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Cyclic Response of Artificially Cemented Soils

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Abstract. This research work studies the cyclic response of artificially cemented sand samples. The material consists of fine silica sand, commercially known as Redhill 110; the cementation is induced by mixing the material with fast setting Portland cement and then applying the confining pressure. The bond formation is inferred from measurements of shear wave velocity using bender elements. It is observed that the small-strain stiffness, calculated by measuring the shear wave velocity, increases significantly in the first 20 hours from 130 MPa to 280 MPa. The sample is subsequently subjected to cyclic loading applied at a constant cyclic stress ratio (0.2). The results show an asymmetrical stress-strain curve that gradually moves towards large compressive strain. It is also noted that higher stiffness of the sample attributed to grain bonds is lost after the application of the first cycle of loading. The macroscopic behaviour observed in the cyclic triaxial test is finally discussed based on the microscopic features of the sample obtained from in X-Ray Computed Tomography Scanning with obtained images with voxel size of 4.998 μm.

Keywords. Cemented, sand, X-Ray CT scan, cyclic, bender element, small strain stiffness.

1. Introduction

1.1. Artificially cemented sands

In this study cemented samples were prepared by mixing Redhill 110 sand with fast setting Portland cement; these represented typical soil conditions of a cemented sand. The paper investigates the cyclic behaviour of these artificially cemented soils using a cyclic triaxial apparatus and bender elements for accurate measurement of shear stiffness. Results show that cemented samples tends to become stiffer as cyclic loads progress. Finally, practical implications for geotechnical centrifuge model design are highlighted. Artificially cemented soil samples have been used as an alternative to study the effect of cementation in the mechanical response of soil, given that during sampling process of undisturbed samples, natural cemented soils can be subjected to partial and even complete decementation, which makes complicated to properly assess the effect of natural cementation in the low and large strain behaviour of the soil. Cementation of soils is a process that begins with the soil deposition and continues over time, even when the

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soil has become a sedimentary rock. These changes in fabric generate a different response to mechanical loads when compared to uncemented specimens.

When more advanced testing of soils is necessary (e.g geotechnical centrifuge testing) it is fundamental to understand the mechanical response of the soil models, so a more accurate interpretation can be made out of the data collected during the tests. The aim of this research is to assess the response of artificially cemented sand to cyclic loads, as part of a more extensive testing programmed to characterize the mechanical behaviour of cemented sand used in geotechnical centrifuge models.

1.2. Background on artificially cemented soils

The amount of cement, confining stress, density, gradation and structure are governing variables in the behaviour of cemented soils [1]. It has also been found that even a small amount of cement increases significantly the cyclic strength of uncemented sands and that the stress-strain curves are often asymmetrical about the zero strain axis [2]. Similar findings were have been found where the strength of cemented sands was found higher for both static and cyclic loads [3]. One aspect, often disregarded, is the effect of changes in confining pressure in the small-strain stiffness of artificially cemented sands and the implications in the cyclic response. The degradation generated on the small-strain stiffness of artificially cemented samples cured under confining pressure, when subjected to changes of the initial curing stress has been studied previously [4] and other researchers have found that there is a relation between the peak strengths of an artificially cemented soil and the relationship void volume and cement volume [5].

2. Materials and Experimental Methods

2.1. Materials

A mixture of sand and fast setting Portland cement was selected to create artificially cemented sand. The sand sample corresponds to a commercially distributed Redhill 110 sand with the following index properties: G_s=2.65, e_{max}=1.035, e_{min}=0.608, D_{50}=0.14 mm and angular shape. The values of e_{min} and e_{max} were determined according to the Standards of Japanese Geotechnical Society for laboratory test as shown in previous work [6]. The cementing agent was fast setting Portland cement with a G_s=3.15.

2.2. Sample preparation

The specimen (50 mm diameter x 100 mm height) was prepared by initially mixing the relevant quantities of sand and cement in dry condition and then mixing them manually with water for 10 minutes. Next, the cement-sand mixture was statically compacted into the 50 mm split mould using in 3 layers so that each layer reached the target void ratio of 0.66. The top of each layer was slightly scarified before placing the following layer. Moisture content was fixed at 19% with cement content of 5%. A sample with no cement addition and same void ration was tested as well under the same conditions. The water content was fixed considering the cement content, so saturation was not achieved at any staged of the test. Mixing and compacting was achieved within 30 minutes of initial curing time, which is less that the setting time of the fast setting Portland cement (3 hours). Once compacted into the mould, the samples were let to cure for 72 hours under a constant confining pressure of 200 kPa. Samples of 75 mm diameter and 150 mm height were prepared using the same procedure and shear wave velocity measurements were used to monitor the changes in small-strain stiffness G_o as cementation took place and then monitor G degradation under monotonic shearing.

