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Characterization of the small-strain dynamic behaviour of silty sands; contribution of silica non-plastic fines content

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ABSTRACT

Dynamic properties of soils at very small strains are of particular interest for geotechnical engineers for the characterization of the behaviour of earth structures subjected to a variety of static and dynamic stress states. This study reports on the small-strain dynamic properties of silty sand with particular emphasis on the effect of non-plastic fines content on the small-strain shear modulus (G_{max}) and material damping ($D_{s,min}$). Several clean sands with a wide range of grain size distribution and particle shape are mixed with different percentages of a silica non-plastic silt. The laboratory created samples are subjected to torsional resonant column tests with small-strain shear moduli and damping ratios measured along an isotropic stress path. It is shown that at low percentages of fines content, there is a significant difference between the dynamic properties of the various samples due to the different characteristics of the sand portion of the mixtures. However this variance diminishes as the fines content increases and the soil behaviour becomes mainly silt-dominant, rendering no significant influence of different sand properties on the small-strain shear modulus and damping ratio. Using the experimental results, new expressions for the prediction of small-strain shear modulus and small-strain damping ratio of non-plastic silty sands are developed accounting for the percentage of silt and the characteristics of the sand portion.

1. Introduction

Dynamic properties of soils are essential in earthquake engineering design and the geophysical characterization of sediments. Of particular interest in soil dynamics modelling is the behaviour of geo-materials at very small strains, i.e. below 10^{-3}%. In this range of behaviour, the dynamic properties are commonly expressed in terms of the small-strain shear modulus (G_{max}) and damping ratio ($D_{s,min}$). Precise prediction of G_{max} and $D_{s,min}$ have been the focus of many previous research studies in the literature. Based on the common practice in geotechnical earthquake engineering, for example following the recommendations of seismic codes, the classification of soils for dynamic characterization and the design of geo-structures, requires the knowledge of soil stiffness and material damping [13,19]. Soil stiffness is also important in liquefaction analyses when the shear wave velocity is used as the quantity to assess empirically the liquefaction susceptibility of sediments, while stiffness and material damping are both required properties in soil-structure interaction analyses.

For clean sands, there is a consensus in the literature about the dependency of small-strain shear modulus to void ratio and confining pressure [12,22,26,33–35,40] as well as the grain size characteristics and particle shape [15,26,34,6]. In addition, most of the experimental data and empirical models in the literature show that small-strain damping ratio of clean sand primarily depends on the gradation and particle shape of sand grains as well as the confining pressure applied to the soil [4,22,33–35,27]. However, as far as the authors are aware, there have been very few studies investigating the influence of fines content on the small-strain dynamic properties of silty sands. Natural soils composed of sand-silt mixtures are found widely, for example in alluvial deposits, and often comprise major portions of colluvium deposits [25]. There is particular interest to understand the behaviour of silty sand mixtures because of their relatively high compressibility and liquefaction potential when found in a saturated state as well as due to their common use in many regions as a remoulded geo-material for construction of road bases and other transportation infrastructures.

With reference to silty sands, the studies performed by Iwasaki and Tatsuoka [14], Salgado et al. [31], Thevanayagam and Liang [38], Chien and Oh [5], Rahman et al. [28], Umberg [39], Goudarzy [9], Choo and Burns [7] and Wichtmann et al. [41] have shown a significant decrease in G_{max} as the percentage of fines content increases and this reduction was reflected in the fitting parameters of G_{max} expression by extending previous proposed models. The concept of skeleton void ratio

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Table 1
Properties of tested sands.

Sand name	Gradation parameters		Particle shape descriptors					
	d_{50} (mm)	C_u	R (MV)	S (MV)	ρ (MV)	R (SD)	S (SD)	ρ (SD)
White sand	0.24	1.75	0.71	0.76	0.74	0.14	0.11	0.13
Crushed Blue sand 1	0.69	1.92	0.24	0.51	0.38	0.12	0.18	0.15
Crushed Blue sand 2	1.88	4.11	0.24	0.51	0.38	0.12	0.18	0.15

R: Roundness; S: Sphericity; ρ: Regularity; MV: Mean Value; SD: Standard Deviation.

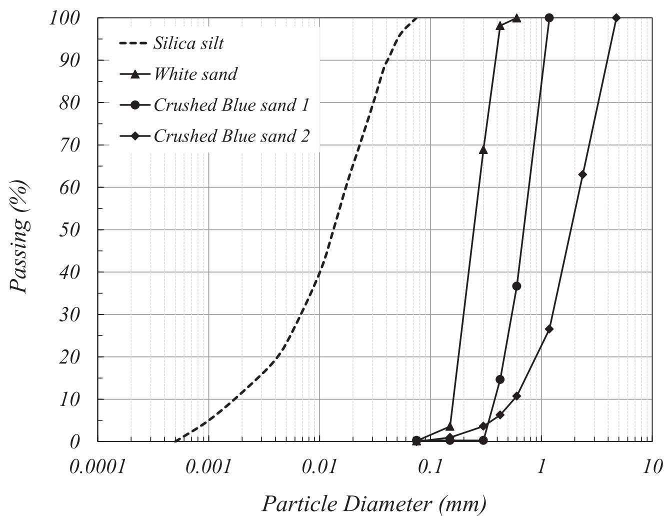

Fig. 1. Particle size distribution curves of tested soils.

