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Comparing the driving and uplift behaviour of a vertical plate in silica and carbonate sands

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ABSTRACT: This paper investigates the driving and uplift behaviour of a vertical plate in sand using centrifuge modelling. A thin plate, potentially representing a segment of a large diameter pile, was tested in three types of sand: silica sand, reconstituted carbonate sand and intact carbonate sand. The plate was dynamically driven using a hammer and subsequently uplifted. The number of hammer blows during driving and the resistance during uplift were recorded, while pre- and post-test particle breakage was measured for all sand specimens. The results show that during driving, intact carbonate sand exhibits a resistance approximately six times greater than that of silica sand and reconstituted carbonate sand. During uplift however, the resistance in silica sand is more than four times higher than that seen in the two carbonate sands. Particle analysis reveals slightly greater particle breakage in the intact carbonate sand compared to reconstituted carbonate sand, with negligible particle breakage observed in silica sand. It is concluded that the observed driving and uplift behaviour is strongly influenced by the fabric (structure) of intact carbonate sand, as well as particle breakage of the carbonate sediment.

Keywords: Carbonate sand; centrifuge; plate driving; uplift resistance; particle breakage

1 INTRODUCTION

Pile foundations are widely used in offshore wind projects. The installation of piles disturbs the surrounding soil, altering soil states and consequently affecting pile bearing capacity during operation (El Haffar et al., 2017). Accurate prediction of pile capacity and displacement remains a challenge for offshore engineering, with the influence of particle breakage on the mechanical behaviour of granular materials like carbonate sands continuing to draw attention (Cheng et al., 2022; Coop, 1990).

Carbonate sediments are formed when the skeletal remains of marine organisms are deposited on the sea floor, leading to properties that differ from silica sands, including high calcium carbonate content, high void ratio, irregularly shaped and easily crushable particles, particle arrangements that lead to collapsible structure, and interparticle cementation (Watson et al., 2019). When subjected to shear stress, carbonate sand particles undergo breakage (Hardin, 1985), influencing the strength and stress-strain characteristics of the material. This breakage reduces the mobilised radial stress due to volume contraction, which in turn governs the geotechnical performance of supported foundations (Yang et al., 2010). Conventional pile-soil interaction approaches may overestimate shaft friction by neglecting the effect of particle breakage, which can cause pile failure (Kuwajima et al., 2009). This emphasizes the importance of understanding the impact of particle breakage at the pile-soil interface.

This paper reports on testing of a pile segment/plate that was penetrated into and then uplifted out of silica and carbonate sands in a geotechnical centrifuge. The penetration was achieved by impact driving in-flight. Both reconstituted carbonate sand and intact carbonate sand were used in the tests, and the different response in all three sands was explored. The potential for particle breakage to occur around the plate was assessed after testing, in order to investigate its effect on driving and uplift behaviour.

2 EXPERIMENTAL SETUP

2.1 Specimen Preparation

Three different sand samples were used in the testing campaign: superfine silica sand, reconstituted carbonate sand and intact carbonate sand. The initial conditions of the three specimens are given in Table 1.

The superfine silica sand is a commercially available quartz sand with sub-rounded to sub-granular particles widely tested at the University of Western Australia (UWA). It has a specific gravity (G_s) of 2.67 and maximum and minimum void ratios (e_{max}, e_{min}) of 0.789 and 0.512, respectively. The intact and reconstituted carbonate sands with sub-granular to granular particles were sampled from a location on the Northwest Shelf of Australia. A specific gravity of G_s = 2.81 was reported from testing of the intact sediment. It is noted that while the G_s of carbonate sand is higher than that of silica sand, the dry density of the carbonate sand is lower – attributed to the higher void ratios of the carbonate sand.

