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Short communication

A grading parameter for evaluating the grading-dependence of the shear stiffness of granular aggregates

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ABSTRACT

To capture the grading-dependence of the shear stiffness of heterogeneous granular aggregates, a new grading parameter that considered the size distribution of the entire aggregates was developed. Both the coefficient of uniformity and median particle size decreased with increasing the grading parameter. A general increase of the shear stiffness with increasing the grading parameter was observed. Comparison with experimental results revealed that the proposed grading parameter had a stronger correlation with the material constants of Hardin's stiffness formula than the coefficient of uniformity, which is a traditional grading parameter.

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Introduction

Granular aggregates are highly heterogeneous materials that consist of particles and voids. The small-strain shear stiffness (G_0) of granular aggregates is usually complex and grading-dependent. A number of studies have been conducted to determine the dependence of the shear stiffness of different granular aggregates on material grading (Bartake & Singh, 2007; Iwasaki & Tatsuoka, 1977; Payan, Senetakis, Khoshghalb, & Khalili, 2017; Suits, Sheahan, Patel, Bartake, & Singh, 2009; Wichtmann & Triantafyllidis, 2009, 2014; Yang & Gu, 2013). The gradation is typically represented by the coefficient of uniformity (C_u) and median particle size (d_{50}) (Enomoto, 2016; Payan, Khoshghalb, Senetakis, & Khalili, 2016). A decrease of G_0 with an increase in C_u has generally been observed. However, the influence of d_{50} on G_0 has not been determined conclusively. A decrease of G_0 with increasing particle size was found in quartz sand (Suits et al., 2009) and glass beads (Bartake & Singh, 2007), while an increase of G_0 with increasing particle size was observed in gravelly soils (Hardin & Kalinski, 2005). Moreover, a G_0 independent of particle size was reported by Yang and Gu (2013). Therefore, expressions for the shear stiffness of soils with varying gradations typically incorporate the effect of C_u (Enomoto, 2016; Payan et al., 2016; Wichtmann & Triantafyllidis, 2009). For instance, Payan et al. (2016) modified the well-known Hardin's formula (Hardin & Richart, 1963) by taking into account the effect of C_u. Menq (2003) suggested the use of both C_u and d_{50} when calculating the shear stiffness. Nevertheless, neither C_u nor d_{50} can fully characterise the grade without other parameters such as the minimum (d_m) and maximum (d_M) particle sizes and the coefficient of curvature (C_c). Therefore, in this study, a new grading parameter (C_g) that considers the whole shape of the material grading by modifying the parallel-column model proposed by Liang and Li (2014) at small strain ($<10^{-3}$) was developed. The proposed parameter was validated with the results from resonant column tests of quartz sands with different grades (Wichtmann & Triantafyllidis, 2009). Comparisons between C_g, C_u, d_{50}, and the corresponding test results were made, and correlations between C_g, C_u, and their corresponding material constants from Hardin's formula for calculating the shear stiffness were also analysed.

A new grading parameter

The varied interaction of the discrete particles in a column causes different resilient responses of aggregates with different particle size distributions (PSDs). Following Liang and Li (2014), stress at small strain was considered to propagate through the column-like force chains formed by the discrete particles within a representative cubic element. The elastic modulus (E_0) of the parallel-column was the sum of all particle columns in the array. Each particle column consisted of N particles with random sizes (d_i) from bottom to top, where the size indicates the aggregate diam-

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eter according to ASTM C136 (2006). Therefore, the height of the column is formulated as (Liang & Li, 2014):

$$L = \sum_{i=1}^{N} d_i. \tag{1}$$

As the number of particles is large for a given element, Eq. (1) is expressed in an integral form by using the sample grading as:

$$L = \int_{d_m}^{d_M} N d f(d) \delta d, \tag{2}$$

where $f(d)$ is the density distribution function of the current particle size (d), and the subscripts m and M denote the minimum and maximum aggregate sizes in the element, respectively. The number of particle columns in a cubic element is given by:

$$m \approx \frac{D^2}{(1+e)\int_{d_m}^{d_M} \frac{\pi d^2}{4} f(d)\delta d}, \tag{3}$$

where e and D are the void ratio and size of the cubic element, respectively. Assuming a compressive loading condition, resilient deformation is attributed to the movement of particles in the stress-carrying column. The overall compressive displacement (U) of the column caused by the external normal force Δ can be regarded as the sum of the normal displacements ($u^n_{i-1,i}$) of all the particle columns in series:

$$U = \sum_{i=2}^{N} u^n_{i-1,i}. \tag{4}$$

Note that the vertical displacement U was assumed to be the same for all the parallel particle columns. By using the elastic law of deformation, Eq. (4) can be rewritten as:

