ABSTRACT: Compared to silica sand, carbonate sand has considerably higher angularity, lower grain hardness and higher intra-particle porosity, which result in high friction angles and compressibility. The corresponding dilatancy is affected strongly by the confining stress. Thus, for low relative densities, dilation occurs at low confining stresses, reflecting the greater particle interlocking compared to silica sand. However, with the increase of confining stress, the dilatancy is suppressed quickly, and finally diminishes completely at a relatively low stress level, due to particle degradation. This distinctive characteristic significantly influences the behaviour of continuously penetrating spudcan foundations in calcareous sediments. Centrifuge tests were carried out on spudcan foundations penetrating multi-layer soils with an interbedded strong layer composed with either carbonate or silica sand. All measures of spudcan punch-through severity were significantly lower for interbedded carbonate sand despite its higher friction angle ($\phi_{crit} = 40^\circ$) compared to silica sand ($\phi_{crit} = 34^\circ$). For the spudcan penetration through the sand layer to the lower clay layer, the soil failure mechanisms quantified by particle image velocimetry (PIV) analysis allowed for identifying the differences in the evolution of sand frustum beneath the advancing spudcan. The spreading angle of the frustum, which determines the size of the projected bearing area, was found to be proportional to the mobilised dilatancy.

KEYWORDS: carbonate, silicate, dilation, spudcan foundations.
foundation punch-through failure depends on the operative friction angle and associated dilation angle, both of which reduce with increasing stress level.

This paper reports the results from a series of basic characterisation tests conducted on reconstituted samples of carbonate sand to understand its behaviour. Centrifuge tests were also carried out on spudcan foundations penetrating four-layer deposits, with an interbedded carbonate or silica sand layer for direct comparison.

Table 1. Values of $Q$ and $\phi_{\text{voi}}$ derived from triaxial compression tests (after Randolph et al. 2004, InSafeJIP 2010).

<table>
<thead>
<tr>
<th>Sand</th>
<th>Mineralogy</th>
<th>$Q$</th>
<th>$\phi_{\text{voi}}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ticino</td>
<td>Siliceous</td>
<td>10.8</td>
<td>33.5</td>
<td>Jamiolkowski</td>
</tr>
<tr>
<td>Toyoura</td>
<td>Quartz</td>
<td>9.8</td>
<td>32</td>
<td>et al. (2003)</td>
</tr>
<tr>
<td>Hokksund</td>
<td>Siliceous</td>
<td>9.2</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>Mol</td>
<td>Quartz</td>
<td>10</td>
<td>31.6</td>
<td>Yoon (1991)</td>
</tr>
<tr>
<td>Kenya</td>
<td>Calcareous</td>
<td>8.5</td>
<td>40.2</td>
<td>Jamiolkowski</td>
</tr>
<tr>
<td>Quio</td>
<td>Calcareous</td>
<td>7.5</td>
<td>41.7</td>
<td>et al. (2003)</td>
</tr>
</tbody>
</table>

2 STRESS-STRAIN BEHAVIOR

Simple shear tests with a Berkeley type apparatus were performed on uncemented skeletal carbonate sand recovered from the seabed of Australian North-West Shelf (NWS). Particles smaller than 75 μm and larger than 2.36 mm were removed by washing and sieving prior to testing. The median grain size and coefficient of uniformity were $d_{50} = 0.22$ mm and $Cu = 2.3$, respectively. The high grain angularity and intra-particle void resulted in a high void ratio with minimum and maximum value of 0.91 and 1.36 respectively.

Drained tests with a lateral stress ratio $K = 0.4$ were performed on loose and medium dense sand to obtain the stress-strain behaviour. The results are shown in Figures 1 and 2, highlighting a strong dependency of the volumetric dilatancy on the confining stress. The values of relative densities ($I_d$) shown in the figures represent the condition just before shearing. Dilative volume change occurred even in loose sand at a vertical stress $\sigma_v = 200$ kPa (see Figure 1). This dilative response is not unusual owing to the particle angularity and interlocking. For most tests, shearing ended in dilative volume state, except two at higher stresses with $\sigma_v \geq 400$ kPa. Interestingly, for dense sand subjected to $\sigma_v \geq 300$ kPa, dilative response at intermediate strains turned to contraction close to the end of shearing, indicating the influence of continual particle breakage. A transient dilation at the highest stress of $\sigma_v = 700$ kPa was also noticed at shear strain levels of 15 to 20%.

