Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-618

Experimental tests to evaluate skirt penetration resistance in scour protection for offshore foundations

Essais expérimentaux pour évaluer la résistance à la pénétration de la jupe dans la protection contre affouillements pour les fondations offshore

M. Miranda, J. Castro*, E. Varela, M. Jahanshahinowkandeh
Universidad de Cantabria, Santander, Spain

J. Sarmiento, R. Guanche
IH Cantabria, Santander, Spain

*castrogj@unican.es

ABSTRACT: Full scale experimental tests were performed to evaluate the penetration resistance of steel plates (skirts), which are present in different types of offshore foundations, like mud-mat foundations. This research is motivated by the design of the jacket foundation for the DolWin kappa offshore substation, within the framework of DolWin6 project Penetration resistance is well-studied in clays and sands, but there is limited information on penetration in coarse granular materials, which are typically used as scour protection. Direct extrapolation of penetration resistance in sands is not possible because of the grain-size effect. Several plate thicknesses and gravel sizes were used to study the influence of the grain-size effect on the penetration resistance. The results of the experimental tests showed a strong dependence of penetration resistance on penetration depth as expected, but also a significant dependence on skirt thickness and gravel grain size. A good agreement with experimental results has been found when analytically interpreting the penetration resistance using traditional bearing capacity formulas, but with an equivalent skirt thickness related to the real skirt thickness and to the grain size, to account for the grain-size effect.

RÉSUMÉ: Des essais expérimentaux à grande échelle, ont été réalisés pour évaluer la résistance à la pénétration des jupes, qui sont présentes dans différents types de fondations offshore, telles que les fondations de type mud-mat. La résistance à la pénétration est bien étudiée dans les argiles et les sables, mais il y a peu d'informations sur la pénétration dans les matériaux granulaires grossiers, qui sont généralement utilisés comme protection contre l'affouillement. L'extrapolation directe de la résistance à la pénétration dans les sables n'est pas possible en raison de l'effet de la taille des grains. Plusieurs épaisseurs de plaques et tailles de graves ont été utilisées pour étudier l'influence de l'effet de la taille des grains sur la résistance à la pénétration. Les résultats des essais expérimentaux ont montré une forte dépendance de la résistance à la pénétration par rapport à la profondeur de pénétration, comme prévu, mais aussi une dépendance significative par rapport à l'épaisseur de la jupe et à la taille des grains de graves. Un bon accord avec les résultats expérimentaux a été trouvé lors de l'interprétation analytique de la résistance à la pénétration en utilisant les formules traditionnelles de capacité portante, mais avec une épaisseur de jupe équivalente liée à l'épaisseur réelle de la jupe et à la taille des grains, pour tenir compte de l'effet de la taille des grains.

Keywords: Offshore; foundations; experimental test; skirt; penetration.

1 INTRODUCTION

Offshore wind has a key role in the path towards a net-zero energy mix, it has a large potential for further development and for supplying cheap, clean and safe energy. In fact, offshore wind offers the opportunity to exploit 80% of Europe's offshore wind resource by unlocking shallow to deep water sites. Besides, in the coming years, the power from offshore wind is expected to become cheaper than that from onshore wind because of the larger turbine sizes and the fact that the consistent winds out on the sea allows higher load factors (UK Department for Business, Energy and Industrial Strategy, 2020).

The foundation of offshore wind structures, and in particular critical structures like offshore substations, poses new challenges to a wide range of engineering disciplines like offshore geotechnics. In some cases, such as in skirted or mud-mat foundations, penetration of steel elements into the sea bottom is required to ensure structure stability (e.g., Lu and Maclaren, 2016).

The foundation of offshore structures sometimes requires a scour protection system, which traditionally is composed of a combination of an armour layer and a filter layer (e.g., Sonneville et al., 2014; Escribano and Brennan, 2017). They are commonly installed in advance and then penetration of foundation steel elements (skirts, shear keys...) must be ensured into the scour protection.

Some existing standards and recommended best practices, namely API RP 2GEO (2011) and DNVGL (2017), provide guidance in evaluating the penetration resistance, by means of bearing capacity formulae (Figure 1) or correlations with cone penetration resistances, respectively. Also, some authors (e.g., Andersen et al., 2008; Houlsby and Byrne, 2005) have further studied the penetration resistance of skirted elements. However, all these studies are focused either on cohesive soils or on sandy soils (fine-grained, non-cohesive soils). Hence, there is limited experience or information in the literature about penetration resistance in gravels, which are the base of scour protection systems.

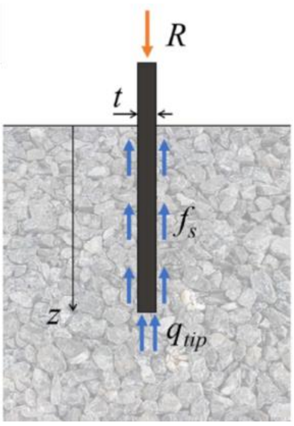

Figure 1. Plate penetration problem and calculation based on bearing capacity.

