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Stiffness Response of Calcareous Soil to a Cementation Event Using Calcite

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Summary: This paper presents results from an experiment designed to simulate the process of natural cementation, where calcite cement was forced to form and precipitate amongst the grains of a freshly deposited calcareous sand. The aim of the experiment was to study the influence of the cementation process on the shear wave velocity (V_s) as it evolves with cementation. Afterwards, V_s was measured at various stress levels to examine the influence of effective stress on the stiffness of the cemented soil. The device used was comprised of a specially designed series of bender elements that enabled measurement of V_s in both vertical and horizontal planes at various depths below the sample surface. The results showed that the cementation removed the initial stiffness anisotropy induced by the normal compression. Post-cementation stiffness showed negligible increase with increasing stress level, with more reduction upon complete unloading. The stiffness deteriorated post yield, though remained higher than the values obtained for the uncemented case.

INTRODUCTION

Calcareous sediments encountered offshore are frequently cemented by calcite, which precipitates out of the supersaturated seawater amongst soil grains, either simultaneously with the soil deposition or at a later stage after initial consolidation. Occasionally, calcite results from biological activity.

The influence of the cement is that it binds together the individual grains of the hosting soil; the cement may also precipitate inside the intra voids of the individual grains, thereby increasing the density. Both processes increase the maximum stiffness of the deposit, which can be determined indirectly by measuring the velocity of elastic shear waves propagating through the deposit.

Many studies have focused on the influence of cement on the behaviour of soils. The main focus of theses studies has been on the influence of cementation on increasing monotonic and cyclic strength (Clough et al., 1981; Clough et al., 1989). With advances in techniques for measurement of dynamic stiffness (such as bender elements and the resonant column device), many studies were carried out on V_s (and hence G_o) of cemented soils and soft rocks, and these provided valuable data in this area. Analysing these studies, however, show the following.

1) Most of the work in this area was undertaken on artificial cements, which may be mechanically and microscopically different to those existing in reality (e.g., Portland cement, gypsum and casting resin versus calcite, aragonite and iron oxide). The work undertaken by Ismail *et al.* (2002a) showed that the type of cement has a significant influence on the shearing behaviour of cemented calcareous soils. This could also be the case with G_o. Therefore, it is imperative in laboratory modelling of offshore, cemented calcareous soils to use calcite or aragonite for artificial cementation.
2) The natural cementation process has not always been mimicked closely in the laboratory (e.g., mixing the cement with soils versus precipitation of natural cements).
3) The emphasis has been on the overall increase in stiffness and its variation with stress history (Acar and El-Tahir, 1986; Baig et al., 1997; Fernandez and Santamarina, 2001), with no attention given to the influence of the cementation process on stiffness anisotropy.

The goal of this paper is to simulate the natural process of calcite cementation in offshore calcareous deposits in the laboratory: the influence of the cementation process on the small-strain shear stiffness, G_o, as it evolves during hardening of the cement, was investigated. To this end, a special device was designed and manufactured, whereby V_s can be measured in both vertical and horizontal planes at various positions. The paper discusses the change in V_s after cementation due to change in the stress level, including post–yield conditions.

MATERIALS TESTED

The calcareous sand used in this study was brought from the coastline of the Indian Ocean near Ledge Point (LP), 100 km North of Perth, Western Australia. This is a coast where beaches consist of eolian skeletal

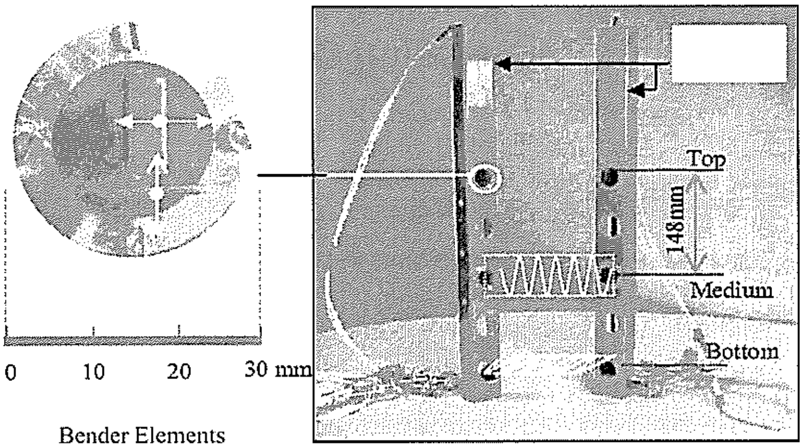

Figure 1. Setup of Bender Elements Showing Bender Rails and Sockets.