The transition from dilative to contractive behaviour occurred at a lower stress level, $\sigma_v < 400$ kPa or mean stress $\sigma' < 240$ kPa, compared to silica sand.

![Figure 1. Volumetric change of carbonate sand in drained simple shear test with lateral stress ratio $K = 0.4$.](image1.png)

Figure 1. Volumetric change of carbonate sand in drained simple shear test with lateral stress ratio $K = 0.4$.

3 EFFECT OF PARTICLE DEGRADATION

In carbonate sands, high crushability and compressibility are led by the high intra-particle porosity, as discussed previously. Datta et al. (1980) reported the effect of grain crushing during shearing and found direct correlations between crushing and reduction of maximum principal effective stress ratio, change from dilative to contractive behaviour, more plastic stress-strain relation, and increase of failure strain.

Golightly and Hyde (1988) performed comprehensive isotropic drained triaxial (CID) tests on three different skeletal carbonate sands, all with a relative density of 97%. They reported results in terms of friction angle $\phi_f$, calculating according to $\phi_f = \phi_{\text{peak}} - \psi$, as shown in Figure 3. The dilation angles of the tested carbonate sands were found lower than those of the silica sand. The critical confinement stress at which dilation was suppressed was also shown to be very low compared to silica sand. For instance, the dilation angle of Dogs Bay sand, which is mainly composed of skeletal mollusc fragments, decreased to zero at a confining stress of only 370 kPa. The siliceous Leighton Buzzard sand, on the other hand, has a constant dilation angle of around 9° to 10° for all tested confining stresses (< 1000 kPa).
A similar tendency can be found from the experimental results reported by Desrosiers and Silva (2002). A direct comparison was made between the behaviour of carbonate sand and silica sand, which are commonly used for centrifuge model tests at UWA and are used industrially. An abundance of reliable data exists regarding the geotechnical properties (e.g. Stewart 1992, Cheong 2002). The carbonate sand was dredged directly from the North-West Shelf of Australia, as discussed previously. The critical state friction angles of the silica and carbonate sands were 34° and 40°, respectively.

The densities of the sand layers, which were determined by measuring the total added sand weight and the volume formed for all cases, corresponded to an average relative density, $D_o$, of 44%. For the clay beds, characterisation tests were carried out using a T-bar penetrometer, of diameter 5 mm and length 20 mm (model scale).

Figures 4 and 5 show the results from full-spudcan and half-spudcan tests, respectively. The load-penetration responses (see Figure 4) are presented in terms of ultimate bearing pressure, $q_u = P/A$ (where $P$ is the penetration resistance and $A$ is the largest plan area of the spudcan), as a function of normalised penetration depth, $d/D$. The potential for punch-through failure, with a local maximum in penetration resistance followed by some reduction, occurred for all cases investigated. The severity of failure is conventionally quantified by (a) the degree of post-peak reduction in resistance and (b) the ‘additional penetration’ before the peak resistance is re-established. By comparing the penetration resistance profiles for Test FS1 and Test FS2, on identical soil profiles with identical sand relative density, the measures of punch-through severity were significantly higher for the sandwiched silica sand despite its lower friction angle ($\phi_{silica} = 34^\circ$ compared to 40°). This is due to the behaviour of carbonate sand, as discussed previously and also described below.

Commercially available kaolin clay and super fine silica sand are commonly used for centrifuge model tests at UWA and an abundance of reliable data exists regarding the geotechnical properties (e.g. Stewart 1992, Cheong 2002). The carbonate sand was dredged directly from the North-West Shelf of Australia, as discussed previously. The critical state friction angles of the silica and carbonate sands were 34° and 40°, respectively.

