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Physical modelling of monopile penetration through scour protection of different grain sizes

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ABSTRACT: The offshore wind industry has expanded rapidly, with more than 80% of offshore wind turbines using monopile foundations. In many cases, scour protection is installed around the foundations of offshore structures to safeguard against seabed loss caused by erosion. In some cases, where scour protection has been pre-placed as a cost-saving measure, the piles need to penetrate through it to reach the target depth. However, the ability of a pile to effectively penetrate an existing scour protection layer remains uncertain, and the impact of rock materials on pile penetration resistance is still not well understood. Single-layer scour protection is composed of a broadly graded layer of rock material, which can affect the penetration resistance of piles through the pre-installed scour layer due to grain size effects (relative to the pile cross-section and underlying soil type). To replicate full-scale stress conditions in small-scale models, centrifuge tests were conducted to study the effect of grain size on the penetration resistance of piles through a scour protection layer overlaying sand. Small-scale open-ended piles of different diameters were utilised in this study. The results reveal that while increasing the diameter of the piles leads to higher penetration resistance as expected, the penetration resistance is also highly dependent on grain size, when this is comparable to the pile annular wall thickness.

1 INTRODUCTION

In recent years, renewable energy has gained prominence as a crucial approach to mitigating greenhouse gas emissions and enhancing long-term energy sustainability. Within this framework, wind energy has seen substantial expansion and notable technological progress. Although wind energy can be harnessed both onshore and offshore, the scarcity of suitable land for onshore projects has accelerated a growing transition toward offshore installations, which provide far greater and more consistent energy potential (Breton and Moe, 2009). Most offshore wind turbines utilise bottom-fixed foundations, including monopiles, which are selected according to site-specific parameters such as water depth, environmental conditions, and seabed properties.

The installation of these foundation systems can alter the local velocity gradients within seawater, driven by the combined effects of waves, currents, and structure interaction, which can induce localised scour in the sediments surrounding the base of the monopile. The depth of local scour around an installed monopile in the seabed can extend to almost 1.3 times the diameter of the pile (DNV, 2011). Since monopiles used in offshore applications have large diameters, a loss of seabed sediment of this magnitude can significantly reduce their load-bearing capacity and, under extreme loading conditions, may even lead to structural failure (Guan et al., 2022).

To mitigate the adverse effects of seabed scour around monopiles, scour protection systems are employed. In some cases, for cost savings and to simplify installation, scour protection is placed on the seabed using a dumping vessel prior to driving the monopiles into position. Scour protection may consist of a single layer of wide-range particle-size rock material whose grain size is comparable to the annular wall thickness of the monopiles. The wall thickness of offshore monopiles can reach over 100 mm, depending on the pile diameter, water depth, and seabed conditions. As previously demonstrated by Miranda et al. (2024) and Varela et al. (2025) through experimental tests on the penetration resistance of skirts in gravel used for scour protection systems, grain size has a significant influence on the penetration resistance of intruding objects. This increase in penetration resistance introduces uncertainty about whether the monopile can penetrate through the scour protection layer under its own self-weight or due to driving forces. Grain size effects may also alter the failure mechanism of the intruding object.

The effect of grain size on the penetration resistance of intruding objects has been studied by several previous researchers (Arroyo et al., 2011; Bolton et al., 1999; Cerfontaine et al., 2023; Miyai et al., 2019; Jahanshahi et al., 2025; Paume et al., 2024). Bolton et al. (1999) investigated how sand grain size influences CPT penetration resistance and found that this effect becomes significant when the ratio of cone diameter to the mean grain size (d_{50}) is below 20. Cerfontaine et al. (2023) concluded using discrete element modelling (DEM) that for open-ended piles, scale effects can arise when the wall thickness is comparable to the particle size, as this may affect whether a soil plug forms or not. Miyai et al. (2019), using DEM results of plate penetration into granular materials, concluded that particle size effects can increase the width of the "wedge-shaped" flow zone ahead of the plate during penetration. The width of this wedge-shaped flow zone increased as the grain size of the granular material increased.

Recently, Miranda et al. (2024) and Varela et al. (2022) conducted field investigations on skirt penetration into gravel to provide additional insight into how grain size influences penetration resistance. Experimental observations revealed an upward trend in penetration resistance corresponding to increases in plate thickness, gravel grain size, and the depth of penetration. Moreover, applying the new equivalent plate thickness method proposed by Miyai et al. (2019) to conventional bearing capacity formulations led to a more consistent interpretation of the experimental results.

