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Effects of Carbonate Distribution Inhomogeneity on the Improvement Level of Bio-cemented Sands: A DEM Study

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Abstract. Microbially induced carbonate precipitation (MICP) involves bacteria to drive calcite precipitation and naturally cement soils, thereby improving soils performance. Experimental studies have shown that bio-cemented specimen can suffer from severe spatial inhomogeneity of the calcite content, leading to large uncertainty in treatment efficiency prediction. To evaluate the effect of inhomogeneity on the mechanical behaviour of bio-cemented soils, the discrete element method (DEM) is used to model bio-cemented samples with a single carbonate distribution pattern (i.e. either bridging or contact cementing) but different characteristics of inhomogeneity. Both drained triaxial compression and triaxial extension simulations are carried out to evaluate the impact of inhomogeneity along different loading paths. The results indicate that inhomogeneity has different effects on bio-cemented samples depending on the carbonate distribution patterns and the loading path. Specifically, the shear strength in compression of samples exhibiting bridging cementation is largely affected by inhomogeneity, while the effect on shear strength in extension is negligible. On the other hand, samples with contact cementing show limited sensitivity to the variation of inhomogeneity under both triaxial compression and triaxial extension tests.

Keywords: Bio-cemented soil · MICP · DEM · Inhomogeneity · Shear strength

1 Introduction

Soils treated with bio-mediated methods, such as microbially induced carbonate precipitation (MICP) and enzyme induced carbonate precipitation (EICP), generally show an improvement in strength, stiffness, dilatancy, and therefore liquefaction resistance (Feng and Montoya 2015; Lin et al. 2015; Han et al. 2016; Terzis et al. 2016; Ahenkorah et al. 2020; Konstantinou et al. 2021a; Xiao et al. 2021; Xu et al. 2021; Nafisi et al. 2021). A critical challenge for bio-mediated methods to be applied in engineering applications is the uncertainty of the improvement of the mechanical properties. Indeed, the treatment efficiency can vary within a large range, which can be attributed to multiple factors, including different distribution patterns of the precipitated carbonate and inhomogeneity of the carbonate content. These factors together control the mechanical performance of

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bio-cemented sands. A previous numerical study by Zhang and Dieudonné (2022) investigated the effects of carbonate distribution patterns on the mechanical behaviour of bio-cemented sands. In that study, four typical carbonate distribution patterns were conceptualised and modelled using discrete element method (DEM): bridging (where carbonates are located at the gap between sand grains, and connect sand grains), contact cementing (where carbonates are located at contacts between sand particles), coating (where carbonates coat sand grains) and pore filling (where carbonates fill in the pore space). These types of microstructure were found to contribute differently to strength improvement: bridging and contact cementing distribution patterns exhibit obvious improvement in strength, while coating and pore filling can hardly contribute to improving the mechanical performance.

On the other hand, the effect of inhomogeneity has not been comprehensively evaluated. The influence of inhomogeneity has been addressed experimentally by Ahenkorah et al. (2020), Konstantinou et al. (2021b) and Xiao et al. (2021), among others. It was found that inhomogeneous bio-cemented samples tend to show lower strength improvement than homogeneous ones. However, we cannot conclude that this discrepancy in strength improvement is fully linked to carbonate distribution inhomogeneity as other factors, such as the carbonate distribution pattern mentioned above, can also affect the mechanical properties of bio-cemented soil specimen. Ideally, the effect of inhomogeneity should be assessed by keeping other configurations the same.

Therefore, following Zhang and Dieudonné (2022), this study sheds the light on the role of inhomogeneity in the carbonate distribution on the mechanical performance of bio-cemented soils. Cemented samples with either bridging or contact cementing distribution patterns are modelled and assigned with different inhomogeneity characteristics. Triaxial compression and extension tests are carried out, and the effects of inhomogeneity on the strength improvement are assessed and analysed.

2 Experimental Evidence of Inhomogeneity of Bio-cemented Soils

As reported in laboratory studies, the treatment protocol can lead to inhomogeneity of bio-cemented samples. For instance, Xiao et al. (2021) found that sands treated with a temperature-controlled one-phase MICP method can achieve a more uniform distribution of carbonates than samples treated with a room-temperature two-phase MICP method. Moreover, the former specimens exhibited higher improvement in strength. Nafisi et al. (2020) reported that more precipitation occurred at the bottom of the specimens by adjusting flow direction during the treatment.

