46mm. Triaxial tests were simulated to calibrate the contact model friction coefficient of both dense and loose sand layers.

Two solutions were adopted to reduce the number of particles and thus the computational time:

- only a portion of the volume limited to a 2m large trench at pile position was modelled with discrete elements. The rest of the volume was modelled with continuum elements in FLAC3D, characterized by an elasto-plastic behaviour.
- the numerical model is limited to 1/16th of the entire size; the width at pile is about 1.6m and about 20 to 30 particles are used in the width.

The above model geometry was validated performing numerical analyses to find a compromise between the need of reducing the DEM model size and potential boundary effects. An image of the obtained model is presented in Figure 3.

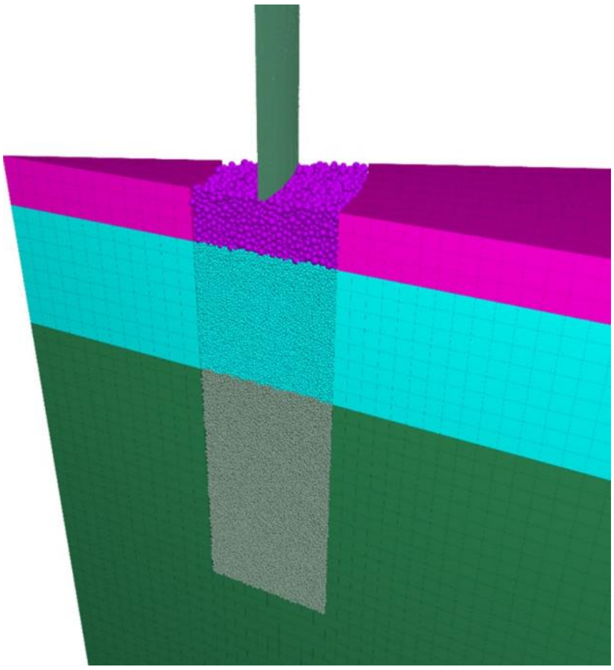

Figure 3. Case Study 2 – Profile 1 – Numerical model

3.3 Results and discussion (Case study 2)

The numerical analyses were carried out considering two different thicknesses of the dense sand layer:

- Profile 1 – 2m thickness;
- Profile 2 – 4m thickness.

The numerical results are presented in Figure 4. In both cases, the monopile penetrates the filter layer under self-weight, stopping after a penetration of about 30cm in the dense sand layer (i.e. about 1m penetration from top of the scour protection). A slight difference is observed between the two soil profiles, assumed to be related to the different assembly of discrete particles in the two numerical models.

The resistance to penetration curves obtained from the numerical simulations are similar to results of small-scale plate penetration tests recently performed to investigate the pile penetration through scour protection, presented in Cengiz et al. (2024). This is reinforcing the confidence in the capabilities of the numerical model to represent accurately enough the penetration of the pile tip into the scour protection.

The resistance to the monopile penetration oscillates around a constant value in the filter layer, while it increases almost linearly with depth in the dense sand layer. A reduction of the resistance to the monopile penetration is observed when the monopile tip approaches the loose sand layer, starting from a distance of about 75cm from the top of the loose sand.

The observed reduction of the mobilized vertical reaction force is the result of a punching failure of the dense sand layer through the loose sand. To better investigate this phenomenon, a comparison between load-controlled and displacement-controlled analyses was done. Considering a dense sand thickness of 2m, the resistance to the monopile penetration did not achieve the monopile+hammer weight, with the monopile rapidly accelerating in the load-controlled analysis, after reaching the resistance peak in the dense sand.

The described phenomenon consists in the so-called “pile run”, typically observed during installation in case of sudden reduction of pile end bearing resistance. In terms of mobilized vertical reaction force, no appreciable differences were obtained between the load-controlled and displacement-controlled analyses.

For a better understanding of the pile soil interaction, the obtained resistance to pile penetration curve was separated in the main two resistance components, shaft and end bearing resistance.

