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A SMALL-STRAIN STIFFNESS MODEL FOR BIO-CEMENTED SANDS

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Abstract: This study introduces a small-strain stiffness model for bio-cemented sands, building upon the existing small-strain stiffness model for sands proposed by Wichtmann and Triantafyllidis. The small-strain stiffness of numerical specimens, including sand specimens with different void ratios and bio-cemented specimens with different microscopic features, is evaluated using the discrete element method (DEM). The acquired DEM results are utilised to develop the small-strain stiffness model for bio-cemented sands. The proposed model is able to describe the small-strain stiffness of DEM bio-cemented sands. In particular, different contributions of carbonates in different distribution patterns to G_0 enhancement can also be described by the proposed model.

1. Introduction

Bio-mediated soil improvement methods have gained considerable attention as alternatives to invasive, carbon-intensive stabilisation techniques. One of these methods is microbially induced carbonate precipitation (MICP), which utilises calcium carbonate minerals caused by bacterial activity to cement soil particles. MICP has demonstrated the ability to improve soil stiffness, strength and dilatancy and can be used for applications such as ground improvement and mitigation of liquefaction upon earthquake.

The small-strain stiffness plays an important role in geotechnical engineering problems, such as analysis of earthquake response and prediction of ground deformation. To advance the applications of MICP on such engineering problems, it is essential to evaluate the small-strain stiffness of MICP-treated soils, and to build a model to describe the small-strain stiffness of MICP-treated soils. The small-strain stiffness of soil has been comprehensively studied, with a focus on, for instance, particle size distribution [1], fine content [2], stress condition [3], particle shape [4] and particle surface roughness [5]. However, fewer studies have been conducted on the small-strain stiffness of (bio-)cemented soils. The small-strain stiffness of bio-cemented soil is still to be investigated, and a model is to be established.

The small-strain stiffness of bio-cemented sand depends not only on the properties of the host sand (e.g. particle size distribution, void ratio) but also on the precipitated cementation (e.g. cementation content, distribution pattern [6, 7]). To evaluate the small-strain stiffness of bio-cemented sand, the discrete element method (DEM) is utilised in this study for its capacity to incorporate grain-scale features of bio-cemented sand. 3D DEM specimens of sands with different densities are first prepared. Then, cementation particles are explicitly introduced into these sand specimens in different contents and distribution patterns to model various bio-cemented sands [8]. The DEM specimens are subjected to a static probing test to assess the small-strain stiffness. The DEM results indicate that cementation particles in different distribution patterns have different impacts on the small-strain stiffness of sand. Moreover, sands with various properties respond differently given the same amount and characteristics of the cementation. Based on the DEM results, a small-strain stiffness model for bio-cemented sands is proposed in this study. The proposed model captures the effect of cementation on the change in small-strain stiffness of sands. In particular, the different effects of the cementation with various distribution patterns on the small-strain stiffness can also be described by the proposed model.

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2. Model development

To develop a small-strain stiffness model for bio-cemented sands, an existing model for describing the small-strain stiffness of sand is utilised and the model parameters are calibrated to fit the DEM results. After that, the adopted model for sand is extended.

2.1. *Small-strain stiffness model for host sand*

Many models have been proposed to predict the small-strain stiffness of soils, e.g. [9, 10], among others. In this study, the model proposed by Wichtmann and Triantafyllidis [10] is adopted to describe the small-strain stiffness of sand derived from DEM simulation. The model is formulated as Eq. 1.

$$G_0 = A\frac{(a-e)^2}{1+e}p_a^{1-b}p^b \tag{1}$$

where e is the void ratio of the sand. p_a is the atmospheric pressure (100 kPa) and p is the pressure. The parameters A, a and b are related to the coefficient of uniformity $C_u = d_{60}/d_{10}$ of the grain size distribution. They are described as follows.

$$a = c_1\text{exp}(-c_2C_u) \tag{2}$$

$$b = c_3C_u^{c_4} \tag{3}$$

$$A = c_5 + C_6C_u^{c_7} \tag{4}$$

where c_1, c_2, c_3, c_4, c_5, c_6, c_7 are constants derived from fitting the model to the data.

Figure 1 presents the small-strain stiffness of DEM sand specimens with various void ratios. It can be seen that the small-strain stiffness of sand shows a decreasing trend with the increase of void ratio. The DEM results are then fitted using Eq. 1, and parameters of c_1 = 1.43, c_2 = 0.13, c_3 = 0.4, c_4 = 0.18, c_5 = 4859, c_6 = 3.13, c_7 = 2.98 give a good description of the DEM results.

