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Closure to “Axisymmetric Simulations of Cone Penetration in Biocemented Sands”

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This paper presents a closure to “Axisymmetric Simulations of Cone Penetration in Biocemented Sands” by Maya El Kortbawi, Diane M. Moug, Katerina Ziotopoulou, Jason T. DeJong, and Ross W. Boulanger. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002914.

The original paper presented a numerical study of cone penetration in cemented sands. Although microbially induced calcite precipitation (MICP) shows promise as a ground improvement technique through extensive laboratory studies (e.g., Montoya and DeJong 2015; Lee et al. 2022), there is no cone penetration test (CPT)-based method for evaluating the increase of cementation due to MICP. The objective of the study was to develop a relationship between change in cone tip resistance (Δq_c) and the “apparent” cohesion (c) attributed to MICP treatment.

The primary points raised by the discusser were the actual difficulty in sampling cemented sands, terminology of characterizing cohesion from MICP as “apparent” cohesion, interpretation of some of the data from published sources for use in the study, and application of the developed relationships between “apparent” cohesion and normalized shear wave velocity to example data, and how cementation levels are classified. Additionally, the discusser raised several practical considerations for MICP treatment application for liquefaction mitigation. The writers of the original paper provide responses to the discussion in the following.

Challenges with Intact Sampling

The discusser provided several examples of projects where intact samples of cemented sands were successfully obtained for laboratory testing. These examples illustrate that intact sampling of cemented sands is feasible. The writers agree with the discusser on the overall description of the mechanical behavior of cemented sand and the importance of obtaining high-quality samples. Several of the writers have compiled a comprehensive database on the mechanical properties of naturally cemented and biocemented sands (the focus of this research), which is currently under review. Based on the extensive review of available test data on biocemented sands, the writers deduced that the shape of the stress–strain response is not an indicator of the quality of the sample. An indication of good sample quality might be, as the discusser mentions, if the retrieved naturally cemented sample is reproduced artificially in the lab, tested under similar conditions, and yields similar results. Another possible indicator of good sample quality might be measuring a shear wave velocity in the laboratory sample that is comparable to that measured in situ. Otherwise, the shape of the stress–strain response can be representative of some cementation level but not necessarily the intact cementation level because cementation bonds tend to be brittle. The ability to obtain quality samples decreases as the cementation level becomes lighter, and sampling of soils with only a few percent cementation (by mass) is very difficult from the writers’ experiences. Cone penetration testing, informed by the paper under discussion, with geophysical testing and soil sampling for MICP-treated sites can be a basis for evaluating the changes in mechanical soil properties and the variability of these changes across a treatment zone.

Cohesion for MICP-Cemented Sands

Many of the discusser’s comments were related to the cohesion in cemented sands and the development of Fig. 4 of the original paper. The discusser was concerned with the use of the term “apparent” for cohesion in cemented sands. The term was used in this paper in the context of cementation to indicate the probable nature of the additional cohesion coming from the cementation. Research on cemented sands continues to mature, and the complexities introduced require more comprehensive work before the depth of understanding is on par with clean sands and clays. Recognizing this, the writers use the term “apparent cohesion” to indicate that the bonding capacity introduced by cementation can be reasonably represented using the cohesion term in the Mohr-Coulomb constitutive model.

The writers thank the discusser for pointing out errors in Fig. 4 of the original paper. The writers confirm that the data from O’Donnell et al. (2017) were not included in the development of this relationship and the data points were mislabeled. The legend should only reference the triaxial tests from Nafisi et al. (2020) and Gomez et al. (2018). Corrections to the original paper can be found in the “Erratum” section of this closure. Both references reported shear wave velocity measurements during their experiments. The strength parameters (cohesion and friction angle) from Nafisi et al. (2020) were interpreted using three envelopes: linear, nonlinear, and bilinear. Therefore, three sets of strength parameters were reported by Nafisi et al. (2020). The data in Fig. 4 of the paper under discussion from Nafisi et al. (2020) corresponded to the cohesion from the linear failure envelope fitted to different soil types treated at light and moderate cementation levels. These values are

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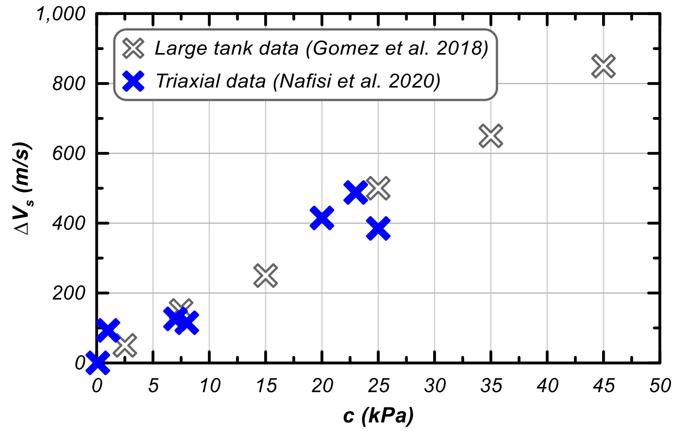