2.3. Experimental method

The samples were tested under an undrained test condition in a Bishop Type triaxial cell manufactured by GDS Instruments and equipped with an internal load cell. A one-way cyclic loading test with a cyclic stress ratio (CSR) of 0.2 was applied to the cemented and uncemented sample subjected to the curing confining pressure of 200 kPa. The test was conducted under a stress controlled configuration. A period of 30 minutes was chosen to avoid significant variation in the confining pressure during the test due to the displacement of the lower chamber. A monotonic test was also performed on a 75mm diameter and 150mm height sample with a computer strain controlled triaxial cell manufactured by GDS where bender element allowed monitoring the degradation of stiffness during shearing. Undrained monotonic shearing was performed at a strain rate of 0.013%/min. Shear wave velocities were measured using a source wave with a frequency of 12.5 kHz. Arrival time was selected using cross-correlation. Due to the cementation process taking place under constant confining pressure, the sample was not subject to a saturation nor consolidation stage.

3. Results

3.1. Evolution of small strain stiffness

The evolution of the small strain stiffness G_o is presented in Figure 1a. The shear wave velocity was measured using bender elements. The time difference between the transmission and reception represents the travel time through the sample from which the shear wave velocity can be calculated and hence the elastic shear modulus of the soils as described by Eq. (1) below:

$$G_o = \rho {V_s}^2 = \rho \left(\frac{L^2}{t^2}\right) \tag{1}$$

where ρ= total mass density of the soil; L= tip to tip length between bender elements; V_S= shear wave velocity; and t= travel time of the shear wave. Shear waves were propagated vertically and cross-correlation was used to interpret and estimate the arrival time of the response wave. It is worth noting that the weight and total volume of the soil sample, and hence ρ, are not changing during the cementation process, meaning the shear wave velocity increase is not due to an increase in bulk density and can be used to assess the increase in small-strain stiffness due to cementation. A G_o of 139 MPa corresponds to an uncemented sand under a confining pressure of 200 kPa, whereas G_o of 285 MPa was achieved by a cemented sand with 5% cement content cured under a confining pressure of 200 kPa. There is a significant increase in G_o during the first 10 hours of curing time and after 20 hours of curing time there is no significant increase in stiffness. Shear wave velocity was measured every hour for 72 hours prior to shearing of the sample under undrained conditions. All cyclic test were conducted after 72 hours when no further increase in shear wave velocity is observed.

Figure 1b shows the degradation of stiffness under monotonic load in a strain-controlled test. The elastic shear modulus of the soil (G) at a given axial strain (ε) was calculated and compared to the elastic shear modulus at small strain (G_o) . After axial strain of 1%, the ratio G/G_o decreases at a higher rate compared to the degradation at 0.1% axial strain. The elastic shear modulus of the soil (G) was measure until a 15% axial strain where the ratio G/G_o reaches a value of less than 0.5.

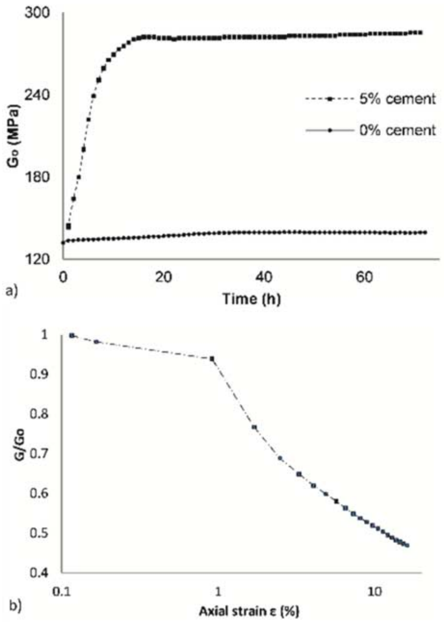

Figure 1. a) Evolution of stiffness during curing. b) Degradation of stiffness under monotonic load in a 5% cement content sample.

3.2. Cyclic triaxial test

The undrained stress-strain responses of a sand sample with 5% cement content and a sample without cement addition under a stress controlled one-way cyclic loading test are shown in Figure 2a. After 20 cycles the increase in accumulated deformation was not significant for the cemented sample, being the maximum axial strain less than half than the uncemented sample (0.12% for a cemented sample and 0.26% for an uncemented sample) which indicated that the addition of cement reduces the accumulated strain. It is clear that the first cycle shows a different response than the consequent cycles. Most of the strain occurred during the first load-unload cycle and the graph shows an asymmetry increase in strain in both samples. The cemented sample shows a stiffer response in the first and subsequent cycles compared to the sample without cement addition. Figure 2b shows the strain variation due to the cyclic load against number of cycles where a greater increase in strain is reached within the first cycles. This effect can be seen in Figure 3, where the accumulated cyclic strain ($\Delta\varepsilon/\varepsilon$) versus normalised number of cycles (N/N_{max}) is plotted to visualize the strain accumulation on each cycle.

