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Model tests on biogrouted granular columns in soft soil

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Abstract

This paper examines the possible use of a bio-cementation process to reduce excessive bulging that occurs during the loading of granular columns in soft clays. A 12-phase percolation biochemical treatment technique was used to bio-cement part of the columns targeting the columns upper section, where bulging usually occurs. Upon application of unit cell surface loads up to 350 kPa, placement of bio-cemented granular column substantially reduced the vertical strains by 43% to 48% compared with un-cemented granular column and 56% to 60% compared with unreinforced kaolin clay for just a low replacement ratio of 11%. Bulging was reduced by 62% to 75% following bio-cementation and mostly occurred where bio-cementation was less evident. Scanning electron microscopy and energy dispersive spectroscopy validated the existence of calcium carbonate. This study presents a relatively new alternative to reducing bulging in granular columns using a promising approach.

Keyword: Biocementation, Biogrouting, soft clay, Microbial induced carbonate precipitation, granular column.

Introduction

Conventional grouped granular columns or stone columns are commonly used to improve soft soils beneath embankments, tank bases and other lightly or moderately loaded structures with a wide area (McCabe et al. 2009, Arulrajah et al. 2009; Babu et al. 2013, Douglas and Schaefer, 2015). To extend the use of granular columns to sites with very soft soils, which have low undrained shear strength (e.g. < 10 kPa), granular columns encased in geosynthetics have been developed over the past two decades (Alexiew et al. 2005, Murugesan and Rajagopal, 2009, Gniel and Bouazza, 2009, 2010, Yoo and Lee, 2012, Cengiz and Guler, 2018, Alkhorshid et al. 2019) as these soils are unable to provide the confinement required to support conventional granular columns. Another alternative which has received increased attention for sites with very soft soils is the possibility of grouting the granular columns by injecting cement-bentonite or cement slurries into them. The aim, in this case, is to reduce the large settlement due to the bulging associated with the use of traditional granular columns (Heitz et al. 2005, Liu et al. 2015; Unver and Unver, 2016, Golait and Padade, 2017, 2018) and to minimize the possible migration of fines through granular columns from natural soils which can be detrimental to the stability of infrastructures such as dams (Avalle et al. 2012).

The passive resistance of the surrounding soil dictates the column performance under load. Generally, the column bulging will be the highest close to the column's top, where the overburden pressures are lowest (McCabe et al. 2007). Thus, it is essential to seek sustainable techniques to mitigate excessive radial expansion during loading and consequently improve granular columns' performance. Bio-grouting, based on biogeochemical processes such as microbial induced calcium carbonate precipitation, offers such an alternative technology instead of cement grouting. The enzymatic activities of microorganisms, such as *Sporosarcina pasteurii*, cause the precipitation of calcium carbonate within a soil matrix and binds aggregate/granular particles together at inter-particle contacts leading to increased soil strength and stiffness (Mitchell and Santamarina 2005, DeJong et al. 2006, Mortensen and DeJong 2011 Montoya 2012, Stabnikov et al. 2015, Mahawish et al. 2017, 2018a, 2019, Terzis and Laloui, 2018, 2019, Wang et al. 2019, Dejong and Kavazanjian, 2019). The applicability of this process has been suggested to have a broad spectrum of applications ranging from ground improvement/stabilization (Whiffin et al. 2007, Van der Ruyt and van der Zon 2009, DeJong et al. 2010, Harkes et al. 2010, van Paassen et al. 2010, Stabnikov et al. 2011, 2013, Weil et al. 2012, Chu et al. 2013, Ivanov et al. 2015, Hamed-Khodadi et al. 2017, Mujah et al. 2017,

Mahawish et al. 2018b,c, Wu and Chu, 2020; Pan et al. 2020) to contamination mitigation (Cheng and Shahin; 2017, Safavizadeh et al. 2019) and seepage control (Gao et al. 2019).

Although the biogrout process and its implication on improving soil engineering properties have been extensively studied over the past decade at laboratory scale, it has mostly been applied to fine and medium sand. It is also yet to be utilized in field applications as it still needs to be optimized for large-scale use. Several physical and environmental parameters that significantly affect the amount and efficiency of calcium carbonate precipitation in a soil matrix need to be understood to enable a controlled use of bio-grouting and scale up the method from the laboratory to field applications. A lack of knowledge also exists concerning the suitability of bio-grouting of coarser materials and whether the biogrout process can be achieved in the same way as in fine and medium sands. Mahawish et al. (2016, 2017, 2018a, 2018b, 2018c, 2019) have investigated in-depth factors that might affect the biogrouting of coarser materials typically representative of field granular columns. These factors included the number of biochemical treatments, reagent concentrations, incubation time and temperature, among many other factors. This paper goes further by examining the efficacy of biogrouting granular columns when installed in soft soils to mitigate excessive radial column expansion during loading. The columns, composed of sub-angular coarse sand particles, were scaled down to maintain the particle size/diameter ratio consistent with field condition. Staged loading of the columns (un-cemented and bio-cemented) was conducted to replicate the staged construction process typically encountered in projects such as in embankments.

