Soils and Foundations 2015;55(5):1196–1210

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Soils and Foundations

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# Dynamics of potential fill–backfill material at very small strains

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Received 24 September 2014; received in revised form 21 April 2015; accepted 22 May 2015
Available online 26 September 2015

## Abstract

The paper presents a synthesis of past and recently acquired laboratory test results on granular soils using wave propagation techniques at very small strain amplitudes. Resonant column tests on uniform to well-graded coarse sands and gravels of angular and low sphericity grains were analyzed. Empirical-type equations were developed for the prediction of the elastic modulus and material damping at small strains considering the effects of the grading characteristics, the isotropic effective stress and the void ratio. The $G_0$–$p'$ relationship, expressed through exponent $n_G$, was affected by the sample preparation method. For the narrow range in relatively low pressures adopted in the study, it was observed that $n_G$ decreased slightly with an increase in relative density. Due to the limited initial void ratios of those tests, the effect of the preparation method was not incorporated into the proposed formulae for the $n_G$ prediction. In this direction, additional experiments from the literature, which adopted the resonant column and bender element methods, were further analyzed, including soils of variable types tested with a wider range in relative densities. By employing typical formulae from the theory of elasticity, the bulk modulus and the changes in void ratio were estimated based on the change in isotropic effective stress in the literature data. Considering the recent micromechanical experimental findings associated with the nature of the contact response of soil particles, the importance of soil type and particle-contact behavior in the constant-state response of soils was demonstrated and quantified. Material damping values ranged from about 1.10% to about 0.45% for $p'$ from 25 to 200 kPa with a slight decrease in $D_{s0}$ with an increase in pressure.

*Keywords:* Resonant column; Bender elements; Dry sand; Shear modulus; Damping ratio; Elastic properties

## 1. Introduction

The resonant column method provides reliable measurements of modulus and damping at very small to medium strains, within a range of about $10^{-4}$–$10^{-2}$%. Modulus derivations refer to secant stiffness and can provide an excellent indication of fabric effects. Constant-state stiffness and material damping are pressure-dependent and the $G_0$–$p'$ and $D_{s0}$–$p'$ relationships are expressed through Eqs. (1) and (2), where $G_0$ and $D_{s0}$ are the small-strain shear modulus and the material damping, respectively, and $p'$ is the isotropic effective stress. The power $n_G$ and $n_D$ in these formulae express the effect of $p'$ in the constant-state properties of soils, whilst $A_G$ and $A_D$ are material-dependent constants (Santamarina and Cascante, 1998; Santamarina et al., 2001). With reference to dry granular soils, material damping at very small strains is not affected significantly by the loading frequency (Menq, 2003); and thus, derivations for energy losses may also be considered in the resonant column method without any considerable effect of viscous damping on dry sands or gravels.

$$G_0 = A_G \times (p')^{n_G} \tag{1}$$

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2015.09.019
0038-0806/

$$D_{s0} = A_D \times (p')^{n_D} \quad (2)$$

Past and recently acquired research works have demonstrated that resonant column test results may also provide useful information related to the effect of properties at the grain scale on the macro-scale response of soils and a better understanding of the dominant mechanisms in particulate media during cyclic/dynamic loading (e.g., Santamarina and Cascante, 1996, 1998; Cascante and Santamarina, 1996; Senetakis et al., 2013a, 2013b). This is because the resonant column method provides an indication of the fabric effects even in the range of extremely small deformations (e.g., Cascante and Santamarina, 1996), and these fabric effects, from a micromechanical point of view, are linked to the magnitude and the distribution of the contact forces (e.g., Radjai and Wolf, 1998) and the probable preferable concentration of normals in the vertical direction within a granular assembly of particles (e.g., Yoshimine et al., 1998). For example, it has been shown through resonant column tests that due to the plastic nature of the particle contact response, which is more dominant in the sliding direction (e.g., micromechanical experimental findings by Cole and Peters, 2007, 2008, Cole et al., 2010, and Senetakis et al., 2013c), the $G_0$–$p'$ relationship cannot be described efficiently by the Hertz–Mindlin theory. This theory could predict a value for the exponent $n_G$ equal to 1/3 (Santamarina and Cascante, 1996), which represents more effectively particulate media with an elastic particle-contact response in nature. However, higher values for $n_G$ have been determined through resonant column tests or derived from other wave propagation techniques, such as the bender element method or cyclic-dynamic triaxial tests (e.g., Hardin and Richart, 1963, Hardin, 1978, Kokusho, 1980, Chung et al., 1984, Tanaka et al., 1987, Goto et al., 1987, Menq, 2003, Cho et al., 2006, Senetakis et al., 2012 among others). This is because of the visco-plastic to brittle nature of the contact response of soil particles (Cascante and Santamarina, 1996).