Figure 5 presents the unit end bearing plotted against the pile tip penetration from top of the loose sand layer. From this plot, it is possible to appreciate a global similar trend of the end bearing resistance, characterized by a reduction when the pile is approaching the top of the loose sand layer and punching occurs. The two curves then progressively tend to the same unit end bearing within the loose sand layer.

In order to benchmark the model, the end bearing factor N_q, was derived from the end bearing pressure q_b, which was obtained by summing the contact force on the base and divided by the base area, and from the formula $q_b = Nq\ \sigma'_{v0}$.

Obtained results, compared in Figure 6 with well recognised analytical solutions, highlight the ability of the model to well reproduce the pile-soil interaction in granular materials.

Regarding the shaft resistance, the unit shaft friction profiles at different penetration depth were derived, as presented in Figure 7. The results indicate globally a linearly increasing unit shaft friction profile, in agreement with the results expected. An increase of the unit skin friction is observed in proximity of the pile tip, which results more pronounced when the pile tip is penetrating the dense sand layer.

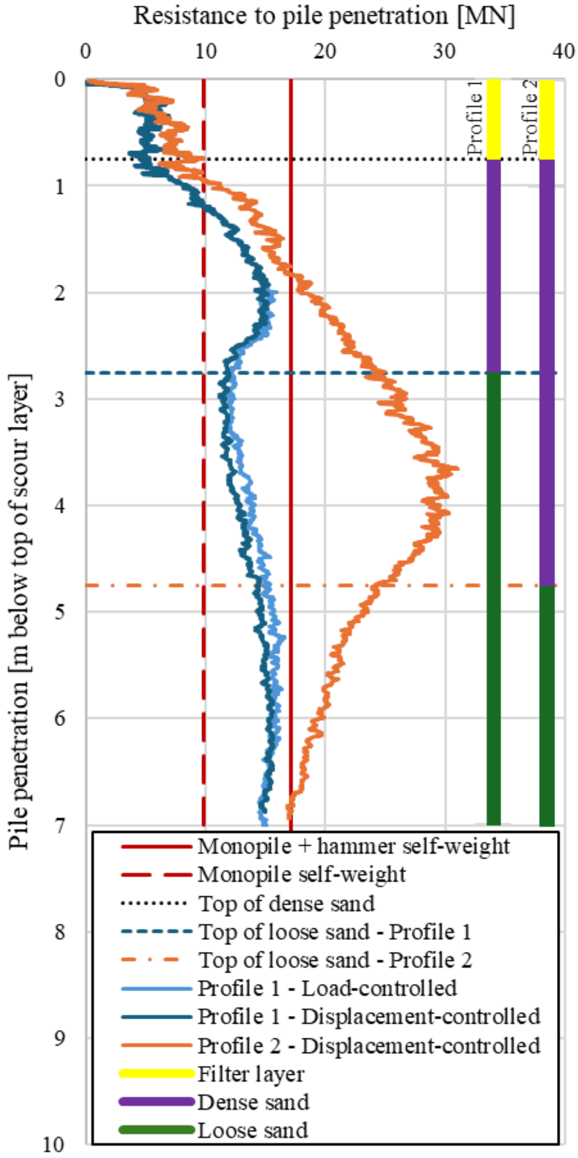

Figure 4. Case Study 2 – Resistance to pile penetration and associated soil stratigraphy

