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Influence of non-plastic fines content on maximum shear modulus of granular materials

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Abstract

Resonant column tests were conducted on clean Hostun sand and Hostun sand mixed with 5%, 10%, 20%, 30% and 40% fines (particle size smaller than 0.075 mm) to assess the influences of void ratio (e), effective confining stress (p') and fines content (f_c) on the maximum shear modulus, G_{max}. A significant reduction of G_{max} was observed with increasing f_c. While the Hardin's empirical relation was adequate to capture the influence of e and p' on G_{max}, each sand with an f_c has to be considered as separate soil. The micro-CT scans of these sand with fines mixture provided a qualitative observation of the initial skeleton structures of the "fines-in-sand" or "sand-in-fines" of equivalent granular void ratio, e^*. Therefore, e was replaced by e^* in Hardin's relation for clean Huston sand to overcome the effect of f_c. The conversion of e to e^* requires two parameters: b and m. Four different approaches, including the calibration of b and m, were used to obtain e^* and to verify the performance of e^* in capturing the effect of f_c. The performances of the calibrations, in terms of the root-mean-square-deviation and R^2, are discussed. The G_{max} of Hostun sand with a range of f_c can be predicted with good accuracy using Hardin's relation for clean Hostun sand when e is replaced by e^*. Then, collected data sets from the literature were also analyzed to validate e^* in capturing the effect of f_c.

Keywords: Maximum shear stiffness; Equivalent granular void ratio; Fines content; Micro-CT; Resonant column

1. Introduction

The maximum shear modulus, G_{max} has a significant effect on the mechanical response of geomaterials subjected to dynamic or earthquake loading. Hardin and Black (1966) were arguably the first to propose one of the most widely used empirical relation to predict G_{max} which was assumed to be a function of void ratio, e and mean effective stress, p'.

This formulation is widely accepted for the characterization and prediction of G_{max} for clean sand and sand with fines. However, for each slight variation in the fines content, the G_{max} differs and thus, sand with each f_c has to be considered as a separate soil which requires a large number of tests. This is a practical challenge where f_c varies along the depth for a single site e.g. Christchurch, New Zealand (Cubrinovski et al., 2010). While there are different empirical relations between G_{max} and f_c found in the literature, the concept of "equivalent" void ratio, e^* (discussed in the literature review) may have the potential to overcome this issue. The influence of fines content, f_c, on force

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chains in sand, from the skeleton structure point of view, was presented by Mitchell (1976) and then many others extended the concept of e^* to correlate with the large strain mechanical responses of transition soils e.g. undrained behaviour (Kuerbis et al., 1988; Georgiannou et al., 1990), the steady state (Thevanayagam, 1998; Ni et al., 2004; Yang et al., 2006; Rahman et al., 2014a), and the instability state (Rahman and Lo, 2012; Baki et al., 2014) etc. However, the use of e^* for the characterization and prediction of small strain (near elastic) behaviour such as G_{max} has yet to be evaluated properly. In recently proposed unified constitutive models, irrespective to f_c, it has been assumed that G_{max} can be predicted with Hardin's equation when e is replaced by e^* (Lashkari, 2014; Rahman et al., 2014b; Lashkari, 2016). This was inspired by the early work of Rahman et al. (2012). However, the dataset used in Rahman et al. (2012) was collected from the literature which was originally not designed for the evaluation of e^* to capture the effect of f_c on G_{max}. Besides, the maximum f_c did not exceed 20%. As such, a rigorous evaluation of e^* for G_{max}, for a range of f_c, remains a topic of research interest.

Therefore, this paper has the following objectives: (i) to conduct resonant column (RC) tests on clean Hostun sand as well as on Hostun sand with non-plastic f_c, covering a range of f_c, e and p', to obtain G_{max} and to evaluate the relative performance of empirical relations, and (ii) to evaluate the concept of e^* for capturing the effect of f_c on G_{max}. Several calibrations were performed for fitting the parameters of Rahman and Thevanayagam's approach to convert e to e^* (Thevanayagam et al., 2002; Rahman and Lo, 2008) and their relative performance is discussed with statistical measures. The advantages and disadvantages of such calibrations are also discussed. Another objective was to evaluate the concept of e^* for G_{max} using published datasets.