Materials

Soils

A commercially available powdered kaolin (Grade HR1F, Unimin Australia) commonly used in our laboratory experiments (Shannon, 2013; Gniel, 2009) was used in the current investigation. It was mixed with water to produce a slurry with an initial gravimetric moisture content of 115%, which reduced air bubbles' formation within the slurry and increased its workability. The slurry was prepared by mixing a predetermined amount of kaolin powder (6700g) with 7705 ml of water, for about three hours, in a large mixing bowl using an electric mixer. The homogenous mix was then left to sit for a further four hours, allowing air bubbles to rise to the surface. The testing of the slurry material in a modified oedometer cell (100 mm height and 155 mm in diameter) indicated that a vertical pressure of 120 kPa caused a vertical strain of around 37%. The resulting undrained shear strength (C_u), measured using a laboratory

vane shear apparatus was about 15 kPa. The consolidated saturated unit weight of kaolin was 17.88 kN/m^3 and had a gravimetric moisture content of 51%. The properties of the consolidated soft clay are presented in Table 1.

Granular columns are usually composed of angular and sub-angular aggregate materials, such as crushed rock, having an average particle size ranging between 25 and 75 mm. A typical column diameter ranges from 0.40 to 1.20 m, and this leads to a standard column diameter to average particle size ratio ranging between 5 and 50. The model aggregate columns used in the current investigation were composed of coarse sand, having an average grain size of 1.6 mm. The granular column diameter to the particle size ratio was about 30, which is within the practical range reported above. The sand particles were typically sub-angular in shape. They were deemed to be representative of stone aggregates used for full-scale granular columns as reported previously by Gniel and Bouazza (2009, 2010). Commercially available sand (Grade 8/16, supplied by Unimin Australia Pty. Ltd., North Sydney, NSW, Australia) was used in the current investigation. The properties of the sand are given in Table 2. Granular columns were prepared to a relative density of 60%, which is within the range of conventional columns encountered in practice (between 60% and 100%).

Type of bacteria and cementation solution

The urease producing bacteria used was *S. pasteurii* (ATCC® 11859). One colony from the stock culture (Petri dishes containing bacterial colonies, 20 g/L yeast extract, 10 g/L ammonium sulphate and 20 g/L agar in 130 mM Tris buffer (pH 9.0), Stocks-Fischer et al. 1999) was transferred to 5 mL of ammonium-YE growth medium (20 g yeast extract, 10 g $(\text{NH}_4)_2\text{SO}_4$ and 130 mM tris buffer (pH=9.0) per litre of distilled water) to grow the bacterial cells at 30°C. Individual ingredients of the recipe were separately dissolved in distilled water bottles and autoclaved separately (121°C, 100 kPa for around 2 hr process) and then combined post sterilization. Suspended bacterial cultures were grown at 30°C in a shaking water bath (200 rpm) for 24 hrs before harvesting at a final optical density (OD600) of 3.0–3.5 to achieve an optimum concentration of bacterial cells in which all readily available nutrients were considered to be consumed from the growth medium (i.e., the start of the stationary growth phase; Cheng and Cord-Ruwish 2012). The final optical density was determined using WPA CO 8000 spectrophotometer (BioChrom Ltd) considering the ten-time dilution factor.

The maximum optical density of the harvested bacterial cells was used to estimate an activity value of 19.38-21.45 mM/min for the urease enzyme. Urease activity was based on an electrical conductivity assay (labCHEM-CP) result. The preliminary culture medium was transferred aseptically to inoculate 250 ml of the growth medium, and the previous process can hence be repeated as required. The bacterial suspension was stored up to 14 days at 4°C until used, and at the time of use had a urease activity of 19.38 mM/min. The preparation process is further documented in details in Mahawish et al. (2016, 2017). The cementation (reagent) solution consisted of 1 M urea ($\text{CO}(\text{NH}_2)_2$) and 1 M calcium chloride CaCl_2 .

Test equipment

The design, development and construction of the column cells used in the current investigation are described in detail in Gniel and Bouazza (2009) and Gniel (2009). The column cell apparatus was required to initially act as an enlarged oedometer cell, consolidating the kaolin slurry to the consistency of soft clay in which the model untreated and bio-treated granular columns could be installed. The cell also needed to be capable of accommodating the applied load to the column using unit-cell boundary conditions to represent a group of columns (Gniel and Bouazza, 2009). A cross-section of the cell (without the granular column) and the column cells are shown in Figure 1, together with the installation process of the granular column. The kaolin slurry was placed inside a stainless steel cylinder (550 mm H by 155 mm internal diameter; 6 mm wall thickness), mounted on a base plate. Both the base plate and top plate were modified from triaxial cells. A piston within the cylinder loaded the slurry using air pressure. A double O-ring system was used to prevent slurry squeezing around the piston and being exposed to pressurized air. Two identical cells were used in the current investigation. The internal surface of each cell was bored and polished to reduce side resistance, and a thin layer of silicone lubricant was applied to the inner surface of the cells before filling them with the slurry. Gniel and Bouazza (2009) indicated that using the above measures, the vertical stress-strain behaviour of the cell closely matched that of a standard oedometer, justifying the much larger height/diameter ratio, and O-ring resistance was also reduced, such that between 85% and 90% of the applied load was transferred to the kaolin. Two-directional drainage through the piston and base plate was provided to the sample during consolidation. The water level in the cell was always kept above the level of the piston to ensure that a fully hydrated condition was achieved.