Despite the research above, important aspects of pile penetration through scour protection layers still remain insufficiently understood, such as the influence of the grain size on the penetration resistance and the changes in resistance that occur when the pile tip transitions from the scour protection to the underlying sand bed, which typically has a smaller grain size.

Aiming to provide valuable information and insight into the above uncertainties, this study investigates the effect of a scour protection layer over a sand bed on the penetration resistance of piles using centrifuge modelling to replicate full-scale stress conditions. To this end, two different scour protection materials—sand and gravel at the model scale—were used to examine the effect of the pile wall thickness (t) to mean grain size (d_{50}) ratio on penetration resistance, along with two scour protection layer heights of 1.44 and 3 m at prototype scale. Piles with two different diameters (2 and 3 m) were used to assess the effect of their diameter on penetration resistance through the scour protection layer. This research forms part of an ongoing experimental programme in which additional pile diameters and scour-protection gravels will be investigated.

2 METHODOLOGY

2.1 Centrifuge modelling

The experimental tests described in this study were conducted using the Actidyn C67-2 geotechnical beam centrifuge, which features a 3-m radius and is located at the University of Dundee (Figure 1). The tests were carried out on a box with internal dimensions of 500 mm × 800 mm × 550 mm. Previous studies have demonstrated that modifying the g-level according to the required scaling laws enables replication of the same effective stress in saturated sand (Davidson et al., 2022; Li et al., 2010). The procedure adopted in this work was as follows: a 1:80 scaling factor was applied to determine the model pile dimensions, and all tests were carried out in dry sand at 50g, which produced the same effective stress as saturated sand would experience at 80g.

Figure 1. Centrifuge facility at the University of Dundee

The testing setup provided accurate control of the vertical movement of the piles, driven by a servo-motor. A load cell mounted at the top of the pile was capable of capturing axial forces from –20 kN to +20 kN. The axial movement was monitored with a WPS500-MK30 draw-wire displacement transducer.

2.2 Soil bed and scour protection layer preparation

The particle size distribution (PSD) curves of the soils used in the experimental tests are shown in Figure 2. The properties of the sand bed (HST95) are shown in Table 1. This type of sand has been widely used by numerous researchers, both numerically and experimentally, at the University of Dundee (Jawid et al., 2024; Sharif et al., 2021; Wang et al., 2025). The soil bed was prepared by dry pluviation of HST95 sand into the box to obtain a medium-dense state (D_r = 53%). The distance between the pluviator and the box was maintained at a constant height during the pluviation. In the box containing only HST95 sand, the sand material was deposited from a height exceeding 434 mm and then levelled with a scraper. However, for the box with scour protection layers of 18 mm and 38 mm in height (1.44 m and 3 m at prototype scale, respectively), the resulting sand-bed heights were 416 mm and 396 mm, respectively.

HST50 sand and CRA gravel, which have coarser grains compared to HST95, were used to prepare the scour protection layers. The properties of these soils are shown in Table 2. Although the grain size of the scour protection is determined by the wave and current design conditions in a real project (Den Boon et al., 2004; De Vos et al., 2012), the key aspects influencing the behaviour of these materials for the testing program were ensuring that the self-weight stresses were correctly represented and that the grain size was suitable and comparable to the pile wall thickness (t). The t/d_{50} ratio for scour protection soil materials was well below 5 (Table 3), allowing for investigation of grain size issues on penetration resistance. This is consistent with findings of Bolton et al. (1999), who noted that a ratio of cone diameter to d_{50} of 7 or less would lead to an obvious increase in resistance during the CPT test. These soils were pluviated with a hand shovel from a height close to the surface of the underlying layer to produce a loose deposit. The calculated dry unit weights of HST50 and CRA using this pluviation method were approximately 14 and 15.1 kN/m^3, respectively.

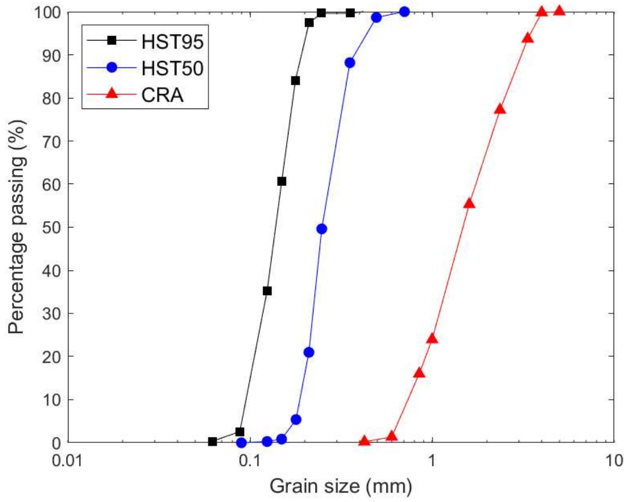

Figure 2. PSD of soils employed in testing

Table 1. Properties of HST95 sand bed (Al-Defae et al. 2013; Lauder 2010)

