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Influence of size disparity on small-strain shear modulus of sand-fines mixtures

Xin Liu[a,*,1], Jun Yang[b]

[a] Department of Geology Engineering, Chang'an University, Xi'an, China
[b] Department of Civil Engineering, The University of Hong Kong, Hong Kong, China

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ABSTRACT

Characterizing the small-strain shear modulus (G_0) of sand with fines is of importance in geotechnical applications since natural sand is usually not clean but contains a certain amount of fines. This paper presents an experimental study to investigate G_0 values of several sand-fines mixtures, formed by mixing clean quartz sands of different sizes with crushed silica fines of varying quantity. Focus of the study is on the possible interplay between the influence of particle size disparity and the influence of fines contents for which current understanding is not adequate. By defining the particle size disparity as D_{50}/d_{50}, where D_{50} is the mean size of base sand and d_{50} is the mean size of fines, a critical range of size disparity is found to be approximately between 4 and 7. When the size disparity is smaller than 4, the role of fines is manifested mainly by fines content; when the size disparity is beyond 7, the contribution of fines to the load transfer gradually becomes negligible because in this case fine grains tend to roll into the voids. A new concept, referred to as combined size disparity, is proposed to capture the influence of fines content and the influence of size disparity in a collective manner. By adopting this concept, an empirical relationship is proposed for estimating G_0 values of sand-fines mixtures. The predictive performance of the relationship is then examined using literature data and a reasonably good agreement between prediction and measurement is obtained.

1. Introduction

Sand-fines mixtures are often gap-graded in the sense that grains within a certain range of size are missing in comparison with conventional granular soils of continuous grading. When studying the various behavior of sand-fines mixtures, the quantity of fines (i.e. fines content) is usually regarded as a key factor [1–3]. In recent years, there is a growing interest in the small-strain shear modulus (G_0) of sand-fines mixtures. (e.g., [4–8]). While a general trend has been found that the G_0 value decreases with fines content, the reduction is not always identical among different sand-fines mixtures. For instance, at similar void ratios, Salgado et al. [6] observed a reduction of G_0 value as much as 60% for Ottawa sand mixed with 15% of silica fines, whereas a much less reduction (~ 17%) was reported by Chien and Oh [4] for a reclaimed sandy soil with 20% fines content. Moreover, a recent finding from Yang and Liu [8] shows that the state dependence of G_0 of sand-fines mixtures can be characterized in a unified way for a range of fines content by using the concept of state parameter [9]. In the framework of critical state soil mechanics, the state parameter is a measure of soil state with reference to the critical state locus in the compression space. It is worth noting that the critical state locus of sand-fines mixtures depends not only on fines content but also on grain characteristics [10–12]. This leads to an important implication that the influence of fines on G_0 cannot be fully characterized by using fines content. The significant differences in the reduction of G_0 at a given fines content, as discussed above, are certainly attributed to factors other than fines content.

In this paper, we propose that the size disparity ratio, defined as the ratio between mean particle sizes of coarse and fine grains, is a major factor for the mechanical property of sand-fines mixtures. Experimental data yielded from a specifically designed testing program on the small-strain shear modulus of several different sand-fines mixtures are presented and analyzed. The aim of the study is to investigate the influence of size disparity along with the influence of fines content. Particular effort is made is to elucidate the possible coupling of these two factors on G_0.

* Corresponding author.
E-mail address: xliu67@chd.edu.cn (X. Liu).
[1] Formerly of The University of Hong Kong.

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Notation

A	coefficient in Eq. (2)
C_u	coefficient of uniformity
d_{50}	mean size of fine grain
D_{50}	mean size of coarse grain
D_{com}	combined particle size
e	void ratio
e_s	skeleton void ratio
e^*	equivalent granular void ratio
F_c	fines content
$F(e)$	void ratio function
G_0	small-strain shear modulus
n	stress exponent
P_a	reference stress
Γ_{com}	combined size disparity
σ'	mean effective stress

2. Experimental program

2.1. Test materials

Three quartz sands, namely Toyoura sand, Fujian sand C, and Fujian sand D, were used as the base sand in the laboratory tests. Table 1 gives the basic physical properties of each base sand, and the microscopy images of these sands are presented in Fig. 1. Clearly all three base sands were uniformly graded with sub-rounded grains. In this connection, the influence on G_0 due to the difference of particle grading [13] and particle shape [14] is considered insignificant in the present study. To produce a sequence of mixtures of being sand dominant, crushed silica fines (less than 63 μm) of varying percentage (0%, 5%, 10%) were added to each base sand. For simplicity abbreviations were adopted for each mixture in the analysis; for example, TSS stands for mixtures with Toyoura sand as the base sand and FSS-C stands for mixtures with Fujian sand C as the base sand. Fines content is given as a number inside parentheses; for example FSS-D(5) represents Fujian sand D mixed with 5% silica fines. It is worth noting that these base sands were chosen such that a set of gap-graded sands of nearly parallel grading with a range of particle size disparities were produced. To make this point clear, the particle size distribution curves of each test material are plotted in Fig. 2. It can be seen that the TSS mixtures exhibit the smallest particle size disparity whereas the FSS-D mixtures have the greatest size disparity.