fragments, oolites and other carbonate grains (Fookes, 1988). The percentage of carbonate content of the Ledge Point sand (LP) was found to be 91%. Sieve analysis showed that LP sand is a uniform, fine to medium sand, with d_{50} of 0.20 mm. The minimum and maximum *dry* densities were 1160 and 1380 kg/m^3, respectively.

An aqueous chemical solution called CIPS [Calcite In situ Precipitation System: (Kucharski et al., 1996)] was used to precipitate calcite on the grain surfaces and at points of contact. Details of the process are described by Ismail *et al.* (2002b).

TESTING EQUIPMENT

Shear wave measuring system

A new system consisting of six pairs of orthogonal piezoelectric bimorphs (bender elements) was designed and manufactured at the University of Western Australia (Ismail and Hourani, 2003). Each pair of bender elements was encapsulated in a cylindrical socket fitted into a stainless steel rail, one for the transmitters and one for the receivers (Figure 1). The overall height of each bender element rail was 400 mm, and the section dimensions were 35 mm length by 35 mm width. The bimorph was made from lead zirconate titanate (LZT) ceramic, with free cantilever length of 10 mm and width of 10 mm. To maximize the mechanical output from the transmitters, they were connected in parallel. Conversely, the receivers were connected in series to augment the received amplitude. As shown by Ismail and Hourani (2003) this system was calibrated against paraffin wax and proven to give excellent results. The overall advantages of the shear wave measuring system can be summarized as follows:

1) the system is mobile; hence it can fit a wide range of 1-g models;
2) the shear wave velocity can be measured at predetermined levels (three levels were selected here);
3) the system can measure the shear wave velocity in any two orthogonal planes. Moreover, the shear wave velocity can be measured along a skew plane. This measurement can help establish the elastic stiffness matrix in the case of cross-anisotropic materials.

The arrival time was taken as the period between the points of initial rise on the transmitter and receiver traces, with the latter matching the same direction of polarisation when the two tips of the bender elements were placed on top of each other (during measuring the time lag of the system).

Sample container and loading device

A tub was made out of a galvanised mild steel, 400 mm diameter and 400 mm height: the wall thickness was 6 mm. This thickness was so chosen to ensure negligible radial strains when the soil was compressed vertically, i.e., a true K_0 condition.

The aluminium circular base of the tub was provided with 5 holes to allow the CIPS solution to be flushed from bottom to top: radial grooves were also provided to allow uniform distribution of the solution throughout the sample. The top loading piston was 40 mm thick and was made of PVC. To accommodate the two rails of the bender elements, two rectangular slots were made into the piston, so that the rails can protrude. The distance between the rails was selected to be 244 mm. For a free length of 10 mm of the bender elements, this arrangement provided an effective travel length of about 224 mm (tip-to-tip) for the shear wave generated at the transmitters. Drainage holes were provided in the top piston.

Two loading devices were used for this study. The first was a large, pneumatic consolidation press, capable of applying pressure up to 650 kPa. This consolidation press was used to consolidate the uncemented sand and

σ'_v (kPa)	Loading										Unloading					
	0	11	69	138	207	276	383	440	548	735	529	386	276	207	69	0

Stress	Loading					Unloading						
	207	227	257	283	310	283	225	207	144	89	61	0.0

kPa, before complete unloading. The stress intervals at which V_s were measured are reported in Table 2. The aim