Fig. 4. Relationship between apparent cohesion and change in V_s due to the cementation using large-tank data from Gomez et al. (2018) and triaxial data from Nafisi et al. (2020).

reported in Table 6 of Nafisi et al. (2020). The cohesion for heavily cemented sands was not included in Fig. 4 of the original paper because heavily cemented sands are governed by fracture failure mechanisms and represent cementation levels that are beyond the paper's research scope. The linear failure envelope was used due to its simplicity in capturing the additional cohesion from the cementation while still conforming with the input needed to the Mohr-Coulomb constitutive model used in the cone penetration simulations. While Nafisi et al. (2020) reported the cohesion values from the direct interpretation of failure envelopes for biocemented sands under triaxial conditions, the cohesion values from the large tank experiment by Gomez et al. (2018) were estimated using the trend established from the triaxial results from Nafisi et al. (2020). The procedure is explained in detail in paragraph 5 of the "Soil Model Calibration" section and the writers do not have any additions to the provided explanation leading to Eq. (1) in the original paper. The writers do acknowledge the uncertainty in the current relationship due to the limited data available to develop the correlation (further giving evidence to the need of continued research).

Classification System for Cemented Sands

The discusser compared cohesion values in this paper with values from Clough et al. (1981), which were classified as weakly cemented sands, and noted a discrepancy in the results. The writers acknowledge that there is no consensus regarding the metrics for reporting levels of cementation and in classifying cemented soils. When portland cement was used as a cementing agent, the percent of cement added was the cementation metric and the classification was qualitative (e.g., weakly, lightly, moderately). This measure alone has limitations because the realized improvement level depends on both the quantity of cementation agent added and the spatial distribution of the agent within the soil matrix (i.e., the same level of cementation agent can produce a 5× difference in the increase in V_s or strength). However, with the advances in testing procedures, instrumentation size and accuracy, and cementing procedures, researchers have pushed for more precise measures of cementation using measurements of the achieved cementation (whether using shear wave velocity or percent calcite content) rather than the percent cement introduced at the start of the cementation phase/reaction. This practice made possible a quantitative classification of the final cemented soil. Therefore, a classification system for cemented sands on the basis of measurements after the achieved cementation is necessary for any further comparison.

The writers agree with the discusser that metrics to evaluate cementation level in sands should continue to be improved. The writers use previously established charts such as Fig. 8 in the paper under discussion to compare the results from the present study to previously established research. It should also be pointed out that the initial sample preparation, the type of cement and location of cementation bonds, the confining stress during the cementation phase and then the testing phase, and the fabric are all factors that affect the behavior of cemented sands even under the same qualitative classification. While additional testing and data are warranted for a universal classification system for cemented sands, this matter is beyond the scope of the original paper.

The additional topics of interest to the reviewer regarding the MICP technology and its application in the field as a viable ground improvement alternative are important and have been discussed by the paper writers (e.g., Montoya and DeJong 2015; Lee et al. 2022), as well as many other researchers elsewhere (e.g., Burbank et al. 2013; Simatupang et al. 2018). Several of these points were recently addressed in the DeJong et al. (2022) International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE) paper.

Conclusion

The writers thank the discusser for the engagement with the paper. The writers agree with the discusser that a classification system for cemented sands is needed before further comparisons of results can be made. Therefore, continued testing is essential in improving the understanding of cemented sands and quantifying the effect of different conditions on their behavior. In parallel, cone penetration testing coupled with geophysical testing and soil sampling for MICP-treated sites can be a basis for evaluating the changes in mechanical soil properties and the variability of these changes across a treatment zone.

Erratum

As noted in this closure, Fig. 4 contained incorrect source information. A corrected Fig. 4 is included herein to correct mislabeled data points and the legend to only reference the triaxial tests from Nafisi et al. (2020).

The description in the text under the "Soil Model Calibration" section should be corrected to reflect that the data included in Fig. 4 of the original paper corresponded to the reported results from Nafisi et al. (2020) and Gomez et al. (2018). The corrected sentence should read, "The data points with c and V_s measurements from triaxial test data on biocemented sands (Nafisi et al. 2020) were fitted with a linear relationship."

The paper from O'Donnell et al. (2017) should be removed from the list of references.

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