Comparison of Stress-Strain Behaviour of Carbonate and Silicate Sediments

Comparaison de la réponse contrainte-déformation de sédiments carbonatés et siliceux

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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, even 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 (ϕ_{crit} = 40°) compared to silica sand (ϕ_{crit} = 34°). 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.

RÉSUMÉ : Comparativement au sable siliceux, le sable carbonaté a une angularité considérablement plus élevée, une plus faible dureté de grain et une porosité intra-particulaire plus élevée, ce qui a pour effet de produire un angle de frottement et une compressibilité élevés. La dilatance de ce dernier est fortement affectée par la contrainte de confinement. Ainsi, même pour de faibles densités relatives, le comportement dilatant peut se produire pour des contraintes de confinement faibles, reflétant une tendance à l'imbriquement des particules plus élevée par rapport au sable siliceux. Cependant, la dilatance est rapidement réprimée lorsque la contrainte de confinement augmente, et finalement disparaît complètement pour des niveaux de contrainte relativement faibles, du fait de la dégradation des particules. Cette caractéristique particulière influence de manière significative le comportement des fondations 'spudcan' lors de leur pénétration dans des couches de sédiments calcaires. Des essais en centrifugeuse ont été réalisés sur des fondations 'spudcan' pénétrant des sols multi-couches comprenant une couche intermédiaire composée soit de sable carbonaté, soit de sable siliceux. Toutes les mesures de sévérité du risque de pénétration du « spudcan » étaient significativement plus faibles pour le cas d'une couche intermédiaire de sable carbonaté, en dépit du fait que l' angle de frottement soit plus élevé (ϕ_{crit} = 40°), par rapport au sable siliceux (ϕ_{crit} = 34°). Pour la pénétration du « spudcan » à travers la couche de sable jusqu'à la couche sous-jacente d'argile, les mécanismes de rupture du sol quantifiés par vélocimétrie d'image de particule (PIV) ont révélé des différences d'évolution du tronc de sable en dessous du « spudcan ». L'angle d'ouverture du tronc de sable, qui détermine la taille de la surface portante projetée, s'est révélé être proportionnel à la dilatance mobilisée.

KEYWORDS: carbonate, silicate, dilation, spudcan foundations.

1 INTRODUCTION

Carbonate sediments are prevalent in Australian waters and in the Caspian Sea, Arabian Gulf, South China Sea, offshore Qatar and offshore Florida. Standard geotechnical analysis models were generally developed for silica sediment. Extreme care should be exercised when applying those models for carbonate sediments and indeed predictions using routine bearing capacity methods linked to the friction angle have been shown to be inappropriate. This is exacerbated for continuous penetration of spudcan foundations due to the gradually rising stress levels (SNAME 2008, InSafeJIP 2010). Discrepancies between the predicted and measured behaviour can be significant, especially in cases involving loose sand or high stresses. This results mainly because of the critical characteristics of calcareous sediments such as crushable particles, high in-situ void ratios and compressibility. With increasing stress level, grain particles are crushed, which alters the stress-strain behaviour.

Many studies have been undertaken in the last decades to improve understanding of the stress-strain behaviour of carbonate sediments (Datta et al. 1980, Evans 1987, Golightly and Hyde 1988, Semple 1988, Coop 1990, Al-Dhouri and Poulos 1992, Randolph et al. 1999, Desrosiers and Silva 2002). Bioclastic carbonate sediments comprising skeletal and shell fragments usually have very angular grains, and hence high friction angles and low particle crushing strength parameter, Q (see Table 1). The use of friction angle as the sole strength indicator for sand often results in excessive overestimation of bearing capacity and underestimation of penetration depth (Overy 2012). Dutt et al. (1985) reported a much lower apparent friction angle (19°), through back analysis of the measured spudcan penetration response, compared to the value obtained from a direct shear test (ϕ_{crit} = 50°). Semple (1988) recorded relatively large settlements of offshore jack-up footings in carbonate sediments, which was attributed to the high compressibility of the soil. Current offshore design guidelines SNAME (2008) and InSafeJIP (2010) recommend using a reduced design friction angle (by as much as 25°) and a mobilisation (reduction) factor of ~0.25, respectively, for assessing spudcan penetration resistance in carbonate sands.

In stratified sediments, with interbedded sand layers, the problem is even more complex. The likelihood and severity of a 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 ϕ_{crit} derived from triaxial compression tests (after Randolph et al. 2004, InSafeJIP 2010).

Sand	Mineralogy	Q	ϕ_{crit}	Reference
Ticino	Siliceous	10.8	33.5	Jamiolkowski et al. (2003)
Toyoura	Quartz	9.8	32	
Hokksund	Siliceous	9.2	34	
Mol	Quartz	10	31.6	Yoon (1991)
Kenya	Calcareous	8.5	40.2	Jamiolkowski et al. (2003)
Quiou	Calcareous	7.5	41.7	

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 achieved median grain size and coefficient of uniformity were d_{50} = 0.22 mm and C_u = 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 σ_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 σ_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, σ_v < 400 kPa or mean stress p' < 240 kPa, compared to silica sand.