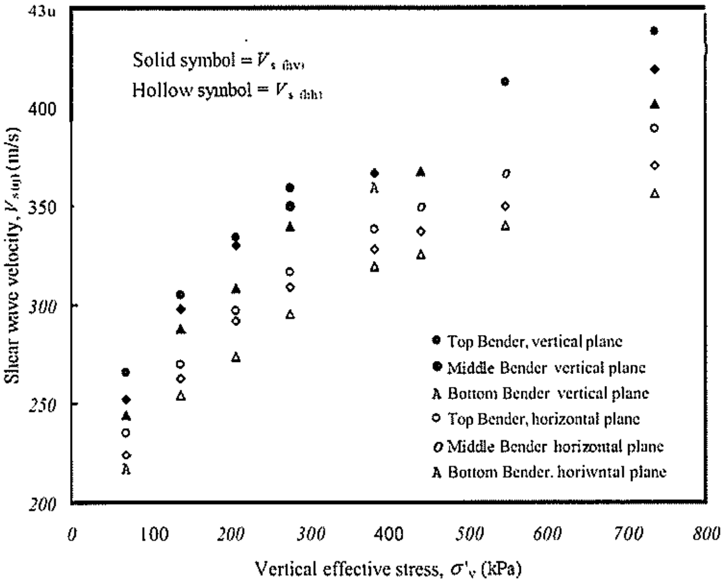

Figure 2. Variation of V_s with Stress Level for Bender Elements at Various Levels in Uncemented LP Sand.

of this phase was to investigate how V_s of the cemented sample responds to vertical stresses that are lower than the value that would cause breakage of cementation in compression.

The aim of the last phase was to load the sample until the cementation breaks and investigate the response of V_s to the disintegration of the bond. This event is likely to occur in natural deposits where cementation may coincide with the early formation of the deposit, before being topped with more sediment in a later stage. The cemented sample was transferred to the Instron machine, and the vertical stress was increased gradually until the cementation was broken as evidenced from the compression curve that will be shown later: afterwards, the sample was unloaded. Again, V_s was measured at various stress levels along the loading path. Table 3 summarizes the events of the five phases along with the stress levels associated with them.

SMALL-STRAIN BEHAVIOR OF UNCEMENTED LP SAND

In the following, the terminology used in Figure 1 will be used. The first subscript in the expression of the shear wave velocity refers to the direction of wave propagation (always horizontal in this study) and the second subscript refers to the direction of particle motion (i.e, horizontal or vertical). Therefore, $V_{s\,(hh)}$ refers to a wave propagating horizontally with soil particles oscillating in the orthogonal horizontal direction. On the other hand, $V_{s\,(hv)}$ refers to a wave propagating horizontally with soil particles oscillating in the orthogonal vertical direction.

Figure 2 summarizes the results obtained for uncemented LP sand with increasing stress from all benders at the three tested levels, in terms of the measured $V_{s\,(ij)}$ versus the applied vertical stress. The solid and hollow symbols in Figure 2 refer to $V_{s\,(vh)}$ and $V_{s\,(hh)}$, respectively.

A generally accepted empirical formula for the relationship between shear wave velocity and effective stresses of uncemented sand was reported by Hardin and Blandford (1989) as follows.

$$V_{s(ij)} = \left[\frac{OCR^{k}\ S_{ij} P_a^{\,1-n}}{F(e)\ 2(1+\nu)} (\sigma'_j \sigma'_i)^{\frac{n}{2}}\right]^{0.5} \tag{1}$$

where *OCR* is the over consolidation ratio, *k* is a soil constant depending on the plasticity index of the soil, S_{ij} is a dimensionless elastic stiffness coefficient, ν is Poissons ratio, *F(e)* is the void ratio function = 0.3 + 0.7 e^2, P_a is the atmospheric pressure, and n is a soil constant (usually taken as 0.5 for sands).

For a normally consolidated sand, Equation (1) may be rewritten as,

$$V_{s(hv)} = A\ (K_o)^{n/4} (\sigma'_v)^{\frac{n}{2}} \tag{2}$$

$$V_{s(hh)} = A\ (K_o)^{n/2} (\sigma'_v)^{\frac{n}{2}} \tag{3}$$

where A is a constant = $\left[\frac{OCR^{k}\ S_{ij} P_a^{\,1-n}}{F(e)\ 2(1+\nu)}\right]^{0.5}$ and K_0 is the coefficient of earth pressure at rest = σ'_h/σ'_v.

Table 3: Testing Phases and Associated Stress Levels.