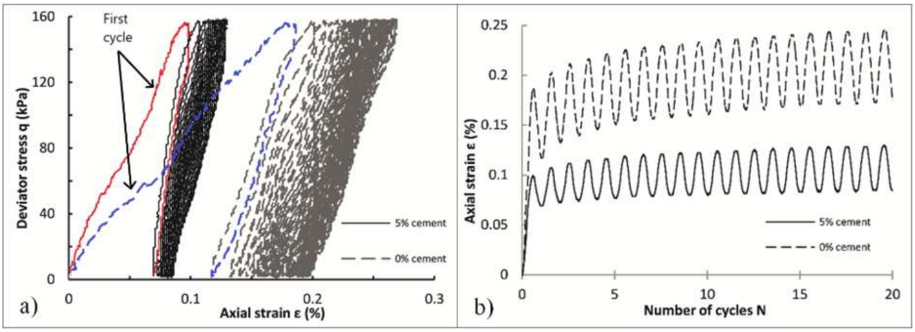

Figure 2. a) Stress-strain response of artificially cemented and uncemented sand. b) Strain accumulation after 20 cycles for a cemented and uncemented sample.

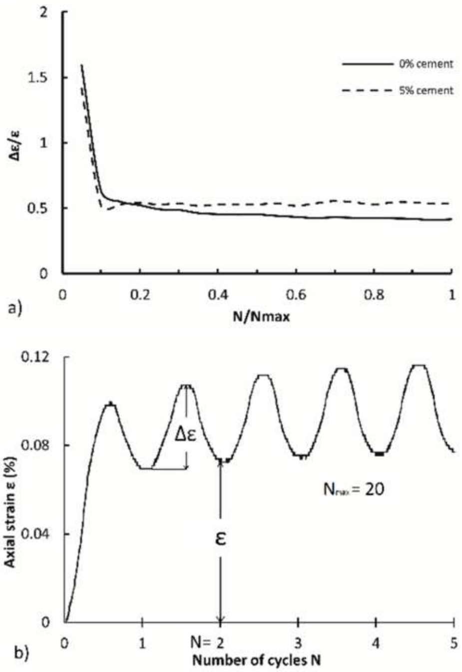

Figure 3. a) Accumulated cyclic strain versus normalized number of cycles. b) Schematic showing the parameters Δε, ε, N and N_{max}.

3.3. X-Ray Computed Tomography

The microstructure of a cemented sample was studied using a Nikon Metrology 225/320 kV computed tomography system in the Manchester Henry Moseley X-Ray Imaging Facility of The University of Manchester. The sample scanned had a diameter of 12.24mm and height of 20.32mm. The image resolution was 3192 x 3192 pixels and the voxel size of the images obtained was 4.998 μm. A cubic subvolume of 15.625 mm^3 (2.5 mm x 2.5 mm x 2.5 mm) was obtained from the centre of the sample to analyse and segment the phases present in the sample. Figure 4 shows a 3D reconstruction of the subvolume where 3 main phases can be identified as Red Hill 110 sand, cement bonds and voids. Light grey represents the grains of Red Hill 110, dark grey represents the voids within the sample and the white areas clustered between contact points of sand grains represent the cement bonds.

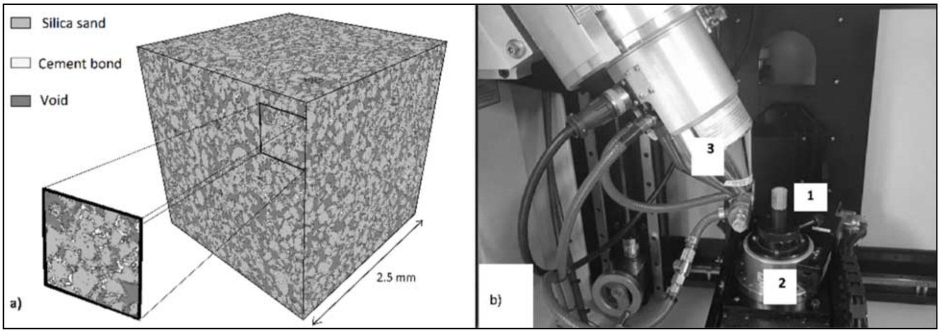

Figure 4. a) volume reconstruction of cemented sample. Each side corresponds to a section of 2.5 mm x 2.5 mm. b) Inside of the Nikon Metrology 225/320 kV showing the cemented sample (1), the rotary stage (2) and the X-Ray source (3).

