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On the influence of a non-cohesive fines content on small strain stiffness, modulus degradation and damping of quartz sand

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ABSTRACT

The influence of a non-cohesive fines content on small-strain shear modulus G_{max}, small-strain constrained elastic modulus M_{max}, shear modulus degradation $G(\gamma)/G_{max}$, damping ratio $D(\gamma)$ and threshold shear strain amplitudes γ_{tl} and γ_{tv} has been studied in approx. 130 resonant column (RC) tests with additional P-wave measurements by means of piezoelectric elements. Specially mixed continuous grain size distribution curves of a quartz sand with varying fines contents ($0 \leq FC \leq 20\%$, defined as the mass percentage of grains with size $d < 0.063$ mm according to DIN standard code) and uniformity coefficients ($1.5 \leq C_u \leq 50$) have been tested at different relative densities and pressures. A significant decrease of G_{max} and M_{max} with increasing fines content was observed, while the modulus degradation curves $G(\gamma)/G_{max}$ were found rather independent of *FC*. A pressure-dependent decrease of the damping ratio and a slight increase of the threshold shear strain amplitudes γ_{tl} and γ_{tv} with fines content were measured. Extensions of several empirical equations for G_{max}, M_{max}, $G(\gamma)/G_{max}$ and $D(\gamma)$ considering the influence of the fines content are proposed in the paper.

1. Introduction

Although measurements of the S- and the P-wave velocity in situ have become a commonplace tool for the design of foundations subjected to a cyclic or a dynamic loading during recent years, empirical formulas for the dynamic soil properties may be beneficial for feasibility studies and preliminary design calculations, for final design calculations in small projects or to provide an order-of-magnitude check against the in situ values [7]. In particular, empirical equations for the modulus degradation or the increase of damping ratio with increasing shear strain amplitude are useful since these curves are difficult to measure in situ.

The secant shear modulus G of the shear strain–shear stress hysteresis is usually described by a multiplicative approach $G = G_{max} F(\gamma)$ with the small strain shear modulus G_{max} and a modulus reduction factor $F(\gamma)$ depending on shear strain amplitude γ. The small strain shear modulus of non-cohesive soils is often estimated using Hardin's formula [11,8] (given in its dimensionless form here):

$$G_{max} = A \frac{(a-e)^2}{1+e} \left(\frac{p}{p_{atm}}\right)^n p_{atm} \tag{1}$$

with void ratio e, mean pressure p, atmospheric pressure $p_{atm} = 100$ kPa and with the constants $A = 690$, $a = 2.17$ and $n = 0.5$ for round grains and $A = 320$, $a = 2.97$ and $n = 0.5$ for angular grains.

Unfortunately, Eq. (1) does not consider the strong influence of the grain size distribution curve on small-strain stiffness. For constant values of void ratio and pressure, the small strain shear modulus considerably decreases with increasing uniformity coefficient $C_u = d_{60}/d_{10}$ while it is rather independent of mean grain size d_{50} [12,25]. Eq. (1) with its commonly used constants may strongly over-estimate the G_{max}-values of clean well-graded granular materials (see Fig. 1). A similar reduction with increasing C_u was observed for the constrained elastic modulus $M_{max} = \varrho v_P^2$ [26]. Furthermore, for a certain shear strain amplitude modulus degradation was found larger for sands having higher C_u-values [27]. Extensions of empirical equations for G_{max}, M_{max} and $G(\gamma)/G_{max}$ considering the influence of C_u have been proposed in [25–27]. These equations are summarized in Section 2.

A further significant reduction of the small strain stiffness may result from a non-cohesive fines content. It is obvious in Fig. 2 which collects respective G_{max} data from several studies in the

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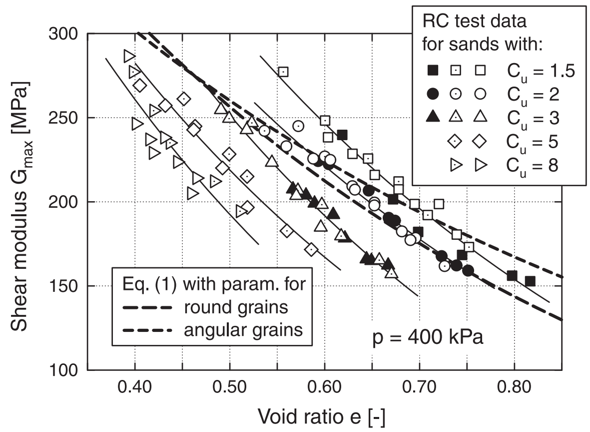

Fig. 1. Decrease of small strain shear modulus G_{max} with increasing uniformity coefficient C_u, figure adapted from [25].

