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Effect of sample preparation method on the small strain anisotropic stiffness of calcareous sands

Effet de la méthode de préparation des échantillons sur la rigidité anisotrope de petites déformations des sables calcaires

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ABSTRACT: It is well known that sands show a directional diversity in shear modulus at small strains which reflects the anisotropic stiffness behavior of the internal structure. Different sample preparation methods in laboratory conditions produce various fabric within the reconstituted sand specimens. Therefore, it is important to correlate the small strain shear modulus, G_0 or G_{max}, to the sample preparation technique and provide an insight into the effects of sand fabrics on the stiffness anisotropy. This is even more the case for calcareous, crushable sands. In this study, air and water pluviation, dry funnel deposition, dry and moist tamping are utilized to prepare specimens with a calcareous sand and a reference silica sand. Multidirectional shear moduli at small strains are obtained by measuring shear wave velocities with the bender element technique. The effects of internal structural dissimilarity introduced by the fabrication method on the anisotropic small strain stiffness are discussed herein.

RÉSUMÉ: Il est bien connu que les sables présentent une variabilité directionnelle du module de cisaillement aux petites déformations reflétant le comportement de rigidité anisotrope de la structure interne. Différentes méthodes de préparation des échantillons dans des conditions de laboratoire produisent différentes structures dans les échantillons de sable reconstitués. Par conséquent, il est important de corréler le module de cisaillement, G_0 or G_{max}, à la technique de préparation des échantillons pour mieux comprendre les effets de la structure du sable sur l'anisotropie de la rigidité. C'est encore plus le cas pour les sables calcaires et broyables. Dans cette étude, la pluviation dans l'air et dans l'eau, le dépôt en entonnoir sec, le compactage à sec et humide sont utilisés pour préparer des échantillons avec un sable calcaire et un sable de silice. Les modules de cisaillement multidirectionnels aux petites déformations sont obtenus en mesurant la vitesse des ondes de cisaillement. Les effets de la variabilité structurelle interne introduite par le procédé de fabrication sur la rigidité anisotrope sont discutés ici.

Keywords: Small strain; Stiffness anisotropy; Shear modulus; Sample preparation method

1 INTRODUCTION

Structural anisotropy is an important factor affecting the mechanical behavior of a sand as well as in laboratory tests as in situ. For example, the small strain stiffness, G_0, is sensitive to the change in fabric. So in order to evaluate the stiffness anisotropy, the shear wave measurement test is often adopted and its reliability has been proven during the last decades (Bellotti et al. 1996; Fioravante 2000; Piriyakul and Haegeman 2007; Escribano and Nash 2015). The relationship between the shear modulus and shear wave velocity is expressed as:

$$G_0 = \rho \cdot {V_s}^2 \quad (1)$$

where G_0 = the maximum shear modulus[MPa]; ρ = mass density of the medium[kg/m^3]; V_s = shear wave velocity [m/s]. To quantify the stiffness anisotropy, shear moduli expressed as G_{HH}, G_{HV} and G_{VH}, are inferred with equation (1), where the first and second subscript indicate the directions of signal propagation and polarization respectively. The ratio, G_{HH}/G_{HV} , is commonly a representative parameter to demonstrate the stiffness anisotropy of soils. Bellotti et al. (1996) stated that this ratio for Ticino sand is in the range of 1.14 to 1.21 for medium dense and very dense specimens respectively. Fioravante (2000) showed the anisotropy ratios of Kenya sand and Ticino sand are 1.04 and 1.11 respectively. With other types of soil or granular material, this stiffness anisotropy ratio is possibly lower than 1, as discussed by Pennington et al. (1997) and Ishibashi et al. (1991) on Gault clay and glass beads.

The difficulty and high cost to obtain undisturbed sand samples from the site promote the development of techniques for reconstituting a sample in laboratory. Previous studies revealed that the sample preparation method (SPM) plays an important role in the fabric anisotropy. Yang et al. (2008) conducted a scanning electronic microscope analysis on Toyoura sand samples and found that air pluviation specimens possess a higher inherent anisotropy than moist tamping specimens. A similar conclusion is also formulated by Ezaoui and Benedetto (2009) on Huston sand. However, investigation on the fabric anisotropy of calcareous sand in relation to the sample preparation method is rare.

