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Experimental and DEM assessment of the stress-dependency of surface roughness effects on shear modulus

Masahide Otsubo [a,*], Catherine O'Sullivan [b]

[a] *Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[b] *Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK*

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Abstract

This contribution assesses the effect of particle surface roughness on the shear wave velocity (V_S) and the small-strain stiffness (G_0) of soils using both laboratory shear plate dynamic tests and discrete element method (DEM) analyses. Roughness is both controlled and quantified to develop a more comprehensive understanding than was achieved in prior contributions that involved binary comparisons of rough and smooth particles. Glass beads were tested to isolate surface roughness effects from other shape effects. V_S and G_0 were accurately determined using a new design configuration of piezo-ceramic shear plates. Both the experimental and the DEM results show that increasing surface roughness reduces G_0 particularly at low stress levels; however, the effect is less marked at high pressures. For the roughest particles, the Hertzian theory does not describe the contact behaviour even at high pressures; this contributes to the fact that the exponent in the G_0 – mean effective stress relationship exceeds 0.33 for sand particles. Particle-scale analyses show that the pressure-dependency of the surface roughness effects on G_0 can be interpreted using roughness index α which enables the extent of the reduction in G_0 due to surface roughness to be estimated.

Keywords: Laboratory tests; Discrete element method; Small-strain stiffness; Roughness; Dynamics; Piezo-ceramic transducer

1. Introduction

Soils are granular materials consisting of many particles, and the overall response of a soil can be considered to be a complex accumulation of the inter-particle responses. The inter-particle responses can be directly affected by particle characteristics including surface roughness; however, our understanding of the link is incomplete.

Accurate knowledge of soil stiffness is important for predicting ground deformation during construction as it directly relates the applied stress to the strain, and hence, the displacement of the ground (Atkinson, 2000; Clayton, 2011). It is well known that small-strain shear modulus G_0 is influenced by effective confining pressure p' and void ratio e, and is often expressed as $G_0 = AF(e)p'^n$ where A and n are material constants and $F(e)$ is a void ratio function for G_0. The material constant, n, that describes the stress-dependency of the soil is often approximated to be 0.5 for sands. From a micromechanical perspective, n is related directly to the response at the grain contacts, and n can be influenced by the presence of surface asperities (Goddard, 1990; Yimsiri and Soga, 2000).

Experimental assessments of the surface roughness effects on G_0 have rarely been reported in the literature, most likely due to limitations associated with accurately measuring and controlling surface roughness. Santamarina and Cascante (1998), Sharifipour and

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* Corresponding author.
E-mail addresses: otsubo@iis.u-tokyo.ac.jp (M. Otsubo), cath.osullivan@imperial.ac.uk (C. O'Sullivan).

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Dano (2006) and Otsubo et al. (2015) observed a reduced shear wave velocity (V_S), and thus, G_0, for roughened spherical materials. The sensitivity of the overall behaviour to the degree of roughness was not ascertained as in each case only one level of roughness was compared with a smooth reference case.

Discrete element method (DEM) studies enable a systematic investigation of the surface roughness effects. Cavarretta et al. (2010) developed a rough contact model based on their particle-scale compression tests. This model, whose input parameters include both surface roughness and hardness, was implemented in a DEM code by O'Donovan et al. (2015). Developing these ideas, and drawing on fundamental tribology research, Otsubo et al. (2017) proposed an alternative contact model that does not include hardness as a model parameter.

Surface topographies of sand grains can now be measured accurately using white light interferometry (e.g., Cavarretta et al., 2010; Altuhafi and Coop, 2011). In this contribution, the surface roughness of spherical particles was systematically varied and measured to advance understanding of how the degree of roughness influences the overall behaviour of soils. Glass beads (ballotini) with four surface roughness values were tested in this study. While the use of ballotini limits the direct and quantitative application of the findings to real soils with angular grains, a fundamental understanding of the effect of surface roughness on G_0 can be developed. Following Brignoli et al. (1996), piezo-ceramic shear plates were used to measure V_S. Equivalent DEM simulations were performed to provide additional insight into the particle-scale response.

2. Experimental procedure

2.1. Test materials

The borosilicate glass ballotini used in the laboratory experiments had a mean particle diameter of $\bar{D} = 1.2$ mm ($1 \leqslant D \leqslant 1.4$ mm) (Table 1). The as-supplied smooth ballotini (Fig. 1(a)) were processed to increase the surface roughness by milling 30 g of the ballotini and 15 g of Toyoura sand (as-supplied) in a glass jar for 0.5, 5 and 25 h, as detailed in Cavarretta et al. (2012), and then separating them using a sieve with 0.85-mm openings. Representative microscopic images and surface topographies of the roughened ballotini are illustrated in Fig. 1. The root mean square (RMS) surface roughness S_q, skewness S_{sk} and kurtosis S_{ku} values were measured using a Fogale Microsurf 3D optical interferometer and quantified as follows:

$$S_q = \sqrt{\frac{1}{m}\sum_{i=1}^{m} Z_i^2} \tag{1a}$$

$$S_{sk} = \frac{1}{m\ S_q^3}\sum_{i=1}^{m} Z_i^3 \tag{1b}$$

$$S_{ku} = \frac{1}{m\ S_q^4}\sum_{i=1}^{m} Z_i^4 \tag{1c}$$

where m = number of discrete data points and Z_i = elevation relative to the reference surface. The measurement area was a square with a side length of 70 μm. Even considering this small area, the reference surface was not planar, necessitating the removal of the curvature effects (Otsubo et al., 2014). Yang et al. (2016) proposed the use of a fractal dimension to characterise the surface roughness; however, here the motif analysis algorithm implemented in the Fogale 3D Viewer software (Fogale, 2005) was used to remove the curvature effects adopting a shape motif size of 17.5 μm. The surface roughness values are the average of 40 measurements taken for each type of particle. In each case, 10 particles were considered and the measurements were taken at four different locations on each particle. The variations in the measured surface roughness parameters (relative to their mean values) are illustrated in Fig. 2 and Table 2 considering both the flattened and the non-flattened (as-measured) data. The S_q values given in the legend are the nominal (average) values for that sample set. The scatter in the S_q data is the greatest for the roughest samples; however, S_{sk} and S_{ku} exhibit considerable scatter for the smoother samples in particular. Measurable differences are observed in S_q, and S_q is used as a representative roughness parameter in the current study. The shapes of the ballotini before and after milling for 25 h were quantified using a Qicpic image analysis sensor (Witt et al., 2004; Altuhafi and Coop, 2011), and both cases showed sphericity = 0.94, aspect ratio = 0.96 and convexity = 0.99, indicating that the overall shape was not affected by the milling process.

The minimum and maximum void ratios (e_{min} and e_{max}) for each mean surface roughness value were measured following the JGS standard (JGS 0161, 2009), as given in Table 1 and Fig. 3. As the maximum particle diameter

Table 1
Experimental cases.

Test case	$\bar{D}$ mm	$\overline{S_q}$ nm	$\overline{S_q}/\bar{R}$	L_0* mm	e_0*	e_{min}	e_{max}
Lab-1	1.2	58	9.67×10^{-5}	111.4	0.606	0.524	0.626
Lab-2		127	2.12×10^{-4}	111.2	0.599	0.564	0.681
Lab-3		267	4.45×10^{-4}	112.4	0.599	0.575	0.691
Lab-4		586	9.77×10^{-4}	111.8	0.595	0.577	0.704

* L_0 and e_0 data were obtained at $p' = 30$ kPa.

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