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Small-strain shear modulus of calcareous sand and its dependence on particle characteristics and gradation

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ABSTRACT

The soil small-strain shear modulus, G_0, is necessary for static and dynamic soil analyses and is often correlated to other soil properties such as density and void ratio, on their turn depending on gradation. The paper first presents a concise literature review of parameters influencing G_0 in detail. Secondly, a particle shape analysis is performed. Silica sand is found much more spherical than calcareous sand, and calcareous sand becomes more spherical after crushing. Bender element test results indicate that not only uniformity coefficient (C_u) but also particle characteristics including particle shape and stiffness are very important to G_0. G_0 of calcareous sand is found higher than that of silica sand. Indeed, with less sphericity and more angularity, the variety of particle shape in calcareous sand produces a better fabric for shear wave propagation. For calcareous sand, the test results show that particle shape is the main factor affecting G_0. Less dynamic stiffness is found for particles owning more sphericity and less angularity. The increase of C_u or finer particles (at low C_u) causes a decrease in G_0. Finally, predictions of G_0 for the tested calcareous sands using empirical equations from previous studies give very high relative errors (16.7–30%).

1. Introduction

Calcareous sand is an essential part of construction material in coastal structures worldwide. Its skeleton is formed from marine shells and other marine organisms (belemnite, corals, mollusks, etc.). The skeletal particles of calcareous sand vary complicatedly in their size, shape and ability.

The shear modulus, G_0 or G_{max}, at small strain amplitude, which is typically 0.0001% or less, is considered one of the basic soil parameters. This shear modulus is determined from shear wave velocity (V_s), which is measured directly in-situ or in the laboratory ($V_s = \sqrt{G_{max}/\rho}$). In the laboratory, the deformation shear modulus is founded by wave propagation velocity measurements or the very precise laboratory measurement of stress and strain in soil samples [1].

Other than the resonant column method (RC), the bender element method (BE) developed is used to obtain G_0 by measuring the velocity of the shear wave propagating through the sample. For saturated soils, the influence of frequency excitation on shear wave velocity was first studied by Biot [2]. He assumed that G_0 was constant with frequency while shear wave velocity was dependent on frequency that caused dispersion of a shear wave in saturated condition. Based on Biot's theory, for BE tests Youn et al. [3] and Gu et al.[4] suggested that the effective density accounting for the wave dispersion effect should be considered to convert the measured shear wave velocity into G_0, otherwise the G_0 of the sand may be overestimated using the saturated density. They indicated that the effective density involved in the shear wave propagation was less than the saturated density due to the relative movement between the solid and the fluid phases. However, Youn et al. [3] found this finding based on the values of G_0 obtained by torsional shear tests (static measurements) on Toyoura and silica sands that can cause the decrease in density due possibly to different strain level in the BE tests lower than that in the torsional shear tests. Indeed, Builes & Riveros [5] reported that the consistency of the G_0 values measured from between tri-axial tests (static measurements) and resonant column or bender element tests (dynamic measurements) depended on soil grading and particle size. They stated that the difference between statically and dynamically measured shear moduli was smaller on fine uniform sands compared to that on well- graded sands having large

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Table 1
Summary of previous empirical equations for estimating G_0.