As presented in the following, extrapolation of formulations for sandy soils to gravels by adjusting the friction angle is not possible due to the influence of the gravel grain size. When the mean grain size (d_{50}) starts to be comparable to the steel plate thickness (t), the grain size increases the penetration resistance. Bolton et al. (1999) studied this particle size effect for cone penetration testing (CPT) in sands and found that the effect appears when the t/d_{50} ratio falls below about 20. More recently, Miyai et al. (2019) presented a notable contribution on the influence of the particle size on plate penetration.

This paper is aimed to study this plate penetration problem accounting for the influence of the gravel grain size and the proposed methodology is based on several full-scale tests. In this manner, this paper further analyses the data presented in Varela et al. (2022) and adds new relevant information, namely the results of direct shear tests on the gravel using a large box (300x300 mm).

2 TEST SET-UP

A 5x5x2.5 m^3 container was designed for the field tests in order to minimize the required volume of gravel and to facilitate the allocation of a 1,000-kN jack. The container was buried in the ground, so that its top part was approximately at the ground surface level. A loading frame was rigidly connected to the container and an auxiliary crane was installed in order to ease the manoeuvring of loads (Figure 2).

Figure 2. Testing container, loading frame and auxiliary crane.

The scour protection required a high-density gravel in this case, and thus an eclogite gravel from Norway was chosen. Two grain size distributions were used, a 0.5-1.5 in. gravel, with a mean grain size (d_{50}) of around 1 in. (25 mm), and 1-3 in. gravel, with a d_{50} of 2 in. (50 mm). Details of some gravel physical properties, grain size distribution and the controlled pouring process to reach the in situ density may found in Varela et al. (2022).

Two steel skirt thicknesses were tested, namely 15 and 80 mm. An additional case with a beveled tip may be found in Varela et al. (2022).

A total of 13 tests were carried out with both gravels and both skirts. The repetitiveness of the tests was ensured through four per test. A summary of the tests performed is given in Table 1. The test procedure was identical for all the configurations. Once the gravel was in place, each skirt was pushed (jacked) into the gravel by means of a hydraulic jack (Figure 3). Both, vertical displacement and vertical load, were measured during each test. The displacement of the skirt was recorded using two ultrasonic displacement sensors (Point 3 in Figure 3).

The hydraulic jack had a maximum capacity of 1,000 kN and a maximum stroke of 500 mm. Thus, for tests with the 80-mm-thick skirt, which had a target maximum penetration depth of 950 mm, the test procedure was a step-based one, combining the available stroke with coupling steel extensions to the hydraulic jack. Therefore, an unloading-loading cycle is visible in the results.

Table 1. Summary of field tests. Test repetitions and penetration depth for the different test configurations.

Particle size	t=15 mm	t=80 mm
d_{50}=25 mm	4 (z<350 mm)	0
d_{50}=50 mm	4 (z<300 mm)	4 (z<950 mm)
	1 (z<500 mm)	

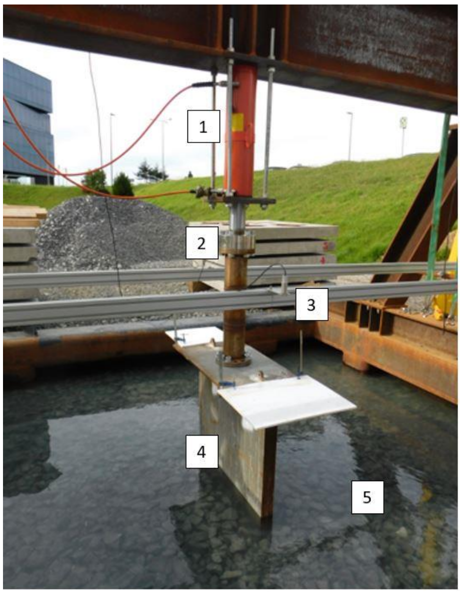

Figure 3. Test set-up. 1-hydraulic jack; 2-load cell; 3-displacement sensor; 4-steel plate; 5-eclogite gravel.

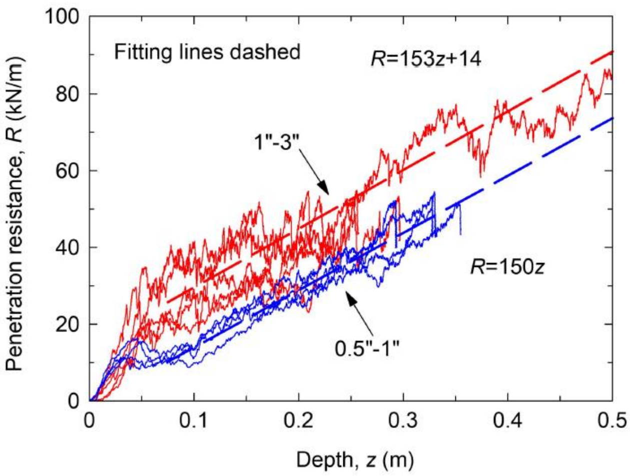

Figure 4. Penetration resistance of 15-mm-thick skirt in both gravels.