Setup Instrumentation

A string potentiometer (string pot transducer) with a travel distance of about 380 mm was attached to each cell to measure the vertical displacement of the piston and settlement of the sample under given loads. Two pore water pressure transducers were mounted on the cylinder wall of both cells at distances of 100 mm and 150 mm, respectively, from the base of the cell. They measured excess pore water pressure during loading and excess pore pressure dissipation and also allowed observation of the impact of the drainage path length on the consolidation rate. A 10 channel DataTaker (D600 Series 2 data logging system) and computer provided the necessary data acquisition system.

Cell operation

The column cells were designed to operate in two stages. The first stage consisted of applying a vertical load to the kaolin slurry by air pressurizing the chamber above the piston and forcing it downwards causing consolidation of the kaolin slurry to the consistency of soft clay ($C_u \approx 15$ kPa). The kaolin slurry took about 71 days to consolidate to the targeted soft clay consistency. Following the consolidation stage, the clay samples were unloaded, and model granular columns were installed. Based on the adopted cell geometry and material availability, a 51 mm diameter sand column was used within a 155 mm diameter cell equating a replacement ratio (ratio of granular column area to loaded footprint area), A_r , of about 11 %. Gniel and Bouazza (2009) indicated that while this replacement ratio value was at the lower end of the range typically adopted for site use, it was considered sufficient for small-scale tests given the controlled conditions within the laboratory. Thus, the adopted A_r was deemed adequate for assessing column behaviour. The second stage of testing consisted of loading the clay-column samples using the piston to create the unit-cell condition. The loading was staged in increments of 50 kPa until reaching a maximum surcharge pressure of about 350 kPa (roughly corresponding to the maximum surcharge pressure that would be applied to a granular column in site). This stress range resulted in five load stages (150, 200, 250, 300 and 350 kPa), enabling suitable assessment of the relationship between applied pressure and vertical strain. The sample was allowed to undergo full consolidation under each load stage, which was assessed by monitoring both settlement and excess pore pressure dissipation. Full consolidation was determined to occur when 95% of the excess pore water pressure dissipated.

Test procedure

Column construction

The kaolin slurry with an initial height of about 480 mm was consolidated in the cells under a pressure of 120 kPa, which was applied in stages starting with 50 kPa to avoid a build-up of excess pore water pressure. At completion, the kaolin clay had an undrained cohesion of 15 kPa (measured using a vane shear test, ASTM D2573) and a height of about 300 mm. This final sample height equated to a model column length/diameter ratio of about 6, within the range (3 to 20) generally accepted for granular columns (Gniel and Bouazza, 2009). Following unloading, a thin-walled aluminium tube measuring 51 mm in outside diameter was pushed slowly through the centre of the sample, located by using a guide attached to the top of the cylinder, to the base of the cell. Once the tube was retrieved, it created a cylindrical cavity of 51 mm diameter at the centre of the clay along the clay column's entire height (Fig.2). A replacement technique was considered to be the most reproducible method for column installation in soft soils. *In-situ* compaction was avoided because the potential for inconsistencies in column density was deemed to be high (Gniel and Bouazza, 2009). Model granular columns were constructed using the freezing method proposed by Sivakumar et al. (2004) and Gniel and Bouazza (2009). Two preparation methods were adopted in the current investigation, including an *in-situ* column method where a frozen coarse sand column was installed in the cavity at the middle of the clay deposit and allowed to thaw before biotreatment and an *ex-situ* column method, where the coarse sand column was biotreated prior to freezing before installing in the clay cavity. This latter was investigated for comparative purposes.

For the *in-situ* column method, a PVC pipe, with an internal diameter of 51 mm, was cut in half length-wise to form a split-mould for the granular columns. This enabled demoulding without disturbance of the coarse sand samples. A wire mesh and filter paper were placed at the bottom of the mould to minimize possible losses of soil particles during preparation and treatment. The granular column was equal in length to the consolidated clay sample height. The sand-filled mould was positioned vertically with the upper surface fully exposed, and a drainage control valve was connected to the base. A dry coarse sand sample was pluviated into the specimen moulds and then compacted, using a vibratory compaction method, to a relative density of 60% (equivalent to a dry density of 1.59g/cm^3). After placement of the soil, tap water (200% pore volume (PV) of granular columns (440 mL)) was flushed through it to expel air from the pore matrix. This step was done by closing the bottom valve, percolating deionized

water until ponding occurred on top of the specimen, then opening the bottom valve to flush the water out, the percolation of water was continued until a total of two-pore volumes (PV) had drained. Afterwards, the bottom valve was closed, and the sand was hydrated with water. The column was then frozen at a temperature of -5°C for twenty-four hours. After the column was removed from the freezer, it was allowed to thaw slightly, enabling the column to be extruded from the mould using low pressure. Once the intact frozen granular column was ejected from the mould, it was inserted in the cavity created in the centre of the consolidated clay (Fig.2). Based on trials undertaken before column tests, a two-hour waiting period was enforced to allow thawing before commencing the *in-situ* biochemical treatment cycles. Note: The untreated granular columns' general preparation process was similar to the *in-situ* columns except that the columns were not subjected to biochemical treatment cycles after installation.

The mould and preparation processes of the *ex-situ* granular columns were similar to the *in-situ* method. For this particular study, the columns were biochemically treated after completion of the preparation process. On completion of the biochemical treatment cycles and curing the columns were frozen to ensure that the bottom portion did not collapse during the disassembling process. The frozen granular column was inserted into the premade cavity and left to thaw and drain with the bottom valve open.