Author	Applicable materials	Empirical equation of G_0	Findings
Hardin and Richard [1963]	Clean sand (round and angular silica sand- Ottawa sand, e = 0.65–0.86)	$$G_0 = A^*\frac{(a-e)^2}{(1+e)}{}^*p'^{n} \quad (2)$$ a = 2.17 for round grain a = 2.79 for angular grain	• Change in A and a caused by a difference in particle shape that affects the void ratio • n = 0.5
Iwasaki and Tatsuoka [1977]	Clean sands (C_u < 1.8), natural sands, artificial sands (e = 0.55–0.86)	$$G_0 = A(\gamma)\,B\,\frac{(2.17-e)^2}{(1+e)}{}^*p'^{n(\gamma)} \quad (3)$$ B = 1: clean sands B < 1: natural sands, artificial sands	• The difference in A and n caused by a difference in shear strain, γ. • The increase in C_u or F_c causes the decrease in B-value leading to the decrease in G_0.
Santos and Correia [2000]	Clay, peat, clayed sand, clean sand, bentonite, crushed rock, gravel	$$G_0 = 4000\ e^{-1.3}p'^{0.5}\ (\text{lower bound}) \quad (4)$$ $$G_0 = 8000\ e^{-1.1}p'^{0.5}\ (\text{upper bound}) \quad (5)$$	• Effect of void ratio on G_0 is based on $F(e) = e^{-B}$ (proposed by Lo-Presti [41]).
Menq and Stokoe [2003]	Gravel (e = 0.6–0.96)	$$G_0 = A^*p^n \quad (6)$$ n: 0.40 − 0.75	• G_0 increases with increasing D_{50}. • n increases with increasing C_u. • Larger effect on G_0 for loose and well graded granular materials than for dense and uniform materials.
Hardin and Kalinski [2005]	Clean sand, gravel (e = 0.33–0.78)	$$G_0 = A^*OCR^{k*}S^*F(p)^*F(e)^*F(D) \quad (7)$$ F(D) = 1 for sands, silts, and clays	• G_0 increases with increasing D_{50}.
Wichtmann and Triantafyllidis [2009]	Sand, gravel (Quartz sand with sub-angular grain shape, e = 0.39–0.92)	$$G_0 = A^*\frac{(a-e)^2}{(1+e)}{}^*\left(\frac{p'}{p_a}\right)^n \quad (8)$$ $A'(C_u) = c_5 + c_6{}^*C_u{}^{c_7}$. $n'(C_u) = c_3{}^*C_u{}^{c_4}$. $a'(C_u) = c_1{}^*e^{(-c_2C_u)}$	• $F(p) = (\frac{p'}{p_a})^n$ proposed by Roesler [42]. • D_{50} does not influence G_0. • The increase in C_u causes a decrease of G_0.
Oztoprak and Bolton [2013]	Clay, silt, silica sand, calcareous sand, gravel (e = 0.1–1.15)	$$G_{secant} = \frac{A(\gamma)^*p_a}{(1+e)^3}\left(\frac{p'}{p_a}\right)^{n(\gamma)} \quad (9)$$ at $\gamma = 0.0001\% \rightarrow G_{secant} = G_0$ A = 5760, n = 0.49	• Correlation is based on a laboratory database of 379 tests.

particles. Also, Wicaksono and Kuwano [6] found scattered values by plotting G_0 values using bender element tests (from 23 institutions of 11 countries) compared to the values conducted by tri-axial compression and torsional shear tests. Due to the effect of particle shape on tortuosity factor (α),Youn et al.[3] and Gu et al.[4] admitted that the proposed equation of Biot density should be applied for silica clean sands. Moreover, the shear wave velocities of Toyoura sand measured by BE tests were lower than those obtained by RC tests [7,8]. This finding is in contrast to the studies of Youn et al. [3] and Gu et al. [4]. Generally, the laboratory experiments indicate that the bender element measurements of G_0 are comparable to the corresponding resonant column measurement [9,10] with differences of less than 10% [11]. This method has generated intensive studies from many researchers in the past [12–14]. By monitoring the density of the specimen during testing and measuring the travel time, shear wave velocity V_s and hence G_0 can be obtained by the formula above.

The most common empirical formulas for the relationships proposed in the literature are shown as in Table 1, where material constants are determined by statistical regression of a laboratory data set. Originally, the difference in G_0 was explained by Hardin and Richart [15]. They investigated the effect of particle shape on G_0 between round and angular Ottawa sands based on the results of resonant column tests. Hence, their two empirical equations for estimating G_0 at a small shear strain of 10^{-4} or less have become popular both in design applications and in research (Eq. (2) in Table 1). Their results showed that a difference in void ratio causes the increase or the decrease in G_0. They found that the grain shape affects V_s through void ratio (e). Indeed, the void ratio of the crushed quartz sand (extremely angular particles) was found to be larger than that of Ottawa sand (round grains) giving lower V_s in the angular material. They concluded that there is no effect of particle shape on V_s if the void ratio is the same for both materials. To extend the study of Hardin and Richart, Iwasaki and Tatsuoka [16] proposed similar empirical equations for estimating shear moduli irrespective of grain shape and grain size. The B-value, a multiplying factor to be used with the function of void ratio shown in Eq. (3) (see Table 1), was proposed to calculate the average value of G_0. In their assumption, the shear moduli of clean sands with the range of mean particle size (D_{50}) from 0.16 mm to 3.2 mm were not related to the grain size. An increase in uniformity coefficient, C_u, (or fines content F_c) caused the decrease in B-value leading to the decrease in G_0. In 2000, Santos and Correia [17] proposed two unified curves representing the lower and upper boundary values of G_0 obtained by regressing the data from