3 EXPERIMENTAL RESULTS

Figure 4 presents the penetration resistance versus penetration depth and their linear fittings for the 15-mm-thick skirt in both gravels. As expected, the load required to jack the skirt through the gravel with the larger grain size was higher and it increases with the penetration depth. Besides, the penetration resistance notably oscillated (noise), which was mainly a consequence of the grain-size effect (larger oscillations in the 1-3 in. gravel).

Figure 5 shows the results of the penetration of the 80-mm thick plate in the 1-3 in. gravel. As already explained, there is an unloading-reloading loop at 0.5 m of penetration. Obviously, the penetration resistance is larger for the 80 mm-thick plate than for the 15-mm thick one, but the penetration resistance is increased by a factor of around 2-2.5 times, while the ratio between plate thicknesses is larger.

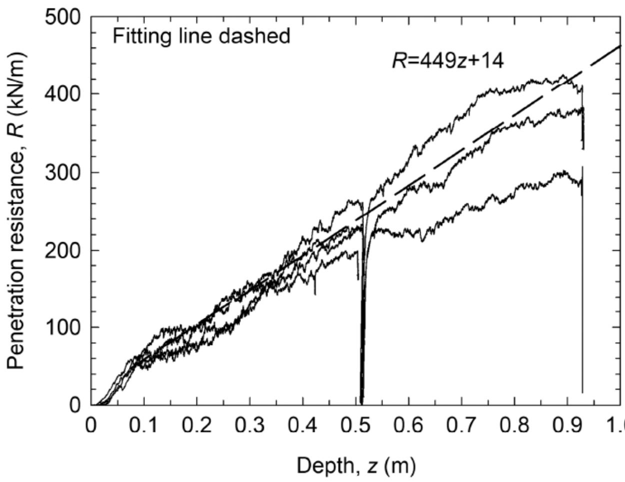

Figure 5. Penetration resistance of 80-mm-thick skirt in 1-3 in. gravel.

The theoretical background for the linear fittings is that the tip resistance is clearly the major component of the penetration resistance (around 98% for these cases, see Varela et al., 2022), while the contribution of the shaft resistance, which increases with the square of the penetration depth, is limited in comparison. From these linear fittings, the back-calculated values of the friction angle for each case using the real and equivalent thicknesses are summarized in Table 2.

It is also worth highlighting that there is a penetration depth beyond which the penetration resistance reduces its increase, e.g., around 0.4 m for the 15-mm-thick skirt and 0.8 m for the 80-mm-thick skirt. This agrees with the limit usually considered for the pile tip resistance of a depth around 20 times the pile diameter (e.g., Tomlinson and Woodward, 2008).

Table 2. Friction angles obtained from back analysis for real and equivalent skirt thicknesses (lengths in mm).

Particle size	t=15	t=80	t=15 + d_{50}	t=80 + d_{50}	t=15 + d_{99}	t=80 + d_{99}
d_{50}=25	54°	--	49°	--	47°	--
d_{50}=50	56°	51°	48°	48°	46°	46°

4 DIRECT SHEAR TESTS

Direct shear tests in a large equipment (300x300 mm box) were performed at different normal pressures, in samples of the smallest gravel (d_{50} =25mm). As expected, peak friction angles obtained decrease with normal stress (Table 3). The high values found, especially for low pressures, might be influenced by the scale factor, as the size of the particles is bigger than 1/6 of the box height. In addition, for loose gravel, the direct shear test results give also higher friction angles than the ones obtained under triaxial conditions, as shown in Varela et al. (2022). Comparing the values of friction angles estimated using the theoretical approaches and those obtained from the direct shear tests, most of them are in the same range, but the friction angles estimated using the equivalent plate thickness are more consistent.

Table 3. Friction angles obtained from direct shear tests at each normal stress for the gravel with d_{50}=25 mm.

σ'=	***25 kPa***	***50 kPa***	***100 kPa***	***200 kPa***	***300 kPa***	***450 kPa***
ϕ	67°	65°	55°	53°	49°	44°

5 CONCLUSIONS

The results of the experimental tests confirm that the penetration resistance increases with the penetration depth, the skirt thickness and the gravel grain size. Tip resistance component is the highest, being the frictional part just around 2% of the total. A good agreement is found between experimental data and semi-empirical approaches when using the equivalent skirt thickness hypothesis proposed by Miyai et al. (2019), in traditional approximations like Andersen et al. (2008). Therefore, this equivalent skirt thickness is the suggested calculation method. In future studies, a wider range of gravel sizes and skirt thicknesses should be tested, in order to increase the reliability of this approach.

ACKNOWLEDGEMENTS

This work is part of the R&D project "Advanced methodology for foundation of critical structures in offshore wind farms (CREMA)" funded by MCIN/ AEI /10.13039/501100011033. This study also forms part of the ThinkInAzul programme and is supported by Ministerio de Ciencia e Innovación with funding from European Union NextGenerationEU (PRTR-C17.I1) and by Comunidad Autónoma de Cantabria through the project entitled: "Tools for the analysis of the interaction between the seabed and the foundations of offshore renewable energy structures (CIMA)".

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