Table 1. Initial specimen conditions of the test sands

Sample Type	Silica sand	Reconstituted carbonate sand	Intact carbonate sand
Dry density (g/cm³)	1.62	1.39	1.29
G_s	2.67	2.81	2.81
e	0.644	1.025	1.177
e_{max}	0.789	-	-
e_{min}	0.512	-	-
Relative density (%)	52.5	-	-

Fig. 1 shows the particle size distributions (PSDs) for all three sands. According to the Unified Soil Classification System (USCS), superfine silica sand is classified as SP (poorly graded sand) whereas intact and reconstituted carbonate sands are classified as SM (silty sand).

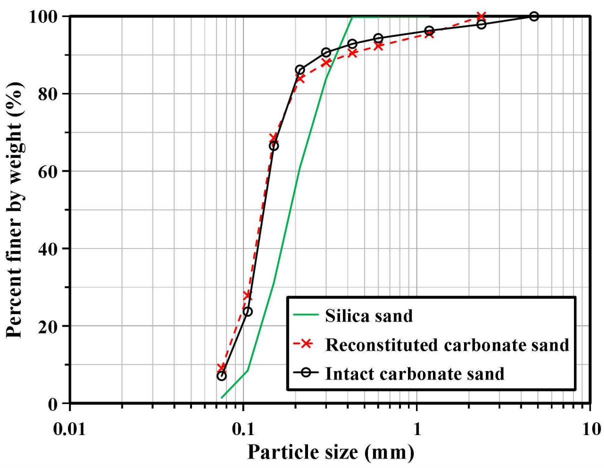


Figure 1. Particle size distributions of the test sands

The intact and reconstituted carbonate sand samples were collected from the same borehole, with the intact samples being from depths of 15-16 m below seabed and the reconstituted samples from 14-15 m – leading to typical in-situ vertical effective stress in the range of 114-130 kPa. To mimic the in-situ stress conditions, all specimens were saturated and consolidated under a vertical stress of 126 kPa in individual tubes with an internal diameter of 72 mm (which was based on the recovered in-situ samples). The reconstituted sand was prepared using a slurry method, following the procedure described by Wijewickreme and Sanin (2010), to (broadly) replicate natural sedimentation conditions - although the fabric inherent in intact carbonate sand, as developed in marine environments (Krage et al., 2020), cannot be replicated in the reconstituted carbonate specimen.

2.2 Plate and Test Setup

The centrifuge model tests were carried out at an acceleration of 100g (where g is earth's gravity) in the University of Western Australia's 3.6 m diameter beam centrifuge. Model aluminium plates (anodised) that were 20 mm in width (w), 3 mm in thickness (t), and 250 mm in length (l) were used; broadly representing a segment of a pile with a wall thickness of 0.3 m. While this is thicker than typical monopiles, it was selected in order to prevent excessive deformation or damage to the plate during driving. The minimum distance between the plate and the tube wall exceeded 11t, leading to the conclusion that boundary effects can be considered negligible, according to Ovensen (1979).

The plate driving and uplift setup for the centrifuge tests (shown in Fig. 2) comprised: a pneumatically powered model driving hammer, a loading plate for providing in-situ stress, a 2 kN capacity load cell for measuring uplift resistance, a mechanical LVDT for measuring installation displacement, and a laser LVDT for detecting uplift displacement. The hammer consists of a 0.184 kg model scale mass free falling from a fixed 15 mm drop height. The base supports only the sand specimen within the tube, with a gap maintained between the base and the tube wall to ensure that vertical stress is applied uniform through the specimen.

After being impact-driven in flight into the specimens to a depth of 160 mm (16 m in prototype scale) the plates were extracted by 20 mm (2 m in prototype scale). All tests were conducted with specimens fully submerged in water to mimic offshore conditions.