From (kPa)	To (kPa)	Event
0.0	735	Loading uncemented sample
735	207	Complete unloading/reloading of uncemented sample
Apply cementation using CIPS solution at 207 kPa		
207	310	Loading cemented sample
310	0.0	Unloading cemented sample
0	2313	Reloading cemented sample

Table 4. Coefficients Fitting Equations 2 and 3 to Data in Figure 2.

Cluster	Velocity	n	r^{2*}	A	
Top Bender	$V_{s(vh)}$	0.428	0.99	107.1	
	$V_{s(hh)}$	0.428	0.99		94.8
Middle Bender	$V_{s(vh)}$	0.424	0.99	104.8	
	$V_{s(hh)}$	0.424	0.99		92.9
Bottom Bender	$V_{s(vh)}$	0.428	0.99	99.4	
	$V_{s(hh)}$	0.426	0.99		88.5

The results of Figure 2 and Table 4 show that the relationship between Vs, in both vertical and horizontal planes, and the applied vertical stress σ'_v could be reduced to Equations (2) and (3) respectively, with a coefficient of determination $r^2 = 0.99$. Three observations are worth commenting from Figure 2.

First, the average value of the power n for the *dry* Ledge Point sand is about 0.426, which lies within the lower range reported for non-carbonate sands (Fioravante et al., 1998). Second, for all benders at the three tested levels (i.e., bottom, medium and top bender clusters), $V_{s\,(hv)}$ is higher than V, $_{(hh)}$. as would be expected for a normally consolidated sand (this is readily inferred from Equations 2 and 3). Third, the values of both $V_{s\,(hv)}$ and $V_{s\,(hh)}$ reduce from top to bottom, reflecting an average reduction of the shear velocity of about 7%. This reduction is attributed to the reduction in vertical stress resulting from the friction at the interface between the sand and the wall of the tub.

SMALL-STRAIN BEHAVIOUR OF CALCITE-CEMENTED LP SAND

Evolution of stiffness during calcite curing

As mentioned earlier, the CIPS solution was applied to the LP sand at $\sigma'_v = 207$ kPa, and the cement was left to cure under this stress. Figure 3 shows the evolution of $V_{s\,(hv)}$ and $V_{s\,(hh)}$ from the top cluster over time during curing. The figure also shows V_s for the uncemented case (after saturation with water). It seems clear that, after the first 15 minutes, the stiffness started to increase with approximately a constant rate over the first 8 hours. Afterwards the stiffness remained essentially constant. Comparing the final V_s with that of the uncemented case suggests that the cementation process increased V_s by about 227%. It is worth noting here that the increase in density due to precipitation of the calcite in the LP sand was as small as 3.5% (Ismail *et al.*. 2002a). Therefore, it is the bond created by the cement that produced the increase in stiffness. Another important influence of the cementation process is that the stiffness anisotropy induced by the normal compression disappeared, with $V_{s\,(hv)}$ and $V_{s\,(hh)}$ converging after curing. This observation is extremely important in ground improvement techniques and merits further research.

Influence of vertical stress on stiffness

There is no consensus in the literature as to the influence of effective stress on the stiffness of cemented sands. For example, Acar and El-Tahir (1986) reported increase of stiffness of artificial cemented sand with confining stress according to a power law of exponent 0.43. Other authors reported exponents ranging from 0.58 to 0.01 (Saxena *et al.*, 1988) and values ranging from 0.7 to 0.15 (Chang and Wood, 1992). On the other hand, Baig *et al.* (1997) pointed out that the experiments in the references cited above were conducted using torsional resonant column devices and some questions were raised regarding the coupling between the specimen and the system end platens. They concluded that confining stress has a negligible effect on G_0 of cemented sands.

The influence of confining stress on stiffness was investigated in Phase 4 and the results are summarized in Figure 4 for $V_{s\,(hh)}$ at the middle cluster. Point "a" in that figure (solid square) refers to the state at which the cementation occurred. It is clear that during the loading path "ab", $V_{s\,(hh)}$ is essentially constant, reflecting a negligible increase of stiffness over this range of stress (see the 3% error bars on Figure 4). Although this finding is in agreement with other studies (e.g., Baig et al., 1997; Fernandez and Santamarina, 2001), it is believed that the influence of stress will be a function of the type of cement, the nature of the bond as well as the magnitude of the applied stress compared with that at which yielding occurs.