The inhomogeneity of bio-cemented soils is usually described by the variation of mass content of carbonate distributed along the sample height. Typically, treated samples are divided into several sections, and the mass content of carbonate (defined as the mass of carbonate over the mass of sand, unless otherwise specified) of each section is determined. In this study, the inhomogeneity of bio-cemented soils is characterised by its spatial variation type and its spatial variation ratio. Five spatial variation types typically observed in experimental studies are illustrated in Fig. 1(a): (1) carbonates uniformly distribute along the sample height (Uni), (2) the majority of carbonates precipitate at the top or bottom of the sample (T/B), (3) at the top and bottom of the sample (T + B), (4) at the middle part of the sample (Mid), or (5) are randomly distributed along the sample height (Rdm). In addition to the typical spatial variation types, a spatial variation ratio (R) is introduced to quantitatively describe the magnitude of the variation in carbonate content among the sample. R is defined as:

$$\mathrm{R} = \frac{\max(c_i) - \min(c_i)}{\min(c_i)}$$

where c_i ($i = 1$ to N) is the mass content of carbonates in the i^{th} section supposing the sample is divided into N sections. The larger the R, the larger the inhomogeneity of the sample. Figure 1(b) summarises a set of R derived from previous studies (Feng and Montoya 2015; Lin et al. 2015; Terzis et al. 2016; Nafisi et al. 2019; Ahenkorah et al. 2020; Nafisi et al. 2020). In Fig. 1(b), R is plotted against the mass content of carbonate of the bio-cemented sample. It can be seen that lightly cemented samples have more potential of showing a larger R, which represents a more severe inhomogeneity. On the other hand, bio-cemented samples with high cementation level tend to show a lower R, representing a more uniform spatial distribution along sample height.

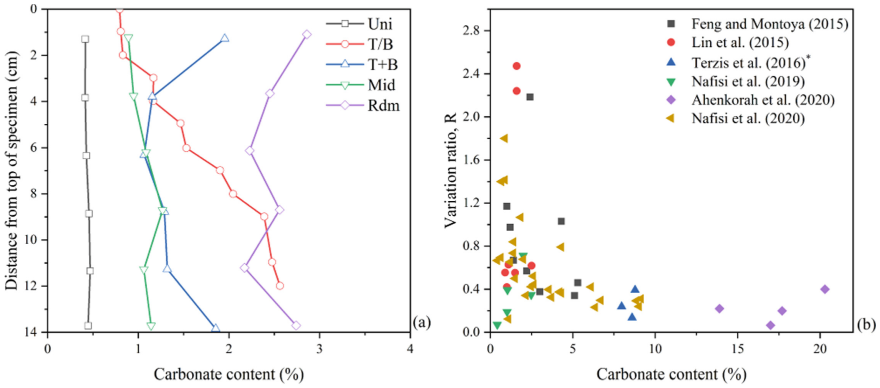

Fig. 1. (a) Illustration of spatial distribution type of carbonate content, data of uniform type, type Mid and type Rdm are cited from Nafisi et al. (2019), data of type T/B is cited from Lin et al. (2015), data of type T + B is cited from Nafisi et al. (2020). (b) Review on variation ratio of experimental data. *Note that carbonate content in Terzis et al. (2016) is defined as the mass of carbonate divided by the total mass of carbonate and sand.

3 DEM Sample Preparation

Bridging and contact cementing types of cemented samples with different inhomogeneity characteristics are prepared for this study. The carbonate content of all the cemented samples presented in this paper is around 1%. Three representative levels of R are selected based on Fig. 1(b). They represent uniform ($\mathrm{R} < 0.2$), lightly inhomogeneous (around 0.4) and heavily inhomogeneous ($\mathrm{R} > 2.2$) levels. Table 1 summarises the properties of each DEM sample that was tested. Figure 2 presents the spatial variation of carbonate content of each DEM sample. The methodology for the preparation of DEM samples, contact law and model parameters are described in Zhang and Dieudonné (2022).

Table 1. Properties of DEM samples. Note: BR and CC means bridging and contact cementing types of distribution respectively.

