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Discrete element modeling of the effect of particle size distribution on the small strain stiffness of granular soils

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ABSTRACT

Discrete element modeling was used to investigate the effect of particle size distribution on the small strain shear stiffness of granular soils and explore the fundamental mechanism controlling this small strain shear stiffness at the particle level. The results indicate that the mean particle size has a negligible effect on the small strain shear modulus. The observed increase of the shear modulus with increasing particle size is caused by a scale effect. It is suggested that the ratio of sample size to the mean particle size should be larger than 11.5 to avoid this possible scale effect. At the same confining pressure and void ratio, the small strain shear modulus decreases as the coefficient of uniformity of the soil increases. The Poisson's ratio decreases with decreasing void ratio and increasing confining pressure instead of being constant as is commonly assumed. Microscopic analyses indicate that the small strain shear stiffness and Poisson's ratio depend uniquely on the soil's coordination number.

Introduction

The shear stiffness at small strain levels (i.e. below 0.001%) is a subject of both theoretical and practical interest. It plays an important role in many geotechnical problems such as deep excavations, machine foundations, and earthquake ground response analysis. Several techniques have been developed in the laboratory for measuring small strain shear stiffness including resonant column (Cascante, Santamarina, & Yassir, 1998; Clayton, Priest, & Best, 2005; Hardin & Richart, 1963), piezoelectric transducers (Brignoli, Gotti, & Stokoe, 1996; Greening & Nash, 2004; Gu, Yang, Huang, & Gao, 2015; Nakagawa, Soga, & Mitchell, 1997), and quasi-static loading with high resolution strain measurements (Ezaoui & Di Benedetto, 2009; Hoque & Tatsuoka, 1998; Kokusho, 1980). With these techniques, numerous studies have been carried out and the results show that small strain shear stiffness, G_0, mainly depends on the void ratio e (i.e. the ratio of the volume of the voids to the volume of the grains) and mean effective stress, σ'. The value of G_0 can be expressed by Eq. (1) (Hardin & Richart, 1963):

$$G_0 = AF(e)\left(\frac{\sigma'}{p_a}\right)^n, \quad (1)$$

where A is a constant reflecting soil type, grain properties, and soil microstructure, p_a is a reference stress, n is the stress exponent reflecting the effect of confining pressure, and $F(e)$ is a void ratio function with the typical form $F(e) = (2.17 - e)^2/(1 + e)$.

For granular soils, one main concern is the effect of soil type on small strain shear stiffness. Soil type is generally classified based on its particle size distribution (PSD) which is usually described by the mean particle size D_{50}, the coefficient of uniformity C_u ($C_u = D_{60}/D_{10}$), and the content of fine particles, FC. The FC content is defined as the weight percentage of particles less than 74 μm in diameter in the soil. D_{60}, D_{50}, and D_{10} stand for the particle sizes such that the mass of particles in the sample having sizes equal to and less than that particle sizes accounts for 60%, 50%, and 10%, respectively, of the total sample mass. Thus D_{50} is the average particle diameter on a mass basis. The following paragraphs review the literature on this subject.

Iwasaki and Tatsuoka (1977) performed extensive resonant column (RC) tests on a number of sands and showed that for clean and poorly graded sands ($C_u < 1.8$, $0.16\ \text{mm} \le D_{50} \le 3.2\ \text{mm}$), G_0 is independent of D_{50}, as shown in Fig. 1(a). Their studies also indicated that the effect of particle shape on G_0 is not significant. Wichtmann and Triantafyllidis (2009) reported similar results for sand with a different D_{50} range ($0.1\ \text{mm} \le D_{50} \le 6.0\ \text{mm}$) and $C_u = 1.5$. However, as shown in Fig. 1(b), Menq and Stokoe (2003) reported that G_0 increases as D_{50} increases, especially at low void ratios. Their study was based on results from resonant column tests on five uniform

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Nomenclature

e	Void ratio
$F(e)$	Void ratio function
G_0	Small strain shear stiffness
G_{13}	Shear modulus in DEM simulations
σ'	Mean effective stress
n	Stress exponent
C_u	Coefficient of uniformity
D_{50}	Mean particle size
μ	Inter-particle friction coefficient
υ	Poisson's ratio
ε	Axial strain
γ	Shear strain
P	Isotropic confining pressure
FC	Fine content
L	Side length of the cubic specimen
BE	Bender element
CN	Coordination number
DEM	Discrete element method
RC	Resonant column
PSD	Particle size distribution