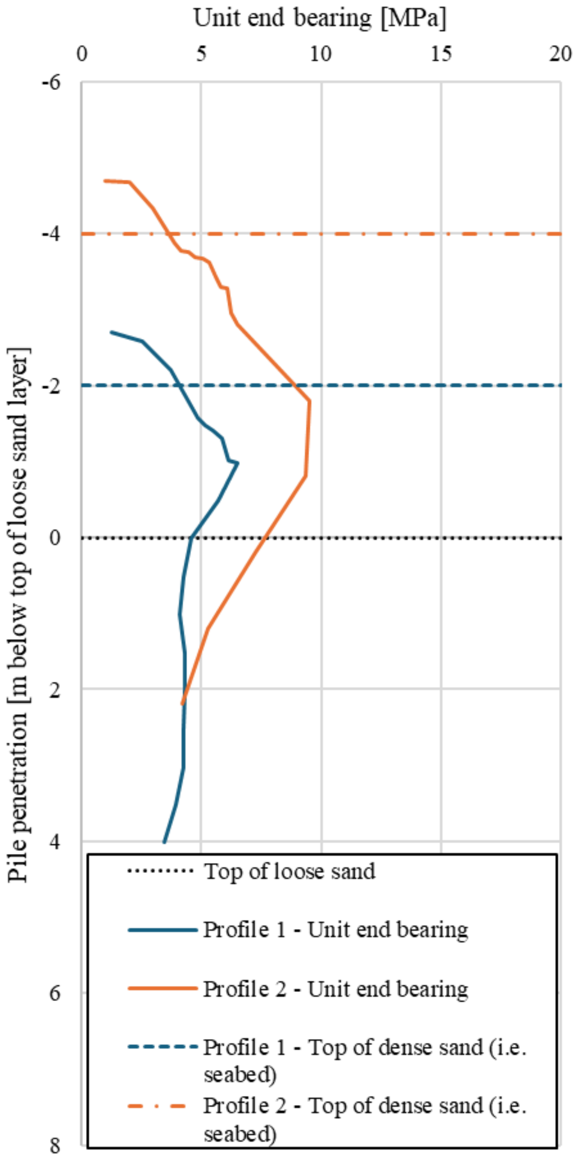

Figure 5. Case Study 2 – Unit end bearing profiles

4 CONCLUSIONS

This paper summarizes two different numerical studies carried out with the aim of better understand the interaction between the tip of a monopile and a pre-installed scour protection, during the self-weight penetration phase. Pre-installation of the needed scour protection is an economically interesting solution that requires a careful assessment of the resistance offered by the scour protection itself to the pile initial penetration, to identify detrimental effects for the pile installation like an unexpected punch-through or a reduced initial penetration.

In the first case presented, results indicate the capability of the DEM modelling to reproduce with good accuracy the pile penetration through the scour protection layer, as confirmed by the comparison with experimental data recorded during a monopile installation offshore.

The second case study aimed at simulating the full penetration through the scour protection layer and in the natural shallow layer below, with the seabed granular soil being modelled with DEM as well. This allowed to reproduce a punching phenomenon, with pile resistance to penetration changing across the interface between the dense and loose sand layers, with a significant reduction approaching and after crossing this interface. A benchmark of the obtained results has been performed comparing the derived unit shaft friction and end bearing resistance with analytical solutions, showing a good correlation.

As well, the agreement between the results of the numerical model and those of an independent testing activity carried out by a third party (Cengiz et al. , 2024) is confirming the robustness of the numerical results, thus encouraging further applications to more challenging cases and to design verifications.

AUTHOR CONTRIBUTION STATEMENT

I. TERRIBILE: Data curation, supervision of numerical analyses, writing- original draft. **E. NICOLINI**.: Scientific lead, Conceptualization, Methodology, Supervision. **A.K. EL HAJ**: Method verification, Writing- Reviewing and Editing,

REFERENCES

Bernard, A., Peyras, L. and Royet, P. (2016). Casagrande large shear box: an experimental test equipment to evaluate the properties of coarse soils and for other applications in geomechanics. *Revue Française de Géotechnique*, 14(4), 1-21. https://doi.org/10.1051/geotech/2016004

GDR MiDi, (2004). On dense granular flows. *The European Physical Journal E,* 14: 341–365A https://doi.org/10.1140/epje/i2003-10153-0

Itasca Consulting Group, Inc. (2021). PFC – Particle Flow Code, (Ver. 7.0).