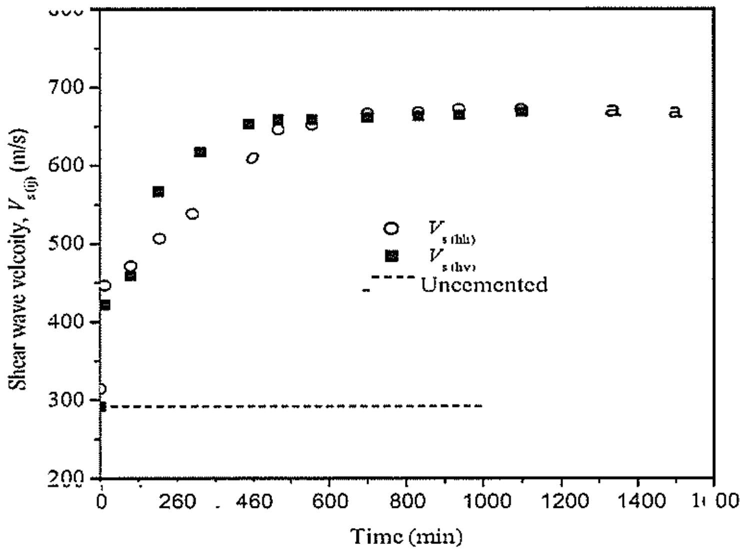

Figure 3. Variation of V_s with Time During Curing of Calcite.

The trend during the unloading path "bc" shows that the stiffness only reduced when the vertical stress reduced to 89 kPa, with more significant reduction in stiffness upon complete unloading. Fernandez and Santamarina (2001) attributed such reduction to the limiting tensile strength of the bond created by the cement, which may fail the bond upon unloading, if such strength is exceeded.

Behaviour at high stress level

The results of reloading (from point c of Figure 4) to d, = 2.3 MPa are shown in Figure 5 for both $V_{s\,(hh)}$ and $V_{s\,(hv)}$ at the middle cluster: also superimposed on the figure is the 1-d compression curve. The stress level was so selected to ensure yielding of the sample during compression. It is apparent that, upon reloading, the stiffness increased due to closure of the cracks that developed during the first unloading (from point "b" of Figure 4). At yield, a reduction in both $V_{s\,(hh)}$ and $V_{s\,(hv)}$ occurred, though more noticeable for $V_{s\,(hv)}$. The reduction of the latter is about 11% from the yield point (d, = 1.1 MPa) to σ'_v = 2.3 MPa. It is interesting to note that, even after yielding, the shear wave velocity of the cemented sample did not reduce to that measured for its uncemented counterpart. It appears that breakage of the cementation is progressive and cemented lumps remained within the soil matrix leading to stiffness higher than the uncemented sand. At very high stress level, however, convergence between the two might occur.

CONCLUSIONS

This paper presented results of a cementation process simulating a possible natural event when calcite precipitates amongst grains of an offshore deposit after initial consolidation. Shear wave velocity for both the uncemented and cemented cases were measured using a technique that enabled the stiffness anisotropy to be evaluated.

The study has shown that calcareous sands are similar to their siliceous counterparts in relation to increase in stiffness with effective stresses in accordance with a power law of an exponent 0.426.

The cementation process eliminated the initial stiffness anisotropy resulting from the normal compression of the uncemented material. This finding is extremely important in deformation calculation of structures founded on naturally cemented soils or artificially stabilized ones. Further investigation is required, however, to examine the role of the type of cement and method of preparation on the stiffness anisotropy.

First loading of the cemented sample showed a negligible increase in stiffness with increasing stress. Upon unloading, a noticeable reduction in stiffness was observed due to partial breakage of the cement in tension, and this was mostly recovered during reloading. At stress magnitudes higher than the yield stress, the cemented sample experienced reduction in stiffness, though the stiffness remained much higher than that measured for the uncemented case.