4. Discussion

The response of artificially cemented sand with 5% of fast setting Portland cement was presented in Figure 2. It is worth nothing the asymmetry of the stress-strain curve, which indicates a stiffening of the soils as cyclic loads continues.

The behaviour of the sample after 10 cycles seems to stabilize and moreover, the slope of the stress-strain curve of every cycle increased from cycle 1 to cycle 20 for both cemented and uncemented sample. As strain increases, the stiffness of the soil is expected to degrade, as shown in Figure 1 where the degradation of G_o was monitored for strains up to 15%. However, the artificially cemented sand seems to become stiffer as the cyclic loading continues. This phenomenon is known as ratcheting and explains the accumulation of strain in the direction of the load applied [7].

The effects of bond breakage can be considered to explain this behaviour in artificially cemented soils. Given the brittle behaviour of cemented sands, once the bonds are broken, the strength is provided by the sand grains, which would lead to a rearrange of particles under cyclic load.

Changes in isotropic confinement can cause decementation (bond breakage) and degradation of small strain stiffness in artificially cemented sands [8] [4].

The analysis of the microstructure of cemented samples shows the spatial distribution of the cement bonds. This provides an advanced characterization of cemented soils to help understand the mechanical response under cyclic loads. The data shows cement bonds tend to form near the contact points between the grains which will provide an increase in strength during the compression of the sample. These cement bonds are quickly broken due to their brittle behaviour and create further plastic strains that accumulates as cyclic loading continues. Further characterisation using Digital Volume Correlation (DVC) will provide information on the microstructural changes caused by loading to the sample.

For the design of physical models for geotechnical centrifuge testing, it is fundamental to replicate a stress-constant state for the cementation to take place. This would imply having the sample to cure under the target acceleration for the centrifuge test. Increasing and decreasing the acceleration once the cementation process has occurred will cause changes in stress condition, which will affect the stiffness of the cemented model and will not accurately represent the response of a natural cemented soil, particularly when modelling lateral loaded piles in the geotechnical centrifuge, given that G_o is one of the most important mechanical parameters governing the response of the soils subjected to pile-induced lateral loads.

5. Conclusions

Undrained cyclic stress-strain behaviour of artificially cemented sand with 5% of cement content leads to the following conclusions:

- Larger strains are expected in the first cyclic loading of the artificially cemented sample and smaller strains for consecutive cycles.
- Increase in cement content decreases the strain accumulation under the same loading condition for a given relative density when compared to an uncemented sample.
- Artificially cemented sand tends to become stiffer as cyclic load continues (Ratcheting).
- Stiffening of the samples can be attributed to the changes in structure cause by the degradation of the cementing bonds.
- From the microstructural analysis, it can be seen that cement bonds are mainly formed in contact points between the silica grains. Small samples (10 – 15 mm) are necessary to obtain high resolution 3D images during an X-Ray CT scanning.
- Particular care has to be put during the docking of cemented samples to apply two-way cyclic loading, since changes in isotropic confinement have been reported to cause cementation degradation. One-way cyclic loading is advised as preferred cyclic loading test, as it would minimise damaging of the sample by accidental changes in confining pressure.

References

[1] Clough, G.W., N. Sitar, and R.C. Bachus, Cemented Sands under Static Loading. Journal of the Geotechnical Engineering Division, 1981. 107: p. 799-817.

[2] Saxena, S.K., K.R. Reddy, and A.S. Avramidis, Liquefaction Resistance of Artificially Cemented Sand. Journal of Geotechnical Engineering, 1988. 114: p. 1395-1413.

[3] Clough, G.W., et al., Influence of Cementation on Liquefaction of Sands. Journal of Geotechnical Engineering, 1989. 115: p. 1102-1117.

[4] Fernandez, A.L. and J.C. Santamarina, Effect of cementation on the small-strain parameters of sands. Canadian Geotechnical Journal, 2001. 38: p. 191-199.

[5] Consoli, N.C., et al., Fundamental Parameters for the Stiffness and Strength Control of Artificially Cemented Sand. Journal of Geotechnical and Geoenvironmental Engineering, 2009. 135: p. 1347-1353.

[6] [Lombardi, D., et al., Construction of simplified design p–y curves for liquefied soils. Géotechnique, 2017. 67(3): p. 216-227.

[7] Ghionna, V.N. and D. Porcino, Liquefaction Resistance of Undisturbed and Reconstituted Samples of a Natural Coarse Sand from Undrained Cyclic Triaxial Tests. 2006.

[8] Baig, S., M. Picornell, and S. Nazarian, Low Strain Shear Moduli of Cemented Sands. Journal of Geotechnical and Geoenvironmental Engineering, 1997. 123: p. 540-545.