Through wave propagation experiments, Cho et al. (2006) found a significant effect of particle shape in the $G_0$–$p'$ relationship. They attributed their observations to the possible effect of the particle contact response which alters between irregular and regular in shape particles, perhaps because of the more pronounced grain crushing or micro-crushing and overall changes in bulk volume when more irregularly shaped particles are considered than regularly shaped particles. Through one-dimensional compression tests on reference particles, Cavarretta et al. (2010) verified the significant effect of particle shape in the overall compression-pressure relationship which, in turn, affects the fabric, and thus, the stiffness of geo-materials. In this direction, Senetakis et al. (2012), who studied the small-strain dynamic properties of fine- to medium-grained sands, reported a significant effect of particle shape on the constants $n_G$ and $A_G$.

Menq (2003) and Menq and Stokoe (2003) noticed in their resonant column experiments a dominant effect of the coefficient of uniformity in the $G_0$–$p'$ relationship. This trend has been correlated, partly, through numerical simulations and quantification of the grain size distribution effects on isotropically consolidated granular assemblies, to the distribution and magnitude of the particle contact forces (e.g., Radjai and Wolf, 1998, Radjai et al., 1998). Recently, Senetakis et al. (2012, 2013a) highlighted the importance of particle type and morphology in the $G_0$–$p'$ relationship. Senetakis et al. attributed their observations primarily to the possibly more pronounced damage of surface roughness because of the coupled normal force – deflection and tangential force – deflection responses at particle contacts. These derivations were based on the recent quantification of particle damage by Senetakis et al. (2013c) and measurements of friction and stiffness at particle contacts by Senetakis et al. (2013c, 2013d) and Senetakis and Coop (2014, 2015) on reference strong particles of a quartz sand and reference weak particles of a biogenic crushable sand. For example, Fig. 1 presents the coupled effect of normal load and tangential load – deflection responses at the contacts of two quartz particles before and after sliding tests by Senetakis et al. (2013c). In this figure, a cross-section of a quartz particle is shown within the area of contact and sliding on the surface of another similar particle before and after micromechanical sliding tests. They quantified the damage of the surface roughness using white light interferometry. As demonstrated in the figure, the coupled effect of the normal force and sliding significantly reduced the magnitude of surface roughness

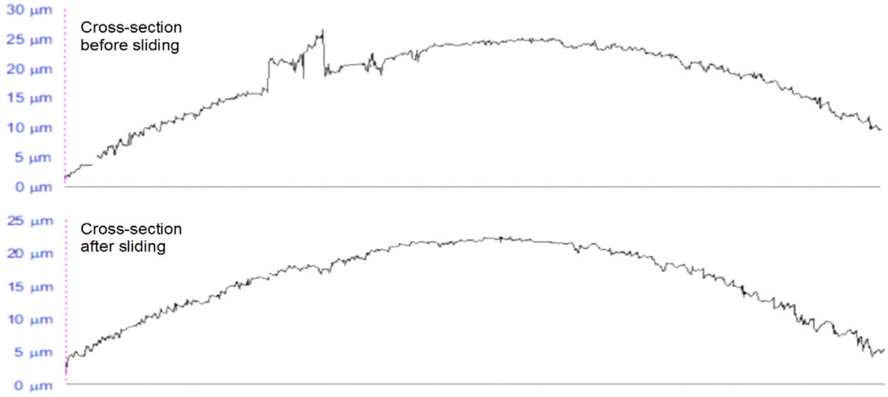

Fig. 1. Quantification of surface roughness damage due to shearing between two quartz particles: interferometer section before and after shearing (Senetakis et al., 2013c) – Horizontal size is 141.5 µm.