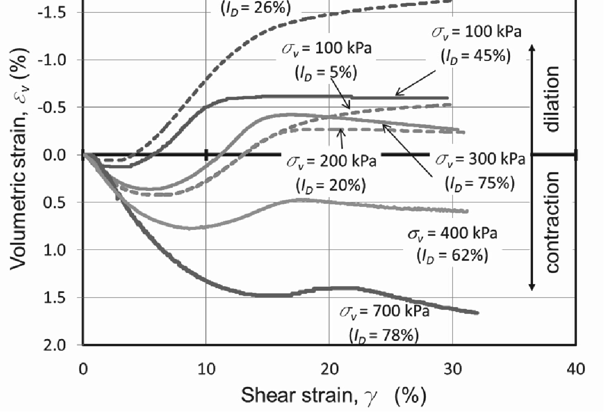

Figure 1. Volumetric change of carbonate sand in drained simple shear test with lateral stress ratio K = 0.4.

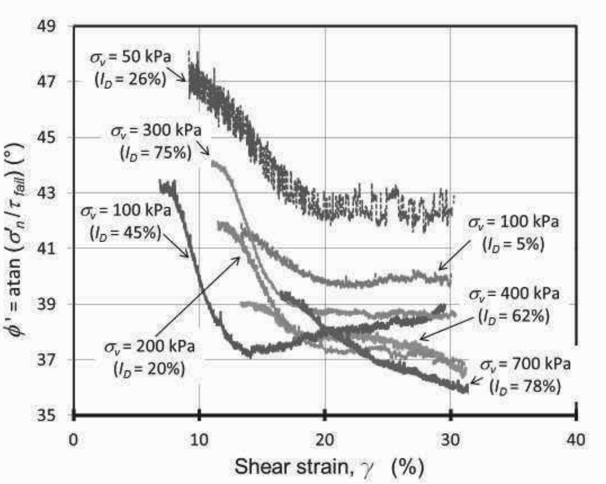

Figure 2. Effective friction angle of carbonate sand in drained simple shear test with lateral stress ratio K = 0.4 (post-peak condition only).

Peak dilation angle ψ_{peak} can be estimated using Bolton's (1986) empirical correlation

$$\phi'_{peak} - \phi_{crit} = 0.8\psi_{peak} = mI_R \tag{1}$$

$$I_R = I_D\left(Q - \ln p'\right) - 1 \tag{2}$$

where m is a constant, taken as 3 for failure under triaxial or general loading conditions and 5 under plane-strain conditions, and I_R is the relative dilatancy. Some reported values for Q for siliceous grains range from 9.2 to 10.8, while lower values of 7.5 to 8.5 are reported for calcareous grains (see Table 1). Assuming that the dilation angle of the NWS carbonate sand turned to zero at a mean stress p' = 240 kPa, a value for Q can be calculated as 5.5.

The friction angle was interpreted using the AG method (Joer et al. 2011) by considering the actual observed shear plane. The normal and shear stresses were calculated for the diagonal shear plane and used to determine the friction angle. This method gave more realistic values compared to the traditional interpretation, which assumes a complementary shear stress on the vertical sample boundary. The calculated peak friction angle ϕ'_{peak} ranges from 39.5° to 48°, while the residual friction angles ϕ'_{res} from 35.8° to 42.9° (see Figure 2). No uniform steady state can be identified, rather a tendency of decreasing ϕ'_{res} with increasing confining stress is evident.

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 ϕ'_f, calculating according to $\phi'_f = \phi'_{peak} - \psi$, as shown in Figure 3. The dilation angles of the tested carbonate sands were found lower than those of the silica sand. The critical confining 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 from South Australia and silica sand from the United Kingdom. At steady state shearing, the carbonate sand was already in contraction under 500 kPa confining stress, while the silica sand was still in dilation under 1000 kPa. The early transition to contractive behaviour attributes the fact of particle degradation of carbonate sand. The low grain hardness caused the grain to start crushing at relatively low stresses and hindered the development of potential maximum dilation. This behaviour agrees well with that observed on the NWS carbonate sand.