Samples	R	Spatial variation type	Shear strength in compression (kPa)	Shear strength in extension (kPa)
Untreated	-	-	233.5	75.9
BR-R0.15-Uni	0.15	Uniform	326.1	95.1
BR-R0.4-T/B	0.43	Top/Bottom	317.6	93.8
BR-R0.4-T + B	0.44	Top + Bottom	319.1	93.9
BR-R0.4-Mid	0.43	Middle	321.3	94.1
BR-R0.4-Rdm	0.39	Random	320.0	93.8
BR-R2.2-T/B	2.19	Top/Bottom	312.1	92.9
BR-R2.2-T + B	2.24	Top + Bottom	308.1	92.9
BR-R2.2-Mid	2.19	Middle	305.6	92.1
BR-R2.2-Rdm	2.20	Random	298.1	91.4
CC-R0.17-Uni	0.17	Uniform	294.2	94.0
CC-R0.4-T/B	0.40	Top/Bottom	292.2	94.4
CC-R0.4-T + B	0.40	Top + Bottom	289.0	94.1
CC-R0.4-Mid	0.40	Middle	291.5	95.2
CC-R0.4-Rdm	0.39	Random	293.3	94.0
CC-R2.2-T/B	2.15	Top/Bottom	295.8	93.1
CC-R2.2-T + B	2.23	Top + Bottom	291.4	94.5
CC-R2.2-Mid	2.23	Middle	290.1	94.2
CC-R2.2-Rdm	2.15	Random	290.4	94.4

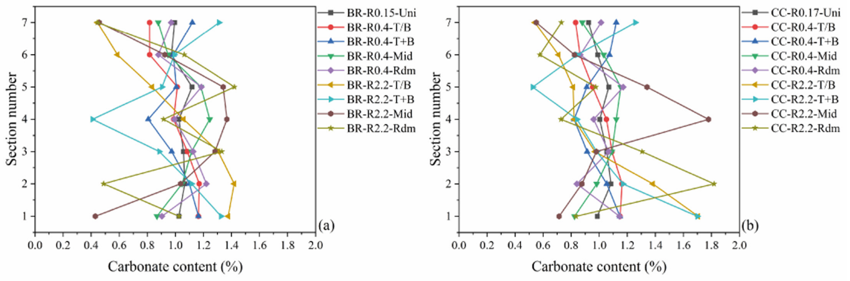

Fig. 2. Distribution of carbonate content along sample height for samples with (a) bridging and (b) contact cementing distribution.

4 Results and Discussion

The DEM samples are subjected to drained triaxial compression and extension tests under 100 kPa of confining pressure. Triaxial compression (extension) simulations are performed by maintaining the confining pressure and applying the axial loading (unloading). The results are summarised in Table 1. Frictionless rigid walls are used as the boundary for all the tests. To quantify the improvement in peak strength of bio-cemented samples with different levels of inhomogeneity, a strength improvement ratio (S) is introduced. It is defined as:

$$S = \frac{q_{max}^{cemented} - q_{max}^{uncemented}}{q_{max}^{uncemented}} \times 100\%$$

where $q_{max}^{cemented}$ and $q_{max}^{uncemented}$ are the maximum deviatoric stresses of cemented and uncemented samples respectively.

4.1 Triaxial Compression Tests

Figure 3(a) shows the strength improvement ratio in compression of bridging samples with different levels and types of inhomogeneity obtained from triaxial compression tests under 100 kPa of confining pressure. The reference red line in Fig. 3(a) denotes the improvement ability of the homogeneous cemented sample (BR-R0.15-Uni), which is 39.7%. It can be seen from Fig. 3(a) that:

(1) The strength improvement ratio of bridging type of samples with R = 0.4 or 2.2 are all below the red line, indicating a reduction in strength improvement as compared to the homogeneous cemented sample. In addition, bridging samples with R = 2.2 show lower strength improvement than samples with R = 0.4 under the same spatial variation type. This suggests that samples with a bridging distribution with higher spatial variation ratio tend to exhibit lower strength improvement.
(2) The type of spatial variation plays a more significant role on the strength improvement level for samples with high R. For bridging samples with a relatively low R (i.e. 0.4), samples show a small difference in reduction of improvement, ranging from 2.1% (BR-R0.4-Mid) to 3.7% (BR-R0.4-T/B) compared to the reference red line. In contrast, bridging samples with R = 2.2 show obvious reduction in strength improvement, and BR-R2.2-Rdm exhibits the most severe reduction in improvement, which reaches 12%.