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Table 2 provides a summary of all centrifuge tests reported. Four tests encompassed two different four-layer profiles: (i) soft clay-carbonate sand-soft clay-stiff clay; (ii) soft clay-silica sand-soft clay-stiff clay. These multi-layer clay samples were prepared by consolidating thoroughly mixed, and then de-aired, kaolin slurry at 1 g in separate cells. Two different final pressures were used to obtain comparatively strong and soft samples. Each clay layer, as detailed in Table 2, was then cut to size of the strongbox. The bottom two (3rd and 4th) clay layers were amassed in the strongbox. A layer of water was poured into the strongbox. Dry super fine silica sand (or carbonate sand) was then air-pluviated into the strongbox on top of the placed lower layers. A loose to medium dense layer was deposited by raining the sand maintaining a relatively small sand drop height of about 100 mm. The sand surface was carefully levelled and the top clay layer was placed.

### Table 2. Summary of centrifuge tests reported ($D = 12$ m).

<table>
<thead>
<tr>
<th>Test</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/D</td>
<td>Soil</td>
<td>t/D</td>
<td>Soil</td>
</tr>
<tr>
<td>HS1</td>
<td>0.25</td>
<td>Soft clay</td>
<td>0.5</td>
<td>Sand</td>
</tr>
<tr>
<td>FS1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HS2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Comparison of dilative behaviour between calcareous and siliceous sand under various cell pressures (Golightly and Hyde 1988).

Figure 4. Effect of interbedded sand mineralogy on load penetration response: severity of punch-through (Tests FS1 and FS2, Table 2).

The accompanying soil deformation patterns are shown in Figure 5 by means of contours of the incremental absolute soil flow velocity $v$ normalised by the foundation speed $v_{spudcan}$. The ratio $v/v_{spudcan}$ of unity indicates that the soil moves with a speed...
equivalent to that of the spudcan. The soil deformations were directed predominantly vertically down in the 2nd layer and laterally out in the lower (3rd) soft layer. The soil around the spudcan edges just started to flow back into the cavity formed above the spudcan. It can be seen that, under this relatively high confining stress in an embedded layer, the load spread angle is about 8° in carbonate sand and 19° in silica sand. The load spread angle is sometimes taken as the dilation angle (Lee et al. 2009; Teh et al. 2009). As such, it can be concluded that the interbedded carbonate sand layer showed less dilatancy. Furthermore, the trapped plug height (and hence the bearing base) is slightly lower for carbonate sand.

In both deposits, with the progress of penetration, the dilatancy was suppressed quickly and hence a plug with the shape of an inverted truncated cone, bounded by clear shear planes, was formed in the stronger (2nd) layer and moved down with the spudcan. Continual backflow provided a seal above the advancing spudcan and limited the cavity depth.

5 CONCLUDING REMARKS

This paper reported results from a series of simple shear tests on carbonate sand dredged directly from Australian North-West Shelf. The stress-strain behaviour was compared with those of silica sand, focusing particularly on dilatancy. To examine the influence of dilatancy on foundation performance, a series of centrifuge model tests were carried out on spudcan foundations penetrating four-layer soils, with a carbonate or silica sand layer interbedded in soft clay layers. The following key conclusions can be drawn from the results presented in the paper.

1. The dilatancy of carbonate sand was affected strongly by the confining stress. Even for relative density as low as 5%, in contrast to silica sand, dilative behaviour was shown to occur, reflecting the greater interlocking compared to silica sand.

2. With the increase of confining stress, dilatancy of carbonate sand was suppressed quickly, and eventually diminished completely at a relatively low stress level, due to particle degradation. In contrast, silica sand showed dilatant behaviour at stresses > 1000 kPa.

3. This distinctive characteristic influenced the behaviour of continuously penetrating spudcan foundations, causing a less severe punch-through failure in an interbedded carbonate sand compared to that in silica sand layer, with significantly lower bearing capacity.

6 ACKNOWLEDGEMENTS

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7 REFERENCES


