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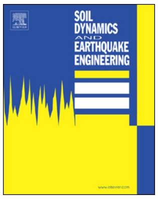

Small and intermediate strain properties of sands containing fines

Meisam Goudarzy*, Diethard König, Tom Schanz†

Chair of Foundation Engineering, Soil and Rock Mechanics, Ruhr-Universität Bochum, Germany

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ABSTRACT

The goal of this paper is to find the influence of fines content, f_c, on the fitting parameters of Hardin's relationship to predict shear modulus and damping ratio at small and intermediate shear strain ($G(\gamma)$ and $\eta(\gamma)$). Therefore, a series of resonant column tests were conducted on dry Hostun sand mixed with 0, 5, 10, 20, 30 and 40 % of fines content. Tests were carried out using the resonant column device at Ruhr- Universität Bochum. Experimental data on the adopted material revealed that maximum shear modulus decreases with an increase in f_c. Analysis of data showed that fitting parameters of Hardin's relationship must be correlated to f_c. In addition, experimental results for an intermediate strain region revealed the significant effect of f_c on damping ratio and shear modulus. The results showed that damping ratio increased with fines content up to $f_c = 20$ % and then decreases with further increase of f_c. Reference shear strain is a key parameter to describe nonlinear behavior of soils and damping ratio. The analyses of results showed that the reference shear strain decreased with f_c up to $f_c = 20$ % and it then increases with further increase of f_c for the adopted mixtures.

1. Introduction

Studies on the effect of site characteristics revealed that strain dependency of shear modulus, $G(\gamma)$, and damping ratio, $\eta(\gamma)$, are two main soil properties that make a significant effect on ground motion parameters (e.g. [4,45] and [27]). Continuous research efforts, since 1960's, show that $G(\gamma)$ and $\eta(\gamma)$ can be affected by parameters which are related to the particle characteristics (i.e., shape of particles, mineral characteristics and size of particles), structure of packing (i.e. grain size distribution, sample preparation) and boundary conditions (i.e. stress induced anisotropy). This led to the development of various prediction models which are applicable into the computer programs for response analysis of soil mass during the vibration of soil layers. Experimental results reveal the independency of the modulus ratio, $G(\gamma)/G_{max}$, and damping ratio, $\eta(\gamma)$, on the density of soils and a significant effect of isotropic pressure (e.g. [35,22,41]). Vucetic & Dobry [40], Ishibashi & Zhang [17] studied the influence of the plastic index (*PI*) on the nonlinear behavior of soils and concluded that the modulus ratio increases and damping ratio decreases with an increase in *PI*. Darendeli [8] and Wichtmann & Triantafyllidis [41] studied the influence of grain size distribution on the shear stiffness and damping ratio. They reported a significant effect of uniformity coefficient, Cu, on the shear stiffness and damping ratio. They also correlated fitting parameters of empirical relationships to Cu. The structure of soil can be also affected by existence of fine particles (e.g. [37,31,28]). Studies on the effect of f_c on the small and intermediate strain properties of soils can be divided into two groups:

i) small strain properties, G_{max}:
A systematic study on the effect of fines content, f_c, on G_{max} was presented by Iwasaki &Tatsuoka [18], Salgado, et al. [31], Tao, et al. [36], Chien & Oh [7], Carraro, et al. [6], Wichtmann et al. [42], Yang & Liu [44] and [13,12]. These studies showed a significant effect of non-plastic f_c on G_{max} and they reported that G_{max} decreases with an increase in fines content.
Hardin & Black [15] are arguably the first that proposed a well-known and most widely used empirical relationship to predict G_{max} in soils, as following general form:

$$G_{max} = Ap_a\left(\frac{p'}{p_a}\right)^n f(e) \tag{1}$$

where, A is a material constant which depends on the type of soil, p_a is the atmospheric pressure (100 kPa), n is the stress exponent and $f(e)$ is void ratio function. Various functions have been proposed in the literature to describe the effect of void ratio on the maximum shear modulus (e.g. [15,19] and [33]). However, in this study, void ratio function in form of Eq. (2) [15] will be employed to capture the effect of void ratio:

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* Corresponding author.
E-mail addresses: meisam.goudarzyakhore@rub.de (M. Goudarzy), diethard.koenig@rub.de (D. König).
† Deceased.

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Notation

A & n	fitting parameters of Hardin's relationship, Eq. (1)
A_i & n_i	fitting parameters of Hardin's relationship, Eq. (1), correspond to x_i
N & M	fitting parameters of Eq. (11)
ξ, Λ, μ & β	fitting parameters of Eq. (10)
$\gamma_{r(CHS)}$	reference shear strain of clean Hostun sand in Eq. (10)
f_c	fines content
f_{thr}	threshold fines content
K_i	fitting values in Eq. (1) for each effective stress
C_1 & C_2	fitting parameters of Eq. (8)
$G(\gamma)$	shear modulus
G_{max}	maximum shear modulus
p'	mean effective stress $\left(p' = \frac{\sigma_1' + 2\sigma_3'}{3}\right)$
p_a	Atmospheric pressure, 100 kPa
α	fitting parameter of Eq. (6)
x	fitting parameter of Eq. (2)
x_i	fitting parameter of Eq. (2) for each mean effective stress
e	void ratio
e_i	initial void ratio
e_{max} & e_{min}	maximum and minimum void ratio
γ_r	reference shear strain
γ_{et}	maximum shear strain that G/Gmax is equal to 1
γ_{r100}	reference shear strain for sample subjected to $p' = 100$ kPa
γ	shear strain
$\eta(\gamma)$	damping ratio
η_{min}	minimum damping ratio
η_{max}	maximum damping ratio