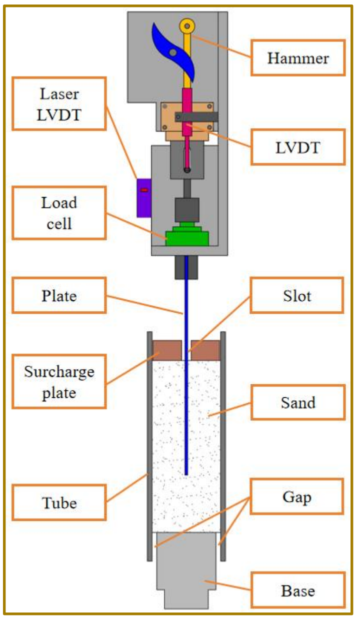


Figure 2. Schematic diagram of testing assembly housed in a beam centrifuge

3 RESULTS AND DISCUSSION

3.1 Plate Driving

The initial horizontal position of the plate was adjusted to keep it centred within the slot on the surcharge plate (see Fig. 2), while the vertical position was fixed such that the plate tip just touched the sand surface prior to centrifuge spin-up. Before commencing driving, the plate was released to penetrate under its own weight (at 100g), then a constant drop height of 15 mm was used for impact driving until full penetration of 160 mm was achieved.

Fig. 3 shows the cumulative blows versus plate penetration depth at prototype scale. At a full penetration depth of 16 m, the number of blows required in silica sand and reconstituted carbonate sand (i.e. 51 and 50 blows, respectively) was nearly identical, whereas significantly more blows were required in the intact carbonate sand (i.e. 291 blows). Despite their similarity at target depth, the driving history in the silica sand and reconstituted carbonate sand are different – at a penetration of 11 m, the number of blows required in the reconstituted carbonate sand was twice that in silica sand; whereas for deeper penetration the number of blows for a set distance increased significantly in silica sand. This might be due to the densification of silica sand below and around the penetrating plate. In contrast, in reconstituted carbonate sand, particle breakage may have caused volume contraction, reducing driving resistance.

The number of blows required to penetrate the intact carbonate sand is nearly six times that in the other two sands. While difficult to explain, this appears to be likely due to its (intact) fabric and structure, similar to the observations in Mao and Fahey (1999). It appears this fabric was preserved at its natural state during sampling, but was lost during the subsequent reconstitution process.

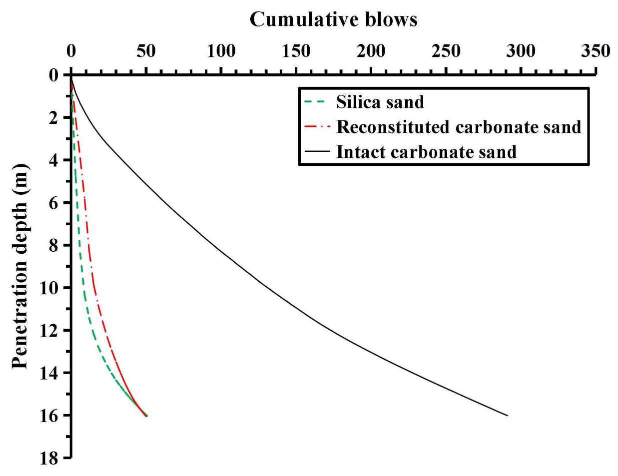


Figure 3. Plate driving response

3.2 Plate Uplift

The uplift stage was performed using a slow rate of 0.1 mm/s, ensuring that the measured uplift resistance reflected the friction between the plate and the sand. Fig. 4 illustrates the uplift resistance per unit area during the first 2 m (prototype scale) for the three sand specimens.