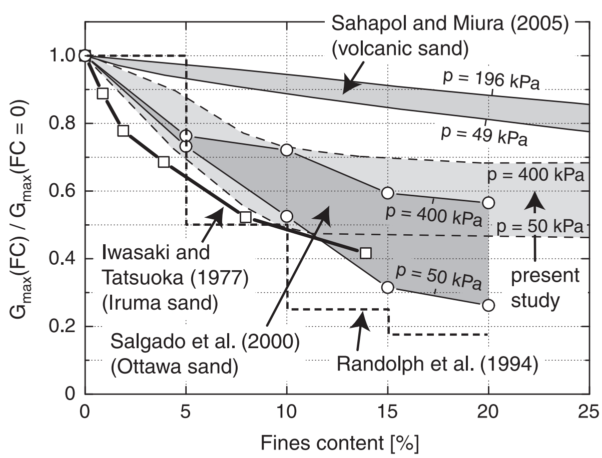

Fig. 2. Reduction of G_{max} with increasing content of non-cohesive fines, comparison of different studies in the literature.

literature [12,19,21,20]. On the ordinate the small-strain shear modulus G_{max} at a certain fines content FC is divided by the value $G_{max}(FC=0)$ for clean sand at same values of void ratio and pressure. Based on Fig. 2 the decrease of G_{max} with FC is pressure-dependent and also influenced by the type of the two ingredients (sand and silt).

In the studies documented in the literature so far either only a low number of tests were performed or relatively coarse granular materials (medium coarse sands up to fine gravels) were mixed with fines, resulting in gap-graded mixtures. However, most real soils with fines are not gap-graded but have a rather continuous grain size distribution curve. Furthermore, no data on the influence of the fines content on constrained elastic modulus M_{max}, Poisson's ratio ν, modulus degradation curves $G(\gamma)/G_{max}$ or damping ratio curves $D(\gamma)$ are available in the literature. Therefore, in order to extend the C_u-dependent empirical equations developed for clean sands (Section 2) by the influence of a fines content, approx. 130 resonant column (RC) tests with additional P-wave measurements have been performed on several silty sands having varying FC- and C_u-values. This paper presents the test results and reports on the extensions of the various empirical formulas by the influence of a fines content.

2. Extended empirical formulas for clean sands

For clean sands, in order to consider the reduction of G_{max} with C_u, the following correlations of the parameters A, a and n of Eq. (1) with C_u have been proposed in [25]:

$$A = 1563 + 3.13 C_u^{2.98} \tag{2}$$

$$a = 1.94\exp(-0.066 C_u) \tag{3}$$

$$n = 0.40 C_u^{0.18} \tag{4}$$

Note, that although the factor A increases with C_u according to Eq. (2), the combination with Eqs. (3) and (4), describing a decrease of a and an increase of n with C_u, predicts a decreasing small-strain shear modulus with increasing uniformity coefficient. The correlations (2)–(4) are based on more than 160 resonant column (RC) tests on 25 different grain size distribution curves with linear shape in the semi-logarithmic scale. Eqs. (2)–(4) have been confirmed for mean grain sizes in the range $0.1 \le d_{50} \le 6$ mm and for uniformity coefficients in the range $1.5 \le C_u \le 15$. A correlation of G_{max} with relative density $D_r = (e_{max}-e)/(e_{max}-e_{min})$ is less accurate than the empirical equations formulated in terms of void ratio, but may suffice for practical purposes [25]:

$$G_{max} = 74\,000 \frac{1 + D_r[\%]/100}{(11.6 - D_r[\%]/100)^2} \left(\frac{p}{p_{atm}}\right)^{0.48} p_{atm} \tag{5}$$

Based on measurements of the P-wave-velocity v_P, a set of equations similar to (1)–(4) has been developed for the small-strain constrained elastic modulus M_{max} of clean sands [26]:

$$M_{max} = A \frac{(a-e)^2}{1+e} \left(\frac{p}{p_{atm}}\right)^n p_{atm} \quad \text{with} \tag{6}$$

$$A = 3655 + 26.7 C_u^{2.42} \tag{7}$$

$$a = 2.16\exp(-0.055 C_u) \tag{8}$$

$$n = 0.344 C_u^{0.126} \tag{9}$$

The correlation between M_{max} and D_r reads

$$M_{max} = 2316\left(1 + 1.07\frac{D_r[\%]}{100}\right)\left(\frac{p}{p_{atm}}\right)^{0.39} p_{atm} \tag{10}$$

Several empirical equations for the modulus degradation curves $G(\gamma)/G_{max}$ have been extended by Wichtmann and Triantafyllidis [27] in order to consider the C_u-dependence. Amongst others, the parameter a of the equation proposed by Hardin and Drnevich [9]:

$$F(\gamma) = \frac{G(\gamma)}{G_{max}} = \frac{1}{1 + \frac{\gamma}{\gamma_r}\left[1 + a\exp\left(-b\frac{\gamma}{\gamma_r}\right)\right]} \tag{11}$$

has been correlated with C_u:

$$a = 1.070 \ln(C_u) \tag{12}$$

In Eq. (11) $\gamma_r = \tau_{max}/G_{max}$ is a reference shear strain [27] and the parameter b can be set to 1.0 [10]. The following simple equation is suitable as well [27]:

$$\frac{G}{G_{max}} = \frac{1}{1 + a\gamma/\gamma_r} \quad \text{with} \tag{13}$$

$$a = 1 + 0.847 \ln(C_u) \tag{14}$$

If Eqs. (11) and (13) are applied with a reference quantity $\sqrt{p/p_{atm}}$ instead of γ_r [10], their parameters a can be estimated from the same correlation [27]:

$$a = 1093.7 + 1955.3 \ln(C_u) \tag{15}$$

Stokoe's equation [22]:

$$\frac{G}{G_{max}} = \frac{1}{1 + (\gamma/\gamma_r)^\alpha} \quad \text{with} \tag{16}$$