2.2. *Small-strain stiffness model for bio-cemented sand*

DEM simulations indicate that the small-strain stiffness of bio-cemented sand is associated with that of the host sand as well as the microscopic features of the cementation. Specifically, the same carbonate content (CC) can lead to different improvements in the small-strain stiffness, depending on the properties of the host sand (e.g. void ratio, C_u) and the characteristics of cementation (e.g. distribution pattern). Therefore, the small-strain stiffness model of bio-cemented sands is developed by integrating the model for sand (Eq. 1) with a stiffness improvement ratio (described in Eq. 5).

$$\frac{G_0^{cemented}}{G_0^{uncemented}} = (1 + CC^{n_1})^{n_2} \tag{5}$$

In Eq. 5, CC is the mass content of carbonates which is defined as the mass of carbonate divided by the mass of sand. n_1 and n_2 are two constants controlling the contribution of the carbonates to the improvement of small-strain stiffness. Consequently, the small-strain stiffness model for bio-cemented sand proposed in this study is formulated as Eq. 6.

$$G_0^{cemented} = A\frac{(a-e)^2}{1+e}p_a^{1-b}p^b(1 + CC^{n_1})^{n_2} \tag{6}$$

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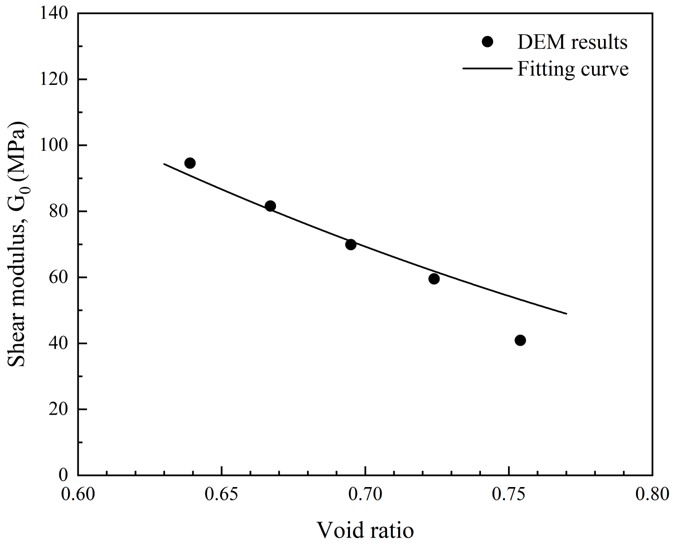

Figure 1. Small-strain stiffness of DEM sand specimens with various void ratios: DEM results and fitting curve using Eq. 1

Figure 2 shows the small-strain stiffness of bio-cemented DEM specimens with different carbonate contents and carbonate distribution patterns (either bridging or contact cementing). All the cemented specimens presented in Figure 2 are generated from the same host sand specimen with an initial void ratio of 0.695. It can be found that the distribution pattern of the precipitated carbonates affect the small-strain stiffness of bio-cemented sands. Given the same amount of carbonates, carbonates in different distribution patterns lead to different improvement of G_0. Therefore, the proposed model is used to fit the data of bridging cases and contact cementing cases, respectively. The mean values of the two cases at the same carbonate content are also plotted in Figure 2 and fitted using the proposed model. The resulted parameters are listed in Table 1. Note that the parameters associated with the host sand part are the same as that given in Section 2.1.

Parameters	Bridging	Contact cementing	Mean value
n_1	0.6	1.41	1
n_2	0.32	0.19	0.245

Table 1. Parameters used to fit DEM results of bio-cemented specimens.

3. Conclusion

This study developed a small-strain stiffness model for bio-cemented sands by extending an existing small-strain stiffness model for sand. The proposed model is able to satisfactorily reproduce the small-strain stiffness of DEM bio-cemented sands. In particular, different contributions of carbonates in different distribution patterns to G_0 enhancement can also be described by the proposed model. This model can be used for predicting and assessing the small-strain stiffness of bio-cemented sands and hence contribute to the practical application of MICP.

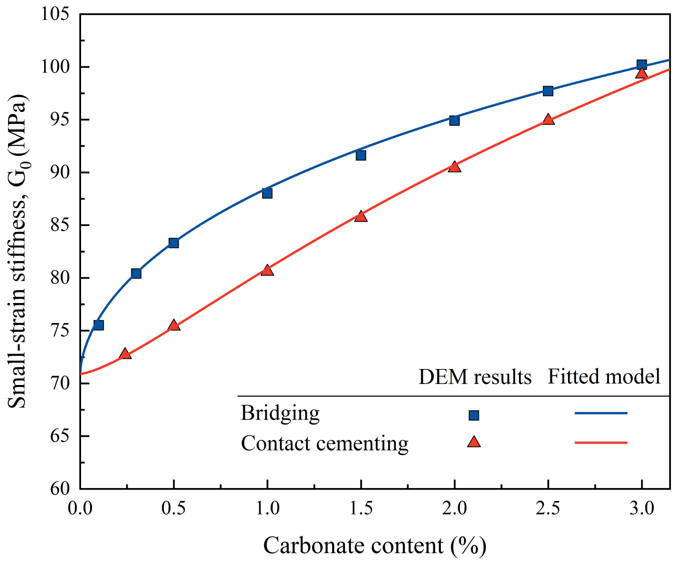

Figure 2. Small-strain stiffness of bio-cemented DEM specimens with different carbonate contents and carbonate distribution patterns: DEM results and fitting curves using Eq. 6

4. Acknowledgement

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