In this study, a calcareous sand and a reference silica sand are used for making samples with five different reconstitution techniques which are air and water pluviation, dry funnel deposition, dry and moist tamping. All tests are conducted under isotropic consolidation stress. Bender elements are used to measure the shear wave velocities in both vertical and horizontal directions. Then, the inferred shear moduli are used to evaluate the stiffness anisotropy for both sands.

2 TEST PROGRAM

2.1 Test materials

S1 sand and Mol sand are selected in this study. S1 sand is a calcareous sand from an artificial island in the Persian Gulf. It contains sharp angular and angular grains and the content of $CaCO_3$ is over 95% due to it biological origin. Mol sand is a uniform silica sand and composed of rounded and subrounded grains. The particle size gradation and physical properties of the two sands are illustrated in Figure 1 and Table 1.

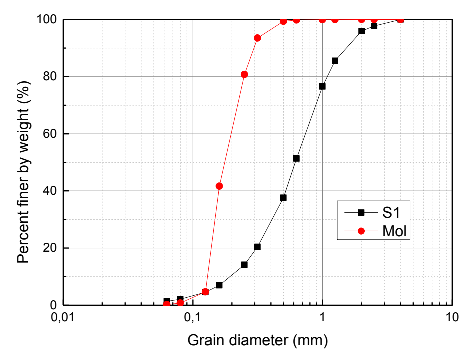


Figure 1. Particle size distribution of S1 and Mol sands

Table 1. Physical properties

Properties	**S1**	**Mol**
G_s	2.81	2.64
D_{50} (mm)	0.602	0.179
C_u	3.89	1.55
e_{max}	1.19	0.90
e_{min}	0.73	0.56

2.2 *Sample preparation methods*

A pluviator is designed for the air pluviation method, as shown in Figure 2. The mass of the sample is determined by the reduced mass of the sand in the sand collector after pluviation. The pluviator is fixed on the pedestal and the relative density is mainly controlled by the funnel opening size, referring to the effect of mass flow rate as stated in Rad and Tumay (1987). Finally, samples with 40% and 60% relative density are constructed based on the relationships found in Figure 3.

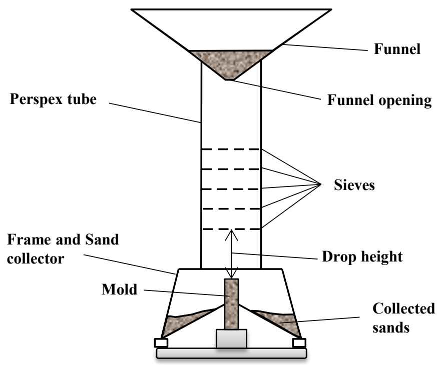


Figure 2. Schematic of the pluviator for the air pluviation method

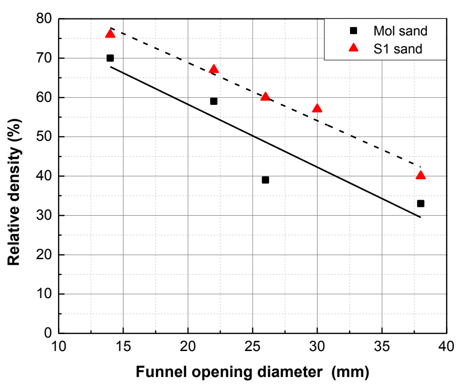
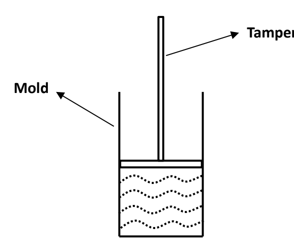