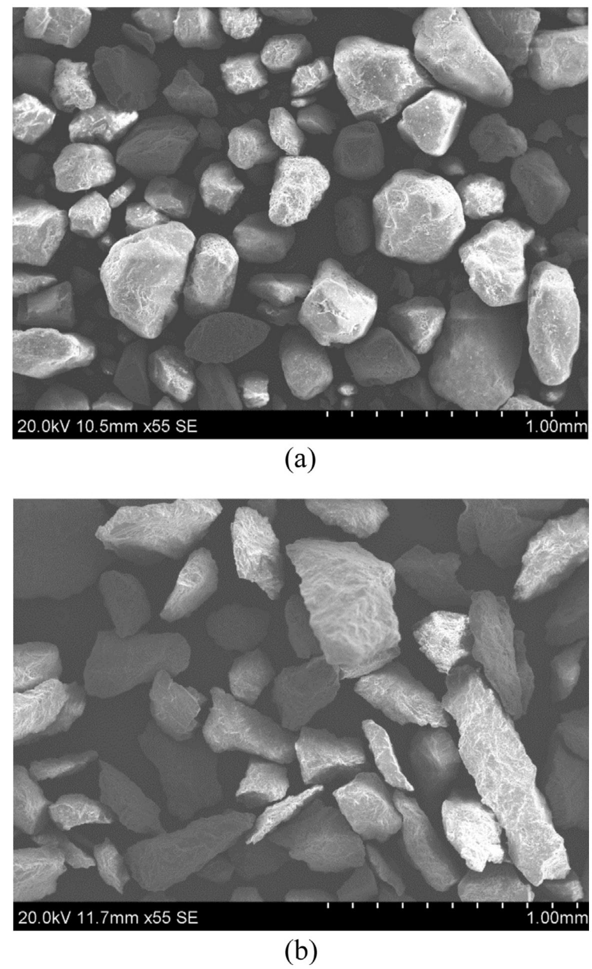

Fig. 2. SEM images of (a) White sand and (b) Crushed Blue sand 2.

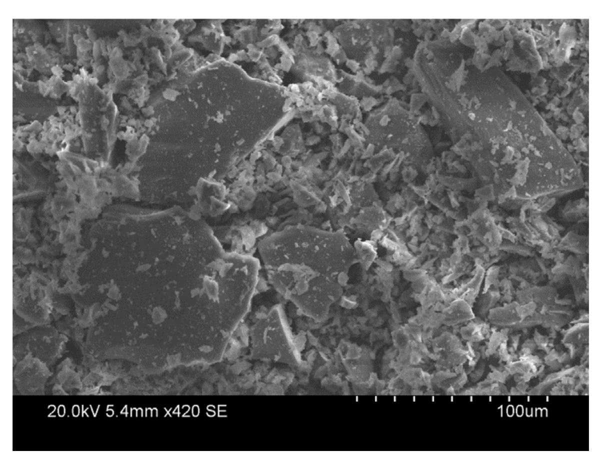

Fig. 3. SEM image of the non-plastic silica silt.

was used by Wichtmann et al. [41] and Choo and Burns [7] to characterise the maximum shear modulus and shear wave velocity of sand-fines mixtures, respectively. However, as discussed by Rahman et al. [29], Lashkari [21] and Yang and Liu [42], the use of skeleton void ratio may lead to underestimation of shear modulus values, soil strength and steady state parameters especially at high percentages of fines content. In the study performed by Yang and Liu [42], using both resonant column and bender elements tests, it was shown that although small-strain shear modulus decreases as fines content increases, no discernible effect of the percentage of non-plastic fines on the sensitivity of G_{max} to confining pressure was observed. In the studies conducted by Thevanayagam and Liang [38] and Rahman et al. [28], the equivalent granular void ratio (e^*), originally developed by Thevanayagam [37], was utilised to define a threshold fines content percentage and to correlate the shear wave velocity to the properties of the mixture as well as the applied pressure. Recently, [10,11] investigated experimentally the effect of non-plastic fines content on the small-strain shear modulus of sand-silt mixtures and they captured this effect adopting the concept of the equivalent granular void ratio. In particular, they used equivalent granular void ratio to present the variation of G_{max} with density and showed that Hardin equation is adequate for predicting small-strain shear modulus of sand – silt mixtures if global void ratio (e) is replaced by e^* in the void ratio function.

In most of the aforementioned studies, the experiments have focused on one type of sand with a given gradation and particle shape. As a result, the possible important role of the sand portion characteristics on the behaviour of the mixtures was not studied in a systematic manner in many of the previous studies and thus, boundaries and transformation from the sand-dominant to the silt-dominant behaviour could not be captured thoroughly. Consequently, the models proposed were the extensions of previous expressions for clean sand with the addition of the effect of fines content on a given type of sand. The possible effects of grain size characteristics and particle shape were therefore overlooked. On the other hand, there is limited information in