2.2. Apparatus and test procedure

The small-strain shear modulus (G_0) was determined using a resonant column (RC) apparatus in the bottom-fixed and top-free configuration. The device can accommodate a cylindrical specimen of 50 mm in diameter and 100 mm in height, with an air-filled cell pressure up to 1 MPa. By applying acceleration through exciters mounted on the top of specimen, an overall response of the specimen can be recorded. An internal LVDT of high-resolution can measure the specimen's deformation with time. The strain level involved in all tests was found in the order of 10^{-5} or below. Readers may refer to Yang and Gu [15] for more details about the apparatus.

All specimens were prepared by the moist tamping method [16] in conjunction with the under-compaction technique (i.e., use 1% of under-compaction ratio) [17] and the global void ratio (e) was used as a target parameter. This method was chosen because it can produce a wide range of void ratios and has the advantage of preventing segregation of fine and coarse grains. All specimens were tested under saturated conditions. Carbon dioxide was used to circulate through the specimen, which was then followed by flushing the specimen with deaired water. To further increase the degree of saturation, back pressure saturation (i.e., 350 kPa) was applied and a B-value greater than 0.95 was ensured. Isotropic confining stress was applied in a stepwise manner on the same specimen, and when bringing the specimen to a specific effective stress level, consolidation of 30 min was adopted so that the reading of LVDT became stable and the volume change of the specimen was recorded. The testing series are listed in Table 2. For completeness, testing series of Toyoura sand mixtures can be found in Yang and Liu [8].

3. Test results and discussions

3.1. Effects of size disparity and fines content on G_0

In Fig. 3 the G_0 values of all base sands are compared. It is clear that void ratio and confining stress are two important factors affecting G_0. For a given confining stress G_0 increases with decreasing void ratio, whereas for a given void ratio G_0 decreases with deceasing confining stress. Under the same confining stress and the same void ratio, the three base sands exhibit similar G_0 values. Recalling that these base sands are of parallel grading (C_u = 1.4–1.5) with different mean particle size (D_{50}), the above observation indicates that mean particle size is not the main factor controlling G_0, in agreement with the finding of Yang and Gu [15] derived from laboratory experiments on glass beads.

In Fig. 4 measured G_0 values for gap-graded sands with fines content of 5% and 10% are plotted as a function of void ratio. It is interesting to note that, under otherwise similar conditions, the influence of fines content on G_0 is differing for different base sand. For example at e = 0.8 and σ' = 100 kPa, the G_0 value of TSS(5) is about 28% higher than that of FSS-C(5) and becomes one-fold greater than that of FSS-D(5). More pronounced distinction can be seen in Fig. 4(b) for specimens with higher fines content. While the differences between FSS-C(10) and FSS-D(10) appear to reduce, the G_0 values of TSS(10) remain markedly high despite having greater void ratios.

To remove the influence of void ratio (e), a common method was adopted by normalizing G_0 with a void ratio function as follows [18]. Note that a = 2.17 was adopted here based on the comprehensive investigation by Iwasaki and Tatsuoka [19].

$$F(e) = \frac{(a-e)^2}{1+e} \tag{1}$$

In Fig. 5 the void ratio corrected G_0 values are plotted as a function of effective stress (σ') that is also normalized by a reference stress (i.e., P_a = 98kPa). The stress dependence is evident from the plots and it can be described using Eq. (2). For each mixture, a high coefficient of determination was obtained (R^2 greater than 0.97).

$$\frac{G_0}{F(e)} = A\left(\frac{\sigma'}{P_a}\right)^n \tag{2}$$

It is worth noting that the void ratio corrected G_0 is the greatest for TSS mixture and is the smallest for FSS-D mixture. The data in Fig. 5

Table 1
Physical properties of tested materials.

Properties	Toyoura sand	Fujian sand-C	Fujian sand-D	Crushed Silica	Crushed glass bead
G_s	2.65	2.65	2.65	2.64	2.65
D_{10} (μm)	166	282	658	27.5	9.1
D_{50} (μm)	216	397	890	54	31.8
D_{60} (μm)	231	432	948	60	37.8
C_u	1.39	1.53	1.44	2.18	4.15