$$f(e) = \frac{(x-e)^2}{1+e} \tag{2}$$

where, e is void ratio and x is the fitting parameter (e.g. $x = 2.97$ for angular sands and 2.17 for rounded sands, [15]). Efforts were also conducted to refine Eq. (1) to capture the influence of fines content on maximum shear modulus. Iwasaki &Tatsuoka [18] defined a reduction factor for Eq. (1). However, this reduction factor was not an appropriate method, because this factor is different for various soils (Rahman & Lo 2012 and [12]). Wichtmann et al. [42] studied the influence of fines content on the fitting parameters of Hardin's relationship. They correlated the fitting parameters of Eqs. (1) and (2) to f_c. However, their study was restricted to the sand containing fines content less than 20%. Yang & Liu [44] performed bender element and resonant column tests on sand containing 0–30% f_c. They assumed that x in Eq. (2) is constant and equal to 2.17 (reported by [15] for rounded sands) for all of their adopted mixtures. They also reported decreasing of parameter A in Eq. (1) with an increase in f_c.

The influence of fine particles on the fabric of samples could be also explained through the concept of equivalent granular void ratio (Tevanayagam, [37]). Thevanayagam et al. [38] recognized the active contribution of a fraction of fines in sand force structure and proposed Eq. (3) to capture the effect of fines, when f_c is less than f_{thr} and the effect of sand, when f_c is more than f_{thr}. f_{thr} is a transition fines content between "fines-in-sand" and "sand-in-fines" skeleton structures and called as threshold fines content (Rahman and Lo, [29,47]).

$$\begin{cases} e* = \dfrac{e+(1-b)f_c}{1-(1-b)f_c} & f_c < f_{thr} \\ e* = \dfrac{e}{f_c + \frac{1-f_c}{{R_d}^m}} & f_c \geq f_{thr} \end{cases} \tag{3}$$

where, b value shows amount of fines which are active in the sand structure or force chains, b value varies from 0 to 1 (b = 0 for inactive fines and b ‡ 0 for higher f_c means that b is a function of f_c). Ni et al. [25] and Goudarzy et al. [12] showed that m can be a function of $\frac{{C_{uf}}^2 C_{uc}}{R_d}$, where, C_{uf} and C_{uc} are uniformity coefficient of fines and coarse material respectively and R_d is size ratio. On the other hand, considering the mathematical attributes of binary packing, Rahman, et al. [28] developed a semi-empirical relation to predict the parameter b.

$$b = \left[1 - exp\left(-0.3\frac{\left(\frac{f_c}{f_{thr}}\right)}{k}\right)\left(r\frac{f_c}{f_{thr}}\right)^r\right] \tag{4}$$

where $r = (D_{10}/d_{50})^{-1}$, D_{10} = size of sand at 10% finer, d_{50} = size of fine at 50% finer, $k = (1 - r^{25})$. Goudarzy et al. [12] showed that b can be also a function of mean effective stress, because sample will be compacted due to the mean effective stress and this will increase the participation of fine in force chains. By further increasing the fines content, fine particles will be dominant (sand-in-fine mixture). In this case, coarse particles will act like reinforced elements inside fine particles packing. Therefore, displacement and sliding of fines controlled by coarse particles, and the stiffness of packing depends on the characteristics of the fine particles.

Rahman et al. [30] first replaced the e in Hardin's relation (Eqs. 1 and 2) of clean sands by the $e*$ to predict the G_{max} of sand with fines. Then, Goudarzy et al. [12] used the same concept to predict G_{max} for Hostun sand with fines. Therefore, the applicability of $e*$ is only briefly described for the sake of completeness and the focus of the current article was extended to the evaluation of e in Hardin's relation with additional fitting parameters to capture the effect of fines. Furthermore, the advantages and disadvantages of this method is compared with $e*$ method in earlier studies.

In parallel of the performed studies to describe the maximum shear modulus using the global void ratio (volume of voids over the

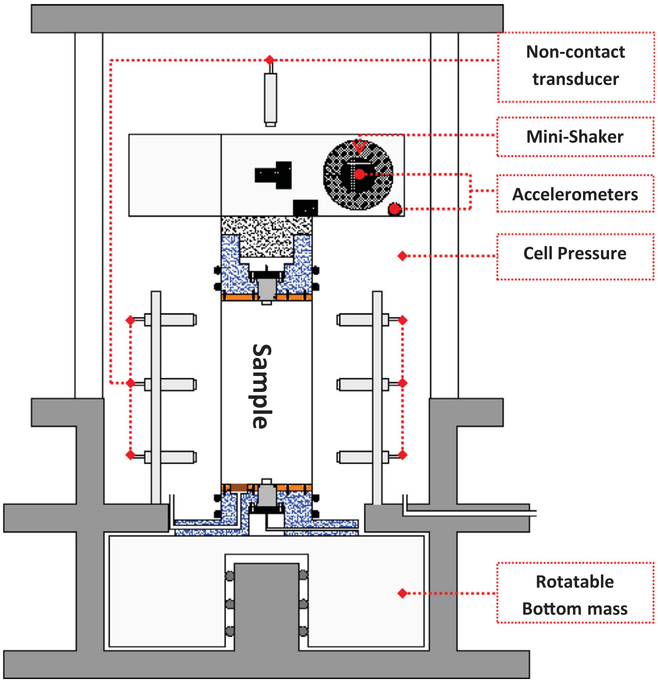

Fig. 1. Schematic sketch of the resonant column device available at Ruhr-Universität Bochum.