sands and gravels (all C_u around 1.2, 0.33 mm ≤ D_{50} ≤ 17.4 mm) (Fig. 1(b)). Note that the largest D_{50} is 17.4 mm and the ratio of sample diameter (150 mm) to the D_{50} is around 8.6, a much smaller diameter to D_{50} ratio than those reported by other studies. Using a bender–extender element (BE), Sharifipour, Dano, and Hicher (2004) indicated that G_0 (or shear wave velocity) of glass beads 0.5–3.0 mm in size increased with increasing particle size. In contrast, Patel, Bartake, and Singh (2009) reported that G_0 decreased as the mean particle size of glass beads, nominally 1.0, 2.0, and 3.0 mm in size, increased in the BE tests. Yang and Gu (2013) performed both RC and BE tests on a single set of samples of glass beads (D_{50} = 0.195, 0.92, and 1.75 mm) and found that, in general, G_0 was independent of D_{50}. Rollins, Evans, Diehl, and Daily (1998) showed that G_0 increased with the gravel content or the mean particle size. However, this increase may be caused by the soil C_u decreasing as the gravel content increased (G_0 decreased as C_u increased) (Iwasaki & Tatsuoka, 1977; Wichtmann & Triantafylidis, 2009). Table 1 summarizes some of the literature on the effect of particle size on G_0. It is clear that no uncontested conclusion can be made about the effect of mean particle size on G_0. The disagreements about the effect of particle size on the G_0 may be caused by differences in grain properties, scale effects due to the specific specimens used, soil microstructure, or other factors. However, these factors cannot be isolated or analyzed in the laboratory.

Iwasaki and Tatsuoka (1977) also showed that at the same void ratio and confining pressure, the G_0 of sands gradually decreases by 25% as the coefficient of uniformity, C_u, increases from around 1.5 to 5.0. They also indicated that the G_0 of sands decreases significantly as the fine content, FC, increases. Wichtmann and Triantafyllidis (2009) carried out a comprehensive set of RC test on the effect of

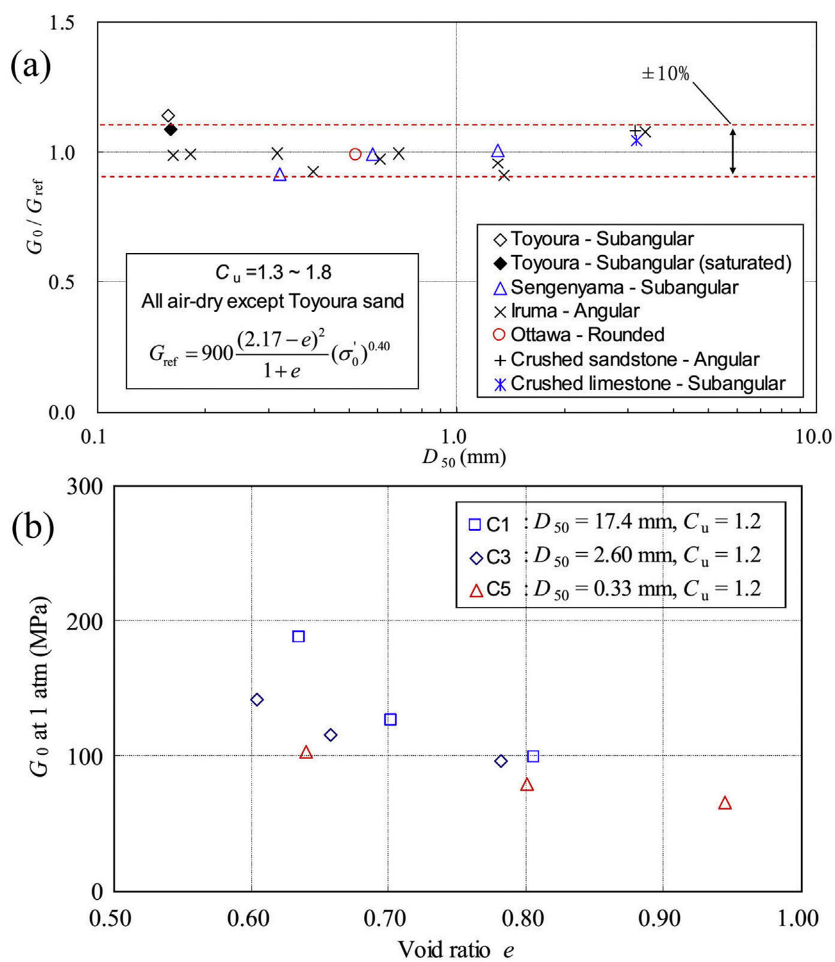

Fig 1. (a) Graph showing the independence of small strain shear stiffness (G_0) on D_{50} (adapted from Iwasaki & Tatsuoka, 1977), (b) G_0 plotted against void ratio (e) for three values of D_{50} (adapted from Menq & Stokoe, 2003).

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