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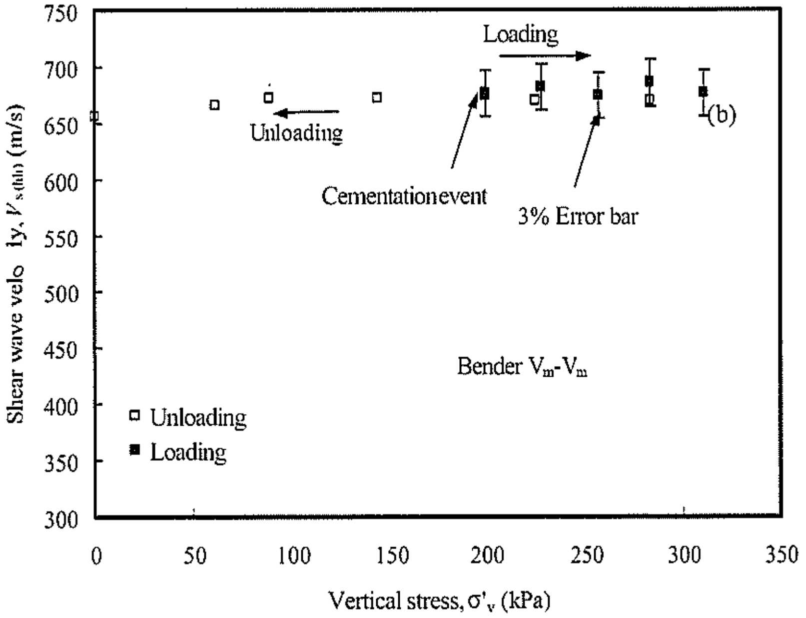

Figure 4. Influence of Loading and Unloading on Stiffness of Cemented LP Sand.

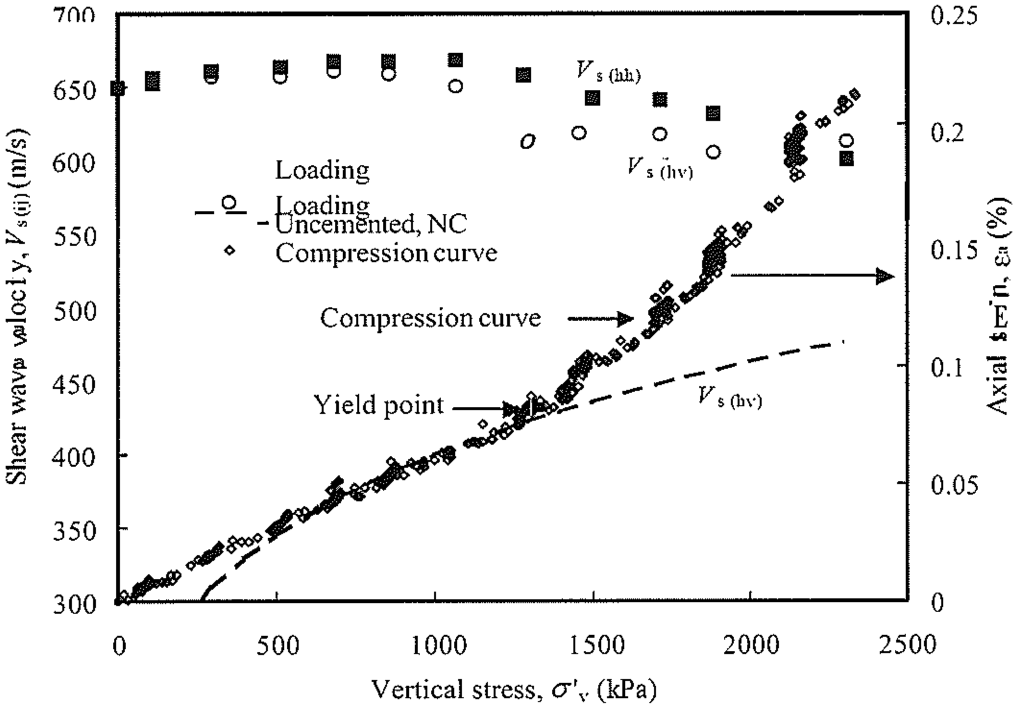

Figure 5. Shear Wave Velocity and Compression Curve During Preloading to Yield

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