$$\frac{\Delta}{K} = \sum_{i=2}^{N} \frac{f^n_{i-1,i}}{k^n_{i-1,i}}, \tag{5}$$

where K is the stiffness of the overall particle column, and $f^n_{i-1,i}$ denotes the contact force between two interacting particles, which is the same at each contact point, i.e., $\Delta = f^n_{i-1,i} (i = 2, 3, \ldots, N)$. A linear contact force model was used to model the normal contact stiffness ($k^n_{i-1,i}$) between two adjacent particles (i.e., particles denoted by i–1 and i),

$$\frac{1}{k^n_{i-1,i}} = \frac{1}{E}\left(\frac{1}{d_{i-1}} + \frac{1}{d_i}\right), \tag{6}$$

where d_i denotes the particle size, $E = \lambda(\sigma/p_a)^{\vartheta}$ is the pressure-dependent characteristic modulus of the material, σ is the applied stress, λ and ϑ are model parameters, and p_a is the atmospheric pressure for normalisation. Therefore, Eq. (6) can be rewritten as:

$$\frac{1}{K} = \frac{1}{E}\left(\sum_{i=1}^{N-1}\frac{1}{d_i} + \sum_{i=2}^{N}\frac{1}{d_i}\right). \tag{7}$$

When the number of aggregates in a representative element is large enough, Eq. (7) can be approximately formulated in an integral form over diameter d by combining with Eq. (2):

$$K = \frac{E}{2L}\frac{\int_{d_m}^{d_M} d f(d)\delta d}{\int_{d_m}^{d_M} d^{-1} f(d)\delta d}. \tag{8}$$

Therefore, the overall contact stiffness can be obtained by summing the contact stiffness of all the parallel particle columns, that is

$$K_t = mK = \frac{2ED^2}{L(1+e)}\frac{\langle d\rangle}{\langle d^2\rangle\langle d^{-1}\rangle}, \tag{9}$$

where

$$\langle d\rangle = \int_{d_m}^{d_M} d f(d)\delta d, \tag{10}$$

$$\langle d^2\rangle = \int_{d_m}^{d_M} d^2 f(d)\delta d, \tag{11}$$

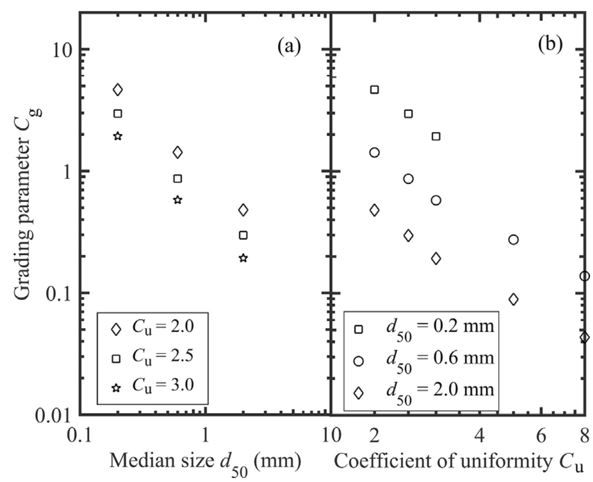

Fig. 1. Correlations between C_g, C_u, and d_{50} (data sourced from Wichtmann & Triantafyllidis, 2009).

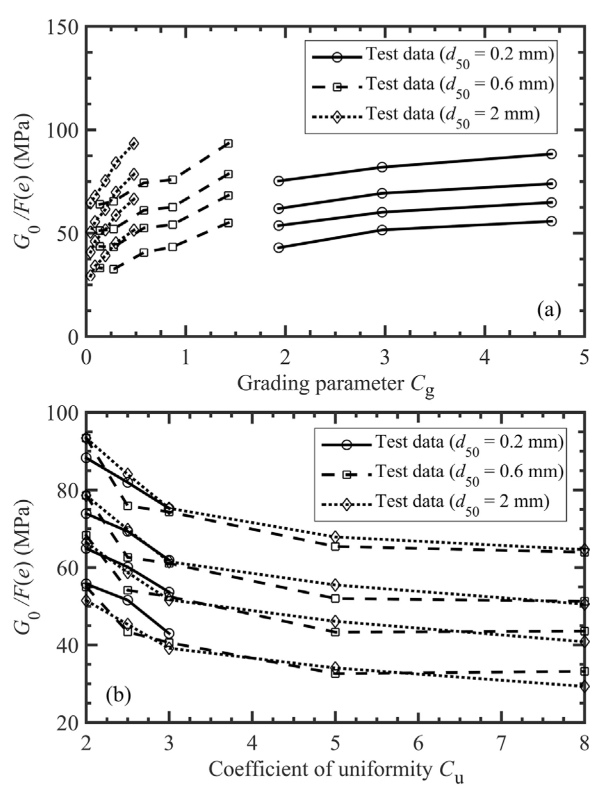

Fig. 2. Variation of $G_0/F(e)$ with (a) C_g and (b) C_u at different d_{50} (data sourced from Wichtmann & Triantafyllidis, 2009).

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