Cengiz et al. (2024). Optimising pile installation though scour protection (OPIS) project and preliminary findings. *Proceedings of the 5th ECPMG 2024. https://doi.org/10.53243/ECPMG2024-148*

Van Baars, S. (2014). The inclination and shape factors for the bearing capacity. *Soil and Foundations*, 54(5), 985-992. https://doi.org/10.1016/j.sandf.2014.09.004

Vesic, B., C., (1967). A study of bearing capacity of deep foundations. Final Report Project B-189, Georgia Institute of Technology, 231-236

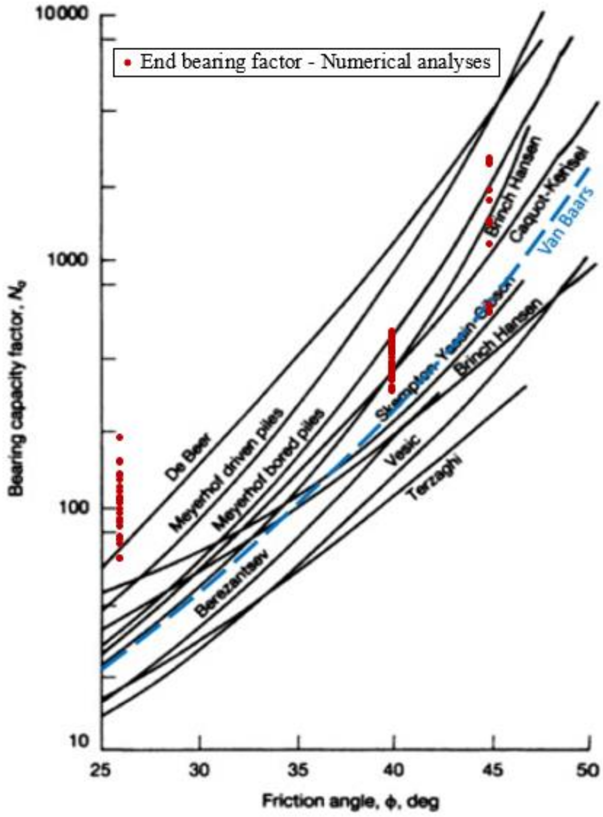

Figure 6. Case Study 2 – Derived end bearing factors (Figure from Vesic, 1967 and Van Baars, 2014) according to different authors

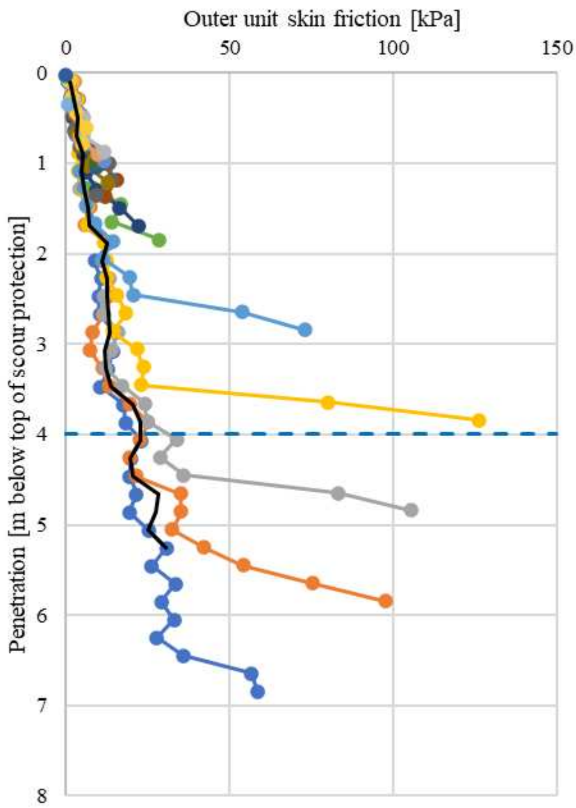

Figure 6. Case Study 2 – Profile 2 - Derived unit shaft friction