The biocementation protocol for both *ex-situ* and *in-situ* columns followed a percolation treatment method described in Mahawish et al. (2018b). The protocol consisted of a twelve-phase percolation strategy aimed explicitly at minimizing bulging of the columns' upper part. Once the bottom valve of the column was closed, 10 mL of bacterial suspension (BS) and 10 mL cementation solution (CS) (no ammonium-YE media) were percolated alternately through the column. This alternation of 10 mL BS and 10 mL CS was repeated six times to achieve a half pore volume flush (120 mL). The solution was allowed to incubate in place for 24-hours, after which, the bottom valve was opened to drain the effluent. Once the effluent was drained, the valve was closed again, and fresh CS (120 mL) was added, incubated for 24 hours and drained. The above procedure was deemed to represent two biochemical treatment cycles and was repeated to achieve 12 treatment cycles. The use of an alternating BS/CS solution percolation in the column has been shown to improve bacterial retention (Cheng and Cord-Ruwisch 2012). Cheng and Cord-Ruwisch (2012) stated that bacterial cells could be filtered out and accumulated near inlet points. After completion of the bio-cementation treatment cycles, all the columns were flushed with tap water (1 litre) to remove any remaining soluble ammonium salts from the granular material in the column.

For the loading stages, the cells were initially loaded by approximately 5 kPa above the clay pre-consolidation pressure to ensure intimate contact occurred between the column and surrounded clay. Afterwards, the cell was loaded in increments of 50 kPa, and the maximum cell pressure applied was about 350 kPa. The sample was allowed to undergo full consolidation under each load increment. Once the test was completed, the sample was extruded from the cylinder using the piston and was carefully bisected vertically to observe column deformation.

Calcium carbonate quantification

Calcium carbonate (CaCO_3) content was measured using a conventional gravimetric acid washing technique (Choi et al. 2017). This technique involved quantifying the carbonate content in the sample by measuring the residue's weight loss when the samples were exposed to 2M HCl. Then, the residue was collected using a filter paper followed by drying. For this purpose, random subsamples (about 5g each, taken randomly within 30mm of the top, middle and bottom of the sample) from the samples that were prepared and bio-treated for column test were first oven-dried at 105°C for twenty-four hours, and their masses were measured before and after the acid wash. The quantification of CaCO_3 was determined by rinsing the samples with a solution of 2M HCl several times (the total solution used was 200 mL) through No.200 sieves and allowing the dissolved salts to be rinsed out from the samples. The difference between dry mass before and after acid washing was taken as the mass of CaCO_3 removed and the % CaCO_3 was obtained by dividing the mass of CaCO_3 by the mass of soil.

Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were undertaken to characterize the calcium carbonate precipitated in the *in-situ* bio-cemented granular column. Subsamples were retained after completing the granular column test; they were oven-dried; carbon-coated, and then examined using an SEM (JEOL 7001F FEGSEM,) with a beam intensity ranging between 5 to 15kV.

Results and discussion of column testing

Vertical stress-strain behaviour

A kaolin consolidation test was initially undertaken in the column cell to provide a base reference, after which an un-cemented granular column test was conducted to establish its performance for comparison. Unit cell loading tests were then performed on either *ex-situ* bio-

cemented granular column and *in-situ* bio-cemented granular column. After the bio-cemented sand was inserted within the consolidated clay, a nominal load of 125 kPa was applied incrementally to facilitate intimate contact between the granular column and surrounding clay. A vertical strain resulting from the application of the nominal load was assumed to be equivalent to the strain associated with consolidation and installation disturbances. The vertical strain was not recorded until the first loading stage (150 kPa) following the nominal loading. The vertical stress-strain behaviour of the column/clay system (i.e., a hypothetical unit cell subject to uniform strain) is presented in Figure 3, where the vertical strain is plotted against the applied vertical pressure. The vertical strain was calculated using the sample height at the completion of nominal loading. Interestingly, it can be seen from Figure 3 that the vertical strain recorded from the test on kaolin in the column cell test paired quite well with that of the oedometer tests, indicating that the silicone lubrication worked successfully.

The inclusion of an un-cemented granular column resulted in a significant reduction in vertical strains compared to clay alone, as shown in Figure 3. This reduction varied according to the range of applied stresses, and it ranged between about 33% for 150 kPa vertical stress to about 16% at around 350 kPa. The average strain reduction across the range of applied vertical stresses was approximately 23% a result which is typical for a low replacement ratio of $A_r = 11\%$ according to Gniel and Bouazza (2009). The *ex-situ* bio-cemented columnar inclusion, with bio-cement mostly in the upper portion of the column, led to an even more substantial reduction in the vertical strain as can be observed in Figure 3. The averaged vertical strain reduction across the range of applied stresses was about 43% and 56%, compared with the un-cemented granular column inclusion and clay alone, respectively.

In the *in-situ* treatment, the overall reduction in vertical strain across the range of applied stresses was about 48 % compared to the un-cemented granular column and about 60% compared to clay alone for just a low replacement ratio of 11% as the bio-cemented granular columns acted as stiff columns. The in-situ biotreated column's settlement was slightly less than that of the ex-situ biotreated column. This may be attributed to the interaction between the bio-cemented granular column and the surrounding clay as less ingress of clay into the pore spaces of the in-situ treated column (Fig. 4a) was observed than in the ex-situ treated column (Figure 4b).