2. Literature review

2.1. G_{max} for clean sand and sand with fines

The continuous research effort since the 1960s has advanced our understanding of the factors affecting G_{max}. Various prediction models have been developed that readily fit computer programs designed for geo-materials response analysis. The empirical relation of Hardin and Black (1966) is the most widely used and can be presented by the following general form (Eq. (1)):

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

where A is a material constant which depends on the type of soil, p_a is the atmospheric pressure (100 kPa), n is an exponent and $f(e)$ is the void ratio function. Two common forms for $f(e)$, as in Eq. (2) (Hardin and Black, 1966) and Eq. (3) (Jamiolkowski et al., 1995), are usually found in the literature.

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

$$f(e) = e^d \tag{3}$$

where, c depends on the angularity of soil particles (e.g. $c=2.97$ for angular sands and 2.17 for rounded sands (Hardin and Black, 1966) and d is a fitting constant. Seed et al. (1984) also proposed a relation between G_{max} and p' as $G_{max}=218.8\,K_{2,max}(p')^{0.5}$ (in SI unit); where $K_{2,max}$ may be a function of e. Although the above relations were adequate to predict G_{max} for a particular soil, evaluations of their relative performance with a large dataset is rare, but emerging.

While attempts have been made to estimate G_{max} for clean sands or gravels, systematic studies on transition soils (i.e. clean sand mixed with fine particle, $d \leq 0.075$ mm) are rare, despite the fact that transition soils are not uncommon. A systematic study on the effect of fines content, f_c on G_{max} was first presented by Iwasaki and Tatsuoka (1977). They mixed different percentages of non-plastic f_c with two clean sands, Iruma Z1 and Iruma W for a resonant column test and reported that G_{max} decreased with increasing f_c. Salgado et al. (2000) conducted bender element tests on Ottawa sand with non-plastic fines and also reported that G_{max} decreased with increasing f_c. Tao et al. (2004) observed that G_{max} decreased with increasing non-plastic f_c up to f_c of 28% and then increased with further increases in f_c. However, Chien and Oh (2002) observed an opposite trend for Yun-Ling sand with plastic fines: based on resonant column tests, G_{max} increased up to f_c of 20% and then decreased with increasing f_c. Carraro et al. (2009) reported that a more pronounced effect of non-plastic f_c on G_{max} than that of plastic f_c, and there was a general trend of decreasing G_{max} with increasing non-plastic f_c.

While Eq. (1) was found adequate for clean sand or sand with a f_c as a separate material, efforts have been made to capture the effects of non-plastic f_c within the same framework of Hardin's relation (i.e. Eq. (1)). Iwasaki and Tatsuoka (1977) reported that parameter A was affected by f_c while the other parameters remained constant. They proposed a parameter, B, that decreases with increasing f_c and can be multiplied with A in Eq. (1) to capture the effect of f_c. Salgado et al. (2000) suggested that the parameters A and n in Eq. (1) might be affected by f_c. Wichtmann et al. (2015) performed RC tests on sand with f_c up to 20% and correlated the fitting constants of Hardin's relation: A, n and c to f_c. The B or A or n or c varies with f_c and the relation is non-linear in nature. Experimental values of G_{max} for each sand with an f_c are required to characterize this relation since it reduces the prediction capability of this approach.

2.2. Equivalent granular void ratio, e^* and G_{max}

The traditional void ratio, e is considered one of the density indexes which represents the skeleton structure corresponding to observed mechanical behaviour. The equivalent granular void ratio, e^* also considers the skeleton structure of the sand-fines mixture. Depending on the amount of f_c, the sand-fines mixture can have two distinct skeleton structures: 'fines-in-sand' and 'sand-in-fines'. The e^* values for these skeleton structures are discussed briefly below.