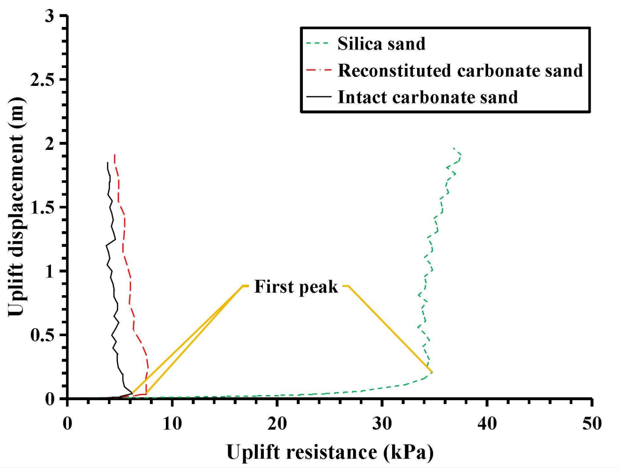


Figure 4. Plate uplift resistance

As shown in Fig. 4, the uplift resistance in silica sand is significantly higher (approximately 4~6 times) than that of the reconstituted and intact carbonate sands. This is likely associated with changes in sand characteristics during plate driving – during driving, the silica sand both densifies and sees high radial stress, contributing to high uplift resistance; while the reconstituted and intact carbonate sands experience particle breakage and volume contraction, leading to lower uplift resistance. This may also explain the observed trend following the first peak resistance, where uplift resistance increases in silica sand (due to dilation) but decreases in both of the carbonate sands.

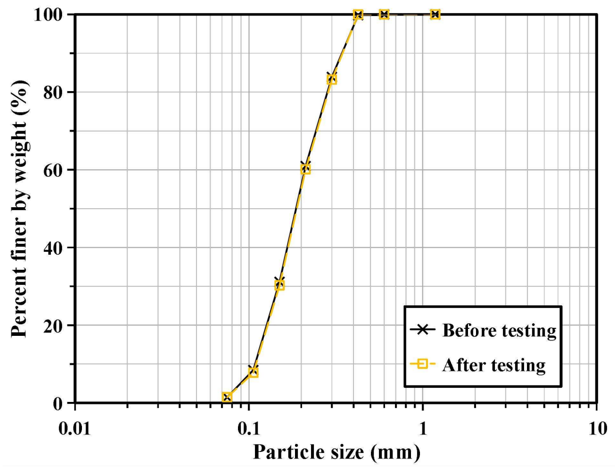
Although harder to confirm, it appears that the first peak resistance is attained earlier in the reconstituted and intact carbonate sands when compared to silica sand – although this likely also relates to the magnitude of the peak. This can be partly attributed to differences in the stiffness of the three sands – Carraro and Bortolotto (2015) found that carbonate sand exhibits higher stiffness than silica sand under comparable density and stress conditions.

3.3 Particle Breakage

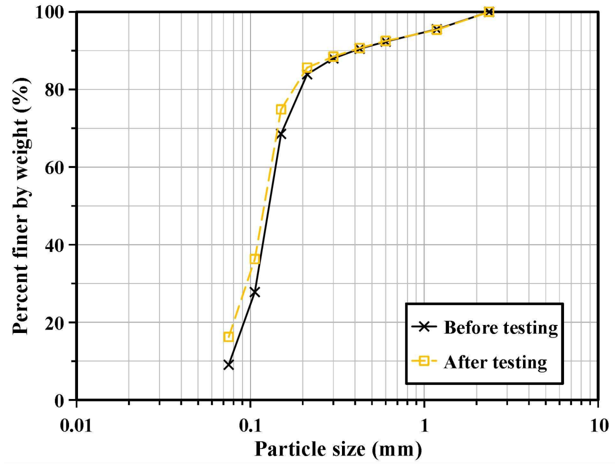
An aim of the research was to both measure and observe particle breakage close to the plate boundary after driving and uplift – which was achieved by sampling soil zones within 3 mm (1*t*) of the plate sides and tip. Fig. 5 presents sieving results before and after the plate tests in silica sand, reconstituted carbonate sand and intact carbonate sand.

Fig. 5a shows that no obvious particle breakage occurs in silica sand. In contrast, both reconstituted and intact carbonate sands exhibit a degree of particle breakage, with the intact specimen showing more pronounced breakage than the reconstituted specimen (Figs. 5b and 5c). After the plate tests, a higher proportion of small particles (size < 0.3 mm) is observed in both reconstituted and intact carbonate sands – in particular, the fines content (size < 0.075 mm) of the reconstituted specimen increased by 7% (from 9% to 16%), whereas in the intact sediment it increases by 14% (from 7% to 21%). While somewhat anecdotal, this suggests greater particle breakage in the intact carbonate sand compared to reconstituted carbonate sand – likely due to the harder driving experienced.