Column radial expansion

The lateral expansion of the columns was measured to an accuracy of about 0.5 mm, by using a calliper and a pi-tape, given the coarse grain size of the sand. These measurements were performed after exhuming the samples and carefully bisecting them to measure column deformation (bulging). Figure 5 shows the lateral expansion of the treated and un-treated granular columns. Bulging of the un-cemented column was observed to occur along the column to a vertical length corresponding to about four diameters of the column (ϕ_c) which is consistent with previous observations reported in the literature (Hughes and Whiters, 1974, Black et al. 2007). The maximum bulging (~21% radial strain) was recorded at the top of the column, whereas the average radial strain along the column length where most bulging occurred (i.e., $4 \times \phi_c$) was about 11%.

In contrast, the bulging along both the *ex-situ* and *in-situ* bio-cemented columns was dramatically reduced as the bulging was minimal at the top portion of the column and mostly occurred at the bottom portion of the biocemented column. Figure 6 provides further evidence that the distribution of calcium carbonate played an essential role in reducing bulging along the length of the granular column. It can be seen that calcium carbonate was observed to be concentrated in the upper two-thirds of the *ex-situ* bio-cemented column. In contrast, it was found along most of the length (93%) of the *in-situ* bio-cemented column, albeit generally at lower concentrations in the upper profile. Less than 0.5% calcium carbonate was observed at a depth of 220 mm in the *ex-situ* column, whereas about 6% was seen at the same depth in the *in-situ* column. It can be seen from Figures 7a and 7c that precipitation of calcium carbonate bridged the sand particles of the *in-situ* column. The chemical composition of the bio-cemented materials was confirmed by EDS analysis (Figures 7b and d), which was conducted on a random specimen from the *in-situ* treated column. Figures 7b and d indicate that the chemical constituents of the precipitated crystals are mainly composed of calcium, carbon, and oxygen. This further validates that these chemical compositions indicate the presence of CaCO_3 in the sample.

More importantly, it can be inferred from Figure 6 that MICP treatment will reduce the bulging of the granular columns. The difference between the *in-situ* and *ex-situ* bio-cemented column's precipitation profiles is due to the column preparation process adopted in the current investigation. In the case of the *in-situ* treated column, it can be postulated that some of the biogenic calcium carbonates that precipitated within the pore spaces of the upper column sections might have moved to the lower section during treatment flushes, resulting in better distribution with depth. In the case of the *ex-situ* treated column, precipitates might have been

washed out during the treatment process, and/or during soaking and freezing after treatment. It is also worth noting that the efficiency of MICP, defined as the amount of deposited calcium carbonate versus the amount of calcium used in the treatment solution, for the *in-situ* and the *ex-situ* bio-cemented columns, was found to be 45.60% and 32.55%, respectively.

It is also interesting to note that the maximum radial strain occurred at the lower portion of both treated columns. It was about 19% in the *ex-situ* bio-cemented column and 13% in the *in-situ* bio-cemented column, respectively. This observation is an indication that bulging occurred in the length of the column where treatment was not as efficient as at the top, as shown in Figure 5b. Radial bulging at the base of the treated columns tended to increase in magnitude with decreased calcium carbonate content. The most substantial lateral deformations occurred along the length of the column where no calcium carbonate precipitation was recorded.

Variation of gravimetric moisture content and undrained shear strength

The gravimetric moisture content measurements of the kaolin were conducted on samples that were extruded before the installation of the columns and at the end of the column tests at 26 mm from the edge of the columns. The measurements were performed at depths of 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 270 mm, respectively. Figure 8 illustrates the variation of the initial and final gravimetric moisture contents along the depth of the un-treated, *ex-situ* bio-cemented and *in-situ* bio-cemented columns. The initial distribution of the gravimetric moisture contents was similar for all cases, confirming the repeatability of the clay deposit preparation procedure. The final average gravimetric moisture content of these samples was about 51%. Furthermore, the uniformity of this distribution along the columns indicated that a homogenous bed of consolidated clay had been achieved which is an essential component to emulate a natural deposit. The distributions of the gravimetric moisture contents after the column tests were completed indicate that a noticeable reduction in moisture content occurred for all tests at test completion with moisture contents being 84 % to 87% of their pre-test values.

A portable vane shear was used to measure the clay's undrained strength before and after testing within the test column. The tests were done at 26 mm from the edge of the granular column for different depths. Figure 9 shows that the undrained shear strength was about 15 kPa along the column, confirming the consistency of the test bed and its repeatability. The undrained shear strengths of the clay samples differed after loading. For the case of the un-treated granular column, the maximum undrained shear strength was observed to occur in the top part of the column and decreased further down in the column. This is associated with the section that had

a significant radial expansion and reduced gravimetric moisture content (see Figure 5b and Figure 8), i.e., where the bulging of the column occurred. However, the bio-cemented columns showed a different pattern. The maximum undrained shear strength occurred in the lower part of the column where there was less bio-cemented material (see Figure 6) and coinciding with a higher lateral column expansion (see Figure 5b). In this particular case, the radial bulging was transferred to the clay layer surrounding the less treated part of the column, which gained strength due to the densification process induced by the bulging process. It is also worthwhile noting that, in contrast to the biocemented columns, no bulging was observed in the bottom portions of the uncemented columns.