Property	Value
Effective particle size, d_{10} (mm)	0.09
Mean particle size, d_{50} (mm)	0.14
Particle specific gravity, G_s (-)	2.63
Minimum void ratio, e_{min} (-)	0.467
Maximum void ratio e_{max} (-)	0.769
Minimum dry density, γ_{min} (kN/m^3)	14.86
Maximum dry density, γ_{max} (kN/m^3)	17.93
Critical state friction angle, ϕ_{cr} (°)	32.0
Interface friction angle, δ_{cr} (°)	24.0

Table 2. Properties of scour protection layers

Property	Value (HST50, CRA)
Effective particle size, d_{10} (mm)	0.19, 0.75
Mean particle size, d_{50} (mm)	0.25, 1.47
Uniformity coefficient, c_u	1.42, 2.3

2.3 Pile models

The piles used in experimental tests were fabricated from steel (Figure 3). The piles were hollow and manufactured with outer diameters (D) of 25.4 mm (denoted P1) and 38.1 mm (denoted P2) at model scale (2 m and 3 m at prototype scale, respectively). The wall thickness of the monopiles (t) was 1.2 mm (96 mm at prototype scale). Table 3 summarises the dimensionless ratio of the wall thickness of the piles to the mean grain size (t/d_{50}) and the pile diameter to the mean grain size (D/d_{50}). Both model piles were designed with the same height of h = 150 mm (12 m at prototype scale). The monopiles were driven to a final penetration depth of z = 65 mm (5.2 m at prototype scale).

Table 3. Dimensionless ratios relevant to grain size effects

Soil	t/d_{50}	D/d_{50} (P1, P2)
HST95	8.6	181, 272
HST50	4.8	101, 152
CRA	0.82	17, 26

Figure 3. Model piles used in testing

Both piles were tested in the same pluviated box. The distance from the centre of each pile to the other pile and to the box boundaries was approximately 8.5 times the average outer diameter of the two piles. After completing the first test in the box, the centrifuge was spun down, the actuator was repositioned manually, and the centrifuge was then spun up again for the second penetration test.

2.4 Testing procedure

Once the centrifuge attained 50*g*, the force reading was reset to zero while the pile was held slightly above the soil surface, before installation commenced. Subsequently, the custom LabVIEW software was configured with an installation velocity of 20 mm/min to ensure smooth penetration of the pile to the target depth. Once the piles reached the desired penetration depth, the vertical movement was stopped.

3 RESULTS

Figure 4 and Figure 5 show the load-displacement response of P1 and P2 in the uniform HST95 sand bed and in scour protection of different heights overlaying the sand bed. As shown in Figure 4, the penetration resistance of P1 in sand and in HST50 scour protection layers increased steadily as the penetration depth increased. No significant variation was observed in the penetration resistance of P1 between the HST50 scour protection layers of 1.44 m and 3 m. This may be attributed to the fact that the difference in d_{50} between the HST50 scour protection layer and the HST95 sand bed was not very significant, being only about a factor of 1.8. Therefore, no further tests were conducted on HST50 for P2.

At a penetration depth of approximately 5 m, the penetration resistance of P1 was about 4.7 MN in HST95 sand, and about 4.0 MN and 4.4 MN for the 1.44 m and 3 m HST50 scour protection layers overlying the sand bed, respectively. Similar to P1, the penetration resistance of P2 continued to increase steadily in the uniform HST95 sand bed with an increase in penetration depth (Figure 5). Also, the penetration force in the same soil material (HST95) for P2 was higher than that of P1 due to the larger perimeter of P2 and, therefore, higher mobilised tip resistance and shaft friction during penetration.

However, the load magnitude of both P1 and P2 showed a considerable increase in the CRA scour protection layers, with a pronounced peak observed for the 3 m scour protection height (and an initial potential peak in the 1.44 m thick layer). Due to greater penetration depth in the CRA-3m scour protection layer, the difference in peak resistance between P1 and P2 became more significant compared to CRA-1.44m. The load-displacement response in the CRA scour-protection tests exhibited noticeable “noise” when compared to the uniform HST95 sand penetration. Similar oscillations in the response of skirts penetrating through gravel were reported by Miranda et al. (2024) and Varela et al. (2022) based on full-scale experimental tests, and these irregularities in the penetration resistance were greater as the t/d_{50} ratio decreased. They are attributed to the discontinuous rearrangement of the particles as the pile penetrates or coarse-grain particle interaction with the pile shaft for the small t/d_{50}. Some signs of arching within the pile as it penetrates the coarser material, especially for smaller-diameter piles, can also be observed. This reduction in penetration resistance, followed by a build-up, can be related to arch failure and reforming within the small-diameter piles, as previously reported by Paikowsky (1990).