Fig. 6 presents representative scanning electron microscopy (SEM) images of the intact carbonate sand before and after testing. As shown in Fig. 6a, the particles exhibit complex external morphology, with angular particles being predominant and pores of varying sizes randomly distributed across the particle surfaces. These characteristics are key contributors to the high crushability of carbonate sand under load. In contrast, after driving (Fig. 6b) a substantial number of fine particles were generated as a result of particle breakage – although some large particles survived.



(a)



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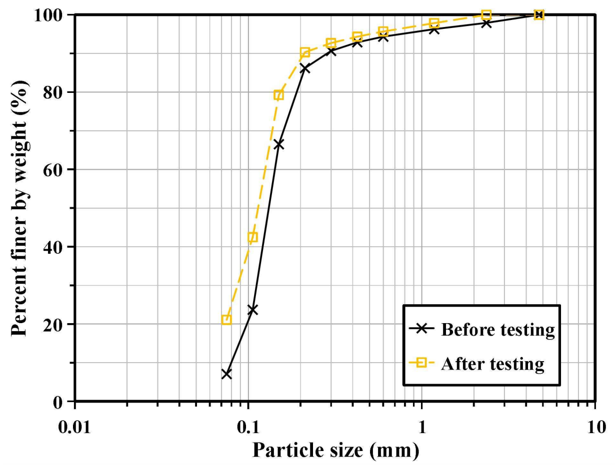
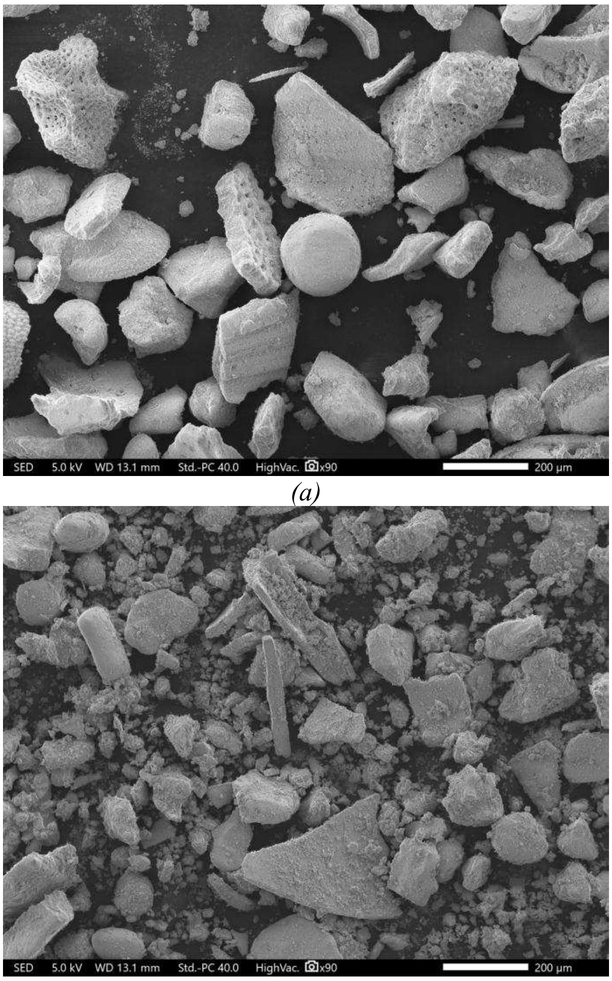


(c)

Figure 5. Particle size distributions before and after testing of: (a) silica sand, (b) reconstituted carbonate sand, (c) intact carbonate sand



(a)

(b)

Figure 6. SEM images of intact carbonate sand: (a) before testing, (b) after testing

3.4 Discussion

The penetration and uplift behaviour of the plate in silica sand, reconstituted carbonate sand, and intact carbonate sand exhibit distinct responses, which can be largely attributed to the different mechanical characteristics of carbonate versus silica sands.

3.4.1 Penetration behaviour

In silica sand, the initial penetration rate of the plate is relatively high, likely due to its comparatively low initial relative density (i.e. D_r = 52.5% in Table 1). However, as penetration progresses, the sand surrounding the plate is expected to densify and become more dilative in response to plate insertion. As a result, the penetration rate decreases significantly during the later stage of plate penetration – and the 'pile' could perhaps refuse with further driving.