Conclusions

The effect of bio-cementation on granular column behaviour was investigated using laboratory scale model testing. Results were presented for un-cemented granular columns, *ex-situ* and *in-situ* bio-cemented granular columns. The salient conclusions that can be drawn from this work are:

1. The reduction of vertical strain for un-cemented column compared with the consolidated kaolin clay on its own varied with the range of applied vertical stresses, with an average decrease of about 22%. However, the inclusion of a granular column, mostly bio-cemented in its upper part, within the clay bed showed a substantial reduction in the vertical strain as the average vertical strain reduction across the range of applied stresses was about 43% to 56% compared with un-cemented sand granular column and 56% to 60% compared with soft kaolin clay, respectively. It is to be noted that this reduction in vertical strain applies to columns with an area ratio of 11% subjected to an imposed uniform vertical displacement.
2. The reduction of the bulging, as measured by the maximum radial strain of the loaded *ex-situ* and *in situ* bio-cemented columns equated about 62% and 75%, respectively compared with the un-cemented column. It was also found that the bulging occurred at the lower section of the bio-cemented column, where there was less precipitation of bio-cement materials as it was observed that the bio-cement materials were found to precipitate mostly within the upper two-thirds of the bio-cemented column. The undrained shear strength variations along the columns supported the above observations.
3. This study presented a new alternative to reducing bulging in granular columns using a biocementation process rather than using cementitious grouting. However, further work is needed to upscale this process to field applications.

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References

- Alexiew, D., Brokemper, D., and Lothspeich, S. 2005. Geotextile encased columns (GEC): load capacity, geotextile selection and pre-design graphs. In *Contemporary Issues in Foundation Engineering*, pp. 1-14.
- Alkhorshid, N. R., Araujo, G. L., Palmeira, E. M., and Zornberg, J. G. 2019. Large-scale load capacity tests on a geosynthetic encased column. *Geotextiles and Geomembranes*, **47**(5): 632-641.
- Arulrajah, A., Abdullah, A., Bo, M.W. and Bouazza, A. 2009. Ground improvement techniques for railway embankments. *Proceedings of the Institution of Civil Engineers, Ground Improvement*, **162**:3-8.
- ASTM. 2018. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM standard D2573. American Society for Testing and Materials. West Conshohocken, Pa. 10.1520/D2573_D2573M-18.
- ASTM. 2014a. Standard test methods for maximum index density and unit weight of soils using a vibratory table. ASTM standard D4253. American Society for Testing and Materials. West Conshohocken, Pa. doi:10.1520/D4253-14.
- ASTM. 2014b. Standard test methods for minimum index density and unit weight of soils and calculation of relative density. ASTM standard D4254. American Society for Testing and Materials. West Conshohocken, Pa. doi:10.1520/D4254-14.
- Avalle, D., Kok, B., and Lennie, T. 2012. Seismic retro-fit of an historic earth dam using grouted stone. *Proceedings 11th Australia New Zealand Conference on Geomechanics*, Melbourne, Australia, pp. 692-697.
- Babu, M. D., Nayak, S., and Shivashankar, R. 2013. A critical review of construction, analysis and behaviour of stone columns. *Geotechnical and Geological Engineering*, **31**(1):1-22.
- Bang, S. S., Bang, S., Frutiger, S., Nehl, L. M. and Comes, B. L., 2009. Application of novel biological technique in dust suppression. *Transportation Research Board 88th Annual Meeting* (No. 09-0831).
- Black J.A., Sivakumar V, and McKinley J.D. 2007. Performance of clay samples reinforced with vertical granular columns. *Canadian Geotechnical Journal* **44**(1):89–95.
- Cengiz, C., and Güler, E. 2018. Seismic behavior of geosynthetic encased columns and ordinary stone columns. *Geotextiles and Geomembranes*, **46**(1):40-51
- Cheng, L. and Cord-Ruwish., R. 2012. In situ soil cementation with ureolytic bacteria by surface percolation. *Ecological Engineering*, **42**(0):64-72.
- Cheng, L., and Shahin, M. A. 2017. Stabilization of oil-contaminated soils using microbially induced calcite crystals by bacterial flocs. *Géotechnique Letters*, **7**(2):146-151
- Choi, S.G., Park, S.S., Wu, S. and Chu, J. 2017. Methods for calcium carbonate content measurement of biocemented soils. *Journal of Materials in Civil Engineering*, **29**(11): 06017015.
- DeJong, J. T., Fritzges, M. B. and Nüsslein, K. , 2006. Microbially induced cementation to control sand response to undrained shear. *Journal of Geotechnical and Geoenvironmental Engineering*, **132**(11):1381-1392.
- DeJong, J. T., Mortensen, B. M., Martinez, B. C. and Nelson, D. C., 2010. Bio-mediated soil improvement. *Ecological Engineering*, **36**(2):197-210.