Figure 3. Relationship between relative density and funnel opening size

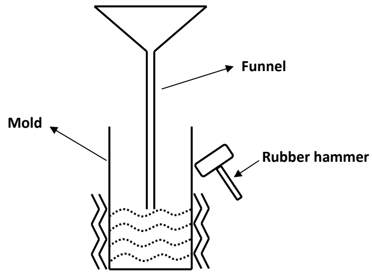
The other sample preparation methods are illustrated in Figure 4. Dry sand and moist sand with 5% water by mass are tamped into the mold in ten layers. The undercompaction technique proposed by Ladd (1978) is adopted for achieving a homogeneous fabric. In the dry funnel deposition method, a funnel with long neck is kept almost at zero height above the sample surface. The densification for achieving a target relative density is carried out by slightly tapping the mold side with a rubber hammer. The water pluviation method is performed with a small pluviator containing sieves. The mold and the drainage system in the triaxial pedestal are saturated before carrying out the pluviation. The densification is also conducted by tapping the mold, as depicted in the dry funnel deposition method.

2.3 *Test procedure*

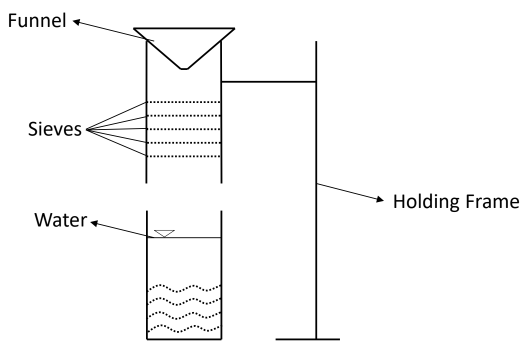
All the samples are reconstituted 50 mm in diameter and 100 mm in height. In order to achieve the saturation of the sample, carbon dioxide followed by deaired water are flushed through the sample for 20 minutes and half hour. Then a back pressure of 200 kPa is applied to the sample while keeping the effective consolidation stress at 20 kPa. The saturation with a B-value larger than 0.95 is obtained after keeping the back pressure for 1 hour. For the water pluviation method, the back pressure is increased to 350 kPa and held for two hours to achieve the target saturation. After the saturation, the sample is consolidated to an effective stress of 400 kPa with an increase step of 50 kPa. The bender element tests are performed after a rest period of 30 minutes within each step. A 20 V sinusoidal signal with a frequency of 15 kHz is used to excite the transmitters and the peak to peak method is selected as the signal interpretation method.



(a) Dry and moist tamping



(b) Dry funnel deposition



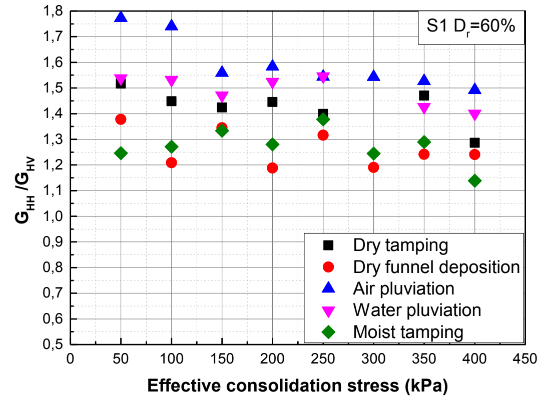
(c) Water pluviation

Figure. 4. Schematic of the other sample preparation methods

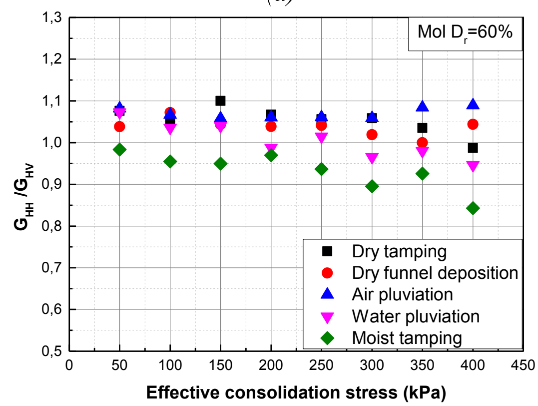
3 TEST RESULTS

3.1 Effect of SPM on the stiffness anisotropy at