In comparison, Fig. 3 showed that the initial penetration rate of the plate in reconstituted carbonate sand is (somewhat) lower than that observed in silica sand. At the same stage, the penetration rate in intact carbonate sand is considerably lower than that in both silica sand and reconstituted carbonate sand. The reasons for this difference are unclear. On the one hand, carbonate sands typically exhibit higher friction angle than silica sand (Shen et al., 2023), which may result in greater resistance for the (relatively thick) plate tip. However, this does not explain the differences between the two carbonate specimens – leaving the fabric (and potential light interparticle cementation) inherent in the intact sand as the most likely reason for the high resistance to driving, likely associated with high tip resistance.

3.4.2 Uplift behaviour

Particle breakage also appears to significantly influence the uplift behaviour of the plate. During this stage, the uplift resistance is governed by friction along the sand-plate interface, with the plate tip not expected to contribute to the resistance. The silica sand specimen, which had minimal particle breakage, exhibits strain-hardening behaviour throughout the uplift process. This response is likely due to the dilation of silica sand during shear, which enhances lateral confinement on the plate.

In contrast, both reconstituted and intact carbonate sand specimens, which did experience particle breakage, display strain-softening behaviour during uplift. This response can be attributed to volumetric contraction in each of the carbonate sands, which lessens lateral confinement around the plate – noting that after plate penetration, the fabric and potential cementation existing within the intact carbonate sand would have been destroyed. While the difference is modest, the potential for higher volumetric contraction in the intact sand likely explains the (slightly) lower uplift resistance in this specimen compared to the reconstituted carbonate sand; while the potential for particle breakage during testing, which aligns with the findings of Hagerty et al. (1993), is also likely to have contributed.

4 CONCLUSIONS

Centrifuge modelling was undertaken to investigate the driving and uplift behaviour of a plate in silica sand, reconstituted carbonate sand and intact carbonate sand under identical initial stress conditions. Post-test analysis of particle breakage was conducted to explore for changes at the sand-plate interface for the three types of sand.

Based on the specific test conditions in this study, the following conclusions can be drawn:

- The number of hammer blows required to drive the plate to a penetration depth of 16 m is comparable in silica sand and reconstituted carbonate sand, but is far higher in intact carbonate sand. This likely reflects the significance of tip resistance to driving behaviour, and the potential for high resistance in the intact specimen due to fabric effects and (potential) interparticle bonding.

- The uplift resistance of the plate in intact carbonate sand is slightly lower than that seen in reconstituted carbonate sand, with both being much lower than that observed in silica sand. While both carbonate sand specimens exhibit strain-softening behaviour during further uplift, the silica sand demonstrates strain-hardening. The observed response likely reflects progressive densification and the development of high radial stress around the plate in silica sand, versus particle crushing and volumetric contraction in the carbonate specimens.
- While particle breakage in silica sand is negligible, noticeable increases in fines content are observed in both carbonate sands, with greater breakage occurring in intact carbonate sand.

This work is part of a wider study into the effect of fabric on foundation response. In this regard, the observations presented in this paper point to two aspects that merit further investigation. Firstly, does fabric and potential interparticle cementation of the natural sediment adequately explain the higher penetration resistance observed in intact carbonate sand, compared to its reconstituted counterpart? Secondly, does the impact of particle breakage on volumetric contraction during shearing explain the dilative/contractive response of the specimens during subsequent shearing? Future studies are encouraged to explore these mechanisms in greater detail, with a view to improving the understanding and modelling of pile behaviour in carbonate sand.

AUTHOR CONTRIBUTION STATEMENT

First Author: Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Second Author:** Supervision, Visualization, Writing – original draft, Writing – review & editing. **Third Author:** Conceptualization, Funding acquisition, Project administration, Resources, Writing – review & editing. **Last Author:** Methodology, Writing – review & editing.

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