Figure 3(b) shows the results of contact cementing samples. Again, the reference red line in Fig. 3(b) represents the improvement ability of the homogeneous cemented sample (CC-R0.17-Uni), which is 26%. It can be seen from Fig. 3(b) that the strength improvement ratio varies within a small range, which could be mostly attributed to the fluctuation in DEM results. This result suggests that the strength improvement level of contact cementing type of samples is less affected by the variation of inhomogeneity than bridging type of samples, regardless of the spatial variation ratio (R) and variation type. It can also be found that contact cementing samples exhibit much lower strength improvement. In particular, the difference can reach 13.7% between BR-R0.15-Uni and CC-R0.17-Uni, which suggests that the strength improvement level in compression is affected not only by inhomogeneity, but also, sometimes even more obviously, by the carbonate distribution pattern.

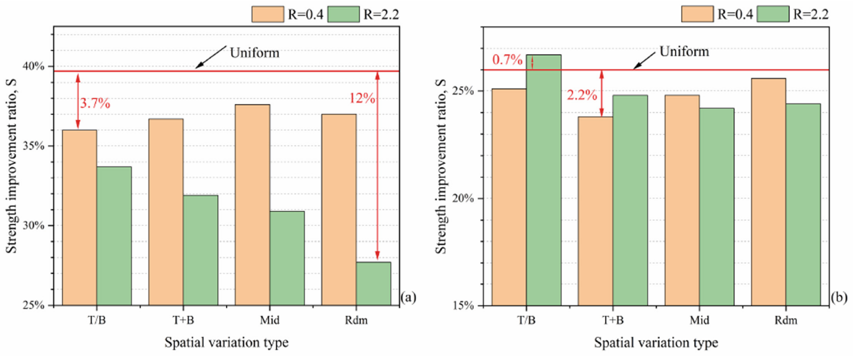

Fig. 3. Strength improvement ratio in compression of (a) bridging and (b) contact cementing samples with different inhomogeneity characteristics.

4.2 Triaxial Extension Tests

Figure 4 shows the strength improvement ratio in extension of bridging and contact cementing samples with different spatial variation ratios and variation types obtained from triaxial extension tests under 100 kPa of confining pressure. It can be found that samples with a bridging distribution exhibit much lower improvement in shear strength in extension than in compression. On the other hand, contact cementing samples show a strength improvement ratio of around 25% in both compression and extension. In addition, all the bridging and contact cementing types of samples exhibit similar levels of improvement ratio in extension, varying from 20.4% to 25.4%, which suggests that inhomogeneity plays a less significant role on the improvement level in extension.

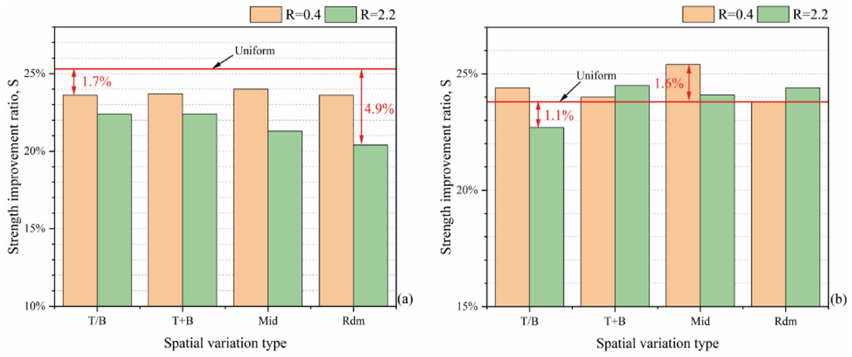

Fig. 4. Strength improvement ratio in extension of (a) bridging and (b) contact cementing samples with different inhomogeneity characteristics.

5 Conclusions

This study aims at evaluating the impact of inhomogeneity on the strength improvement level of bio-cemented samples. To investigate the effect of inhomogeneity, bio-cemented samples with a single carbonate distribution pattern (i.e. either bridging or contact cementing) were modelled and assigned with different characteristics of inhomogeneity. Samples were used for both triaxial compression and triaxial extension tests. In general, bio-cemented models with a lower level of inhomogeneity tend to show higher strength improvement, which is in agreement with experimental observations by Xiao et al. (2021). The present numerical study provides further insights into the effect of inhomogeneity, which are not accessible from experimental tests. The obtained results indicate that inhomogeneity has different effects on samples with different carbonate distribution patterns and along different loading paths. Specifically, the strength improvement level in compression of samples with a bridging distribution is largely affected by inhomogeneity. In contrast, inhomogeneity plays a less significant role on the improvement level in extension for samples with a bridging distribution. Contact cementing samples show limited sensitivity to the variation of inhomogeneity, as all of them show similar levels of improvement ratio in both compression and extension.

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