The penetration force began to decrease at a depth above the full scour protection depth in both CRA layers, regardless of their thickness. This can be attributed to the combined effects of lower friction resistance of the sand bed, smaller grain size, and plug failure in this layer (for the smaller diameter pile). In addition, as previously observed through numerical modelling by Miyai et al. (2019), the failure zone beneath the intruder's tip (here, the pile) decreases to a noticeable extent as grain size decreases. When passing the CRA scour protection layers, the force level for both piles reached nearly the same magnitude as that observed in the uniform HST95 sand bed. Similar observations were reported by Cengiz et al. (2024), who noted that the penetration resistance of skirts decreases upon entering the sand bed layer underlying the scour protection rock material, before increasing again due to the increase in effective stresses with depth.

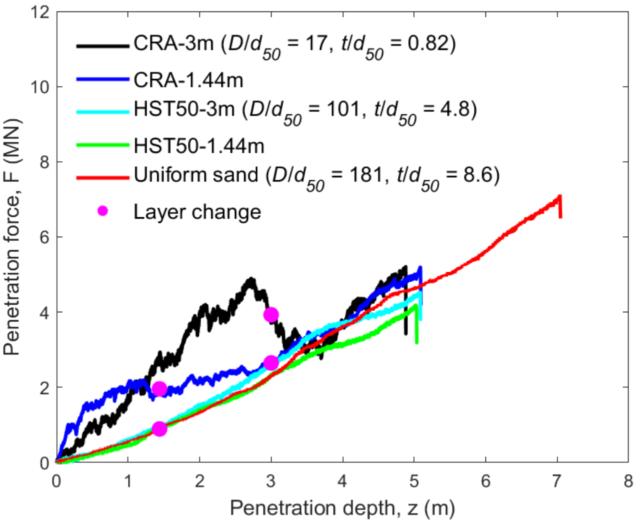

Figure 4. Penetration force versus penetration depth of P1 (D = 2 m) in different soil materials

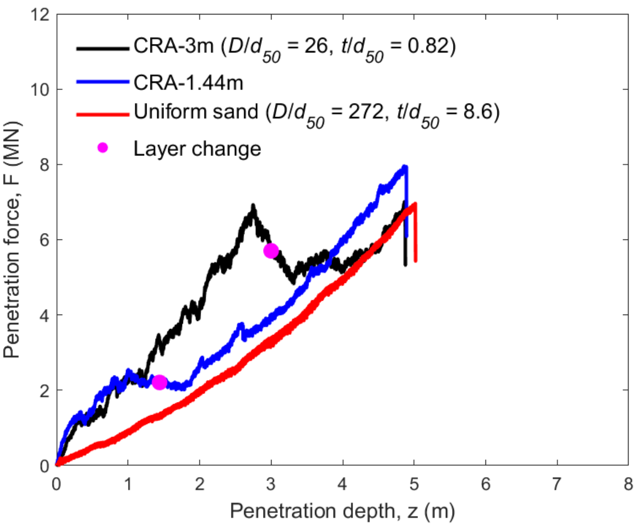

Figure 5. Penetration force versus penetration depth of P2 (D = 3 m) in different soil materials

4 CONCLUSION

This physical model study, using centrifuge testing, examined how monopiles penetrate through pre-installed scour protection layers and how grain size, scour height, pile diameter, and thickness influence that response.

Grain size played a decisive role in the measured penetration forces. The CRA gravel material produced larger penetration resistance and more irregular load–depth curves than those observed for the two HST sands used.

At the interface between the CRA scour layer and the HST95 underlying sand, the piles consistently showed a temporary reduction in resistance before the response stabilised again in the sand. The sharpness of this transition depended on the thickness of the CRA scour layer.

Overall, the results highlight how grain size, scour layer thickness, and pile diameter combine to influence penetration through pre-installed scour protection. These findings can help reduce uncertainty in installation predictions for monopile foundations in offshore wind applications.

These are preliminary results of a more exhaustive testing campaign that the authors are performing with additional pile diameters and gravel materials for the scour protection layer.

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