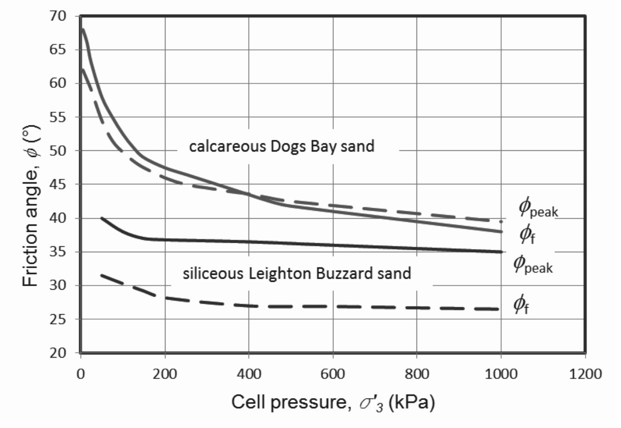

Figure 3. Comparison of dilative behaviour between calcareous and siliceous sand under various cell pressures (Golightly and Hyde 1988).

4 PRACTICAL APPLICATION: SPUDCAN RESPONSE

In order to examine the influence of this disparate characteristic of carbonate and silica sands on practical applications, model tests were carried out on spudcan foundations penetrating through four-layer soils, with a carbonate or silica sand layer interbedded in soft clay. The experimental program was carried out at 200 g in a drum centrifuge. The soil was confined within a purpose designed strongbox to facilitate producing multi-layer specimens, with the box mounted within the drum channel (Hossain and Randolph 2012).

Spudcan penetration tests were performed using a half-spudcan (HS) and a full-spudcan (FS) model of 60 mm (12 m prototype) diameter. The models were made from duraluminium and included a 13° shallow conical underside profile (included angle of 154°) and a 76° protruding spigot. The half-spudcan was designed to penetrate adjacent to the strongbox window, permitting the soil deformation to be captured by a camera. Separate full-spudcan penetration tests were performed away from the edges of the box to measure the load-penetration response, avoiding frictional resistance from the window.

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 off the centrifuge. Two samples of uniform strength 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).

Test	Layer 1		Layer 2		Layer 3		Layer 4	
	t_1/D	Soil	t_2/D	Soil	t_3/D	Soil	t_4/D	Soil
FS1	0.25	Soft clay	0.5	Carbonate sand	0.96	Soft clay	0.33	Stiff clay
HS1								
FS2				Silica sand				
HS2								

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.

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, I_D, 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 (ϕ_{crit} = 34° compared to 40°). This is due to the behaviour of carbonate sand, as discussed previously and also described below.

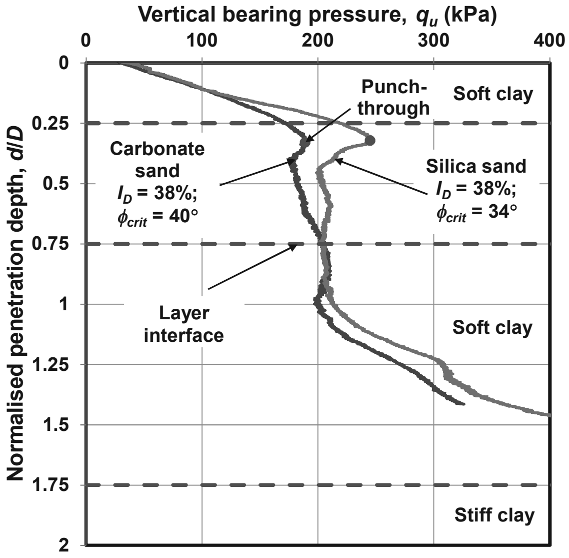

Figure 4. Effect of interbedded sand mineralogy on load penetration response: severity of punch-through (Tests FS1 and FS2, Table 2).

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_{spud}. The ratio v/v_{spud} 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.

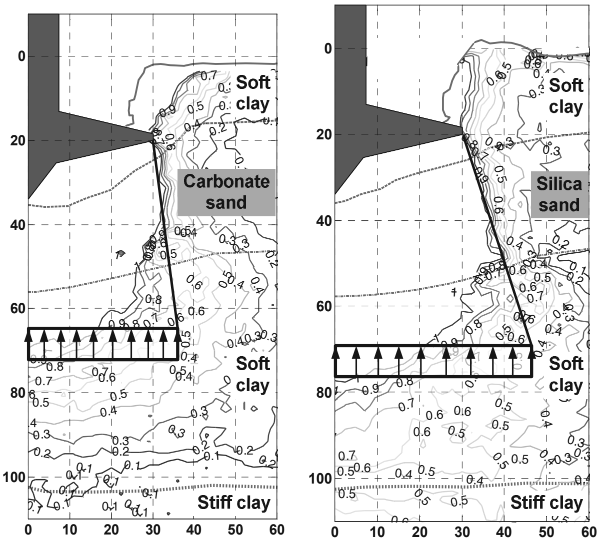

Figure 5. Effect of interbedded sand mineralogy on dilation and load spread angle (Tests HS1 and HS2, Table 2).

5 CONCLUDING REMARKS

This paper reported results from a series of simple shear tests for characterising 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.

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