- DeJong, J. T., and Kavazanjian, E. 2019. Bio-mediated and bio-inspired geotechnics. In *Geotechnical Fundamentals for Addressing New World Challenges* (193-207). Springer, Cham
- Douglas, S. C., and Schaefer, V. R. 2015. Stone columns: Lessons learned, settlements, and future project considerations. *Proceeding IFCEE 2015*, pp. 612-626. March 17-21, San Antonio, USA.
- Gao, Y., Tang, X., Chu, J. and He, J. 2019. Microbially induced calcite precipitation for seepage control in sandy soil, *Geomicrobiology Journal*, **36**(4):366-375.
- Golait, Y. S. and Padade, A. H. 2017. Analytical and experimental studies on cemented stone columns for soft clay ground improvement. *International Journal of Geomechanics*, **17**(4): 04016100.
- Golait, Y. S., and Padade, A.H. 2018. Enhancement in effectiveness of cemented stone columns for soft clay ground improvement by providing underreamed bulbs. *International Journal of Geomechanics*, **18**(11):04018149.
- Gniel, J. R., 2009. An investigation into ground improvement using geogrid encased stone columns. PhD Thesis, Monash University, Melbourne, Australia.
- Gniel, J. and A. Bouazza 2009. Improvement of soft soils using geogrid encased stone columns. *Geotextiles and Geomembranes* **27**(3):167-175.
- Gniel, J. and A. Bouazza 2010. Construction of geogrid encased stone columns: A new proposal based on laboratory testing. *Geotextiles and Geomembranes* **28**(1):108-118.
- Heitz, C., Kempfert, H., and Alexiew, D. 2005. Embankment project on soft subsoil with grouted stone columns and geogrids. *Proceedings 16th International Conference on Soil Mechanics and Geotechnical Engineering*, Osaka, Japan, Vol. 16, No. 3, 1359-1362, AA Balkema Publishers
- Hamed Khodadadi, T., Kavazanjian, E., van Paassen, L., and DeJong, J. 2017. Bio-grout materials: A review. In *Grouting 2017*, 1-12
- Harkes, M. P., Van Paassen, L. A., Booster, J. L., Whiffin, V. S. and van Loosdrecht, M. C. , 2010. Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement. *Ecological Engineering*, **36**(2):112-117.
- Hughes J.M.O., and Withers N.J., 1974. Reinforcing of soft cohesive soils with stone columns. *Ground Engineering* **7**(3):42-49.
- Ivanov, V. and Chu, J. 2008. Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ. *Reviews in Environmental Science and BioTechnology* **7**(2):139-153.
- Ivanov, V., Chu, J., Stabnikov, V. and Li, B. 2015. Strengthening of soft marine clay using bioencapsulation. *Marine Georesources and Geotechnology* **33**(4):325-329.
- Liu, H., Kong, G., Chu, J., and Ding, X. 2015. Grouted gravel column-supported highway embankment over soft clay: case study. *Canadian Geotechnical Journal*, **52**(11):1725-1733.
- Mahawish, A., Bouazza, A. and Gates, W. P. 2016. Biogrouting coarse materials using soil-lift treatment strategy. *Canadian Geotechnical Journal*, **53**(12): 2080-2085.
- Mahawish, A., Bouazza, A. and Gates, W. P. 2017. Effect of particle size distribution on the bio-cementation of coarse aggregates. *Acta Geotechnica*, **13**(4):1019-1025.
- Mahawish, A., Bouazza, A. and Gates, W.P. 2018a. Factors affecting the bio-cementing process of coarse sand. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, **172**(1):25-36.
- Mahawish, A., Bouazza, A. and Gates, W. P. 2018b. Improvement of coarse sand engineering properties by microbially induced calcite precipitation. *Geomicrobiology Journal*, **35**(10): 887-897.
- Mahawish, A., Bouazza, A. and Gates, W. P. 2018c. Strengthening crushed coarse aggregates using bio-grouting. *Geomechanics and Geoengineering Journal*, **14**(1):59-70.

- Mahawish, A., Bouazza, A., and Gates, W. P. 2019. Unconfined compressive strength and visualization of the microstructure of coarse sand subjected to different biocementation levels. *Journal of Geotechnical and Geoenvironmental Engineering*, **145**(8):04019033.
- McCabe, B.A., McNeill, J.A. and Black, J.A. 2007. Ground improvement using the vibro-stone column technique, The Institute of Engineers of Ireland, NUI Galway: 1-12.
- McCabe BA, Nimmons GJ and Egan D 2009. A review of field performance of stone columns in soft soils. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **162**(6):323–334,
- Mitchell, J. and Santamarina, J. 2005. Biological Considerations in Geotechnical Engineering. *Journal of Geotechnical and Geoenvironmental Engineering* **131**(10):1222-1233.
- Montoya, B. M. , 2012. Bio-mediated soil improvement and the effect of cementation on the behavior, improvement, and performance of sand. PhD Thesis, University of California, Davis, USA.
- Mortensen, B. M. and DeJong, J. T. , 2011. Strength and stiffness of MICP treated sand subjected to various stress paths. *ASCE Proceedings of Geo-Frontiers 2011 conference*, Dallas, Texas, D20110000, ASCE.
- Mujah, D., Shahin, M. A., and Cheng, L. 2017. State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP) for soil stabilization. *Geomicrobiology Journal*, **34**(6):524-537
- Murugesan, S., and Rajagopal, K. 2009. Studies on the behavior of single and group of geosynthetic encased stone columns. *Journal of Geotechnical and Geoenvironmental Engineering*, **136**(1):129-139.
- Pan, X., Chu, J., Yang, Y. and Cheng, L. 2020. A new biogrouting method for fine to coarse sand, *Acta Geotechnica*, 15(1), 1-16.
- O'Donnell, S. T., Kavazanjian Jr, E., and Rittmann, B. E. 2017. MIDP: liquefaction mitigation via microbial denitrification as a two-stage process. II: MICP. *Journal of Geotechnical and Geoenvironmental Engineering*, **143**(12):04017095
- Safavizadeh, S., Montoya, B. M., and Gabr, M. A. 2019. Microbial induced calcium carbonate precipitation in coal ash. *Géotechnique*, **69** (8):727–740.
- Shannon, B. M. 2013. Fracture propagation of cohesive soils under tensile loading and desiccation. PhD Thesis, Monash University, Melbourne, Australia.
- Stabnikov, V., Naeimi, M., Ivanov, V. and Chu, J. 2011. Formation of water-impermeable crust on sand surface using biocement. *Cement and Concrete Research* **41**(11):1143-1149.
- Stabnikov, V., Chu, J., Myo, A. N. and Ivanov, V. 2013. Immobilization of sand dust and associated pollutants using bioaggregation. *Water, Air, & Soil Pollution* **224**(9):1-9.
- Stabnikov, V., Ivanov, V. and Chu, J. 2015. Construction Biotechnology: a new area of biotechnological research and applications. *World Journal of Microbiology and Biotechnology* **31**(9):1303-1314.
- Terzis, D., and Laloui, L. 2018. 3-D micro-architecture and mechanical response of soil cemented via microbial-induced calcite precipitation. *Scientific reports*, **8**(1):1416
- Terzis, D., and Laloui, L. 2019. A decade of progress and turning points in the understanding of bio-improved soils: A review. *Geomechanics for Energy and the Environment*, **19**: 100116.
- Ünver, A. M. and Ünver, İ. S. 2016 A preliminary design of ground improvement by grouted stone columns for a shopping centre. *Proceedings 5th International Conference on Geotechnical and Geophysical Site Characterisation*, Gold Coast, Australia, pp.1387-1392.
- Van der Ruyt, M. and van der Zon, W. 2009. Biological in situ reinforcement of sand in near-shore areas. *Proceedings of the ICE-Geotechnical Engineering* **162**(1): 81-83.
- van Paassen, L. A., Ghose, R., van der Linden, T. J., van der Star, W. R. and van Loosdrecht, M. C. 2010. Quantifying biomediated ground improvement by ureolysis: large-scale

- biogrout experiment. *Journal of Geotechnical and Geoenvironmental Engineering*, **136**(12):1721-1728.
- Wang, Y., Soga, K., DeJong, J. T. and Kabla, A. J. 2019. Microscale visualization of microbial-induced calcium carbonate precipitation processes. *Journal of Geotechnical and Geoenvironmental Engineering*, **145**(9):04019045
- Weil, M. H., DeJong, J. T., Martinez, B. C. and Mortensen, B. M. 2012. Seismic and resistivity measurements for real-time monitoring of microbially induced calcite precipitation in sand. *Geotechnical Testing Journal* **35**(2):330-341.
- Whiffin, V. S., van Paassen, L. A. and Harkes, M. P. , 2007. Microbial carbonate precipitation as a soil improvement technique. *Geomicrobiology Journal*, **24**(5):417-423.
- Wu, C. and Chu, J. 2020. Biogrouting method for stronger bond strength for aggregates. *Journal of Geotechnical and Geoenvironmental Engineering*, **146**(11), 06020021.
- Yoo, C. and Lee, D. 2012. Performance of geogrid-encased stone columns in soft ground: full-scale load tests. *Geosynthetics International*, **19**(6):480-490.

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Table 1. Properties of consolidated kaolin clay.

Parameter	Unit	Value
Specific gravity	--	2.64
Plastic limit	%	29
Liquid limit	%	62
Compression index, C_c	--	0.7
Recompression index, C_r	--	0.09
Saturated unit weight	kN/m ³	17.88
Moisture content	%	51
Average undrained shear strength, C_u	kPa	15*

* tested using a vane shear apparatus.

Table 2. Properties of sand used in sand columns

Parameter	Unit	Value
Specific gravity, G_s	-	2.64
Coefficient of curvature, C_c	-	0.97
Coefficient of uniformity, C_u	-	1.35
Median grain size, D_{50}	mm	1.60
Maximum void ratio, e_{max}	-	0.84
Minimum void ratio, e_{min}		0.55
Minimum dry density	kN/m ³	14.4
Maximum dry density	kN/m ³	17.0
Compacted dry density	kN/m ³	16.2
Compacted saturated density	kN/m ³	20.2
Residual angle of internal friction, ϕ	°	35
Dilation, ψ	°	8 – 11
Average permeability, k	m/s	4.5×10^{-2}

(a)

(b)

Figure 1. (a) Cross section of enlarged oedometer, (b) Column cells

(a)

(b)

Figure 2. (a) Cavity created in the centre of the clay; (b) Installed sand column

Figure 3. Variation of vertical strain against applied vertical stress.

Figure 4. Clay ingress into the column: a- *in-situ* bio-cemented sand column; b- *ex-situ* bio-cemented sand column.

Figure 5. Radial expansion of sand columns: (a) Picture of exhumed uncemented column; (b) Radial expansion along the tested columns.

Figure 6. Distribution of precipitated calcium carbonate with depth of treated columns.

Figure 7. (a) and (c) SEM showing typical precipitated calcium carbonate; (b) and (d) EDS for chemical composition of the CaCO_3 crystals between sand particles.

Figure 8. Variation of gravimetric moisture content with depth before and after loading.

Figure 9. Variation of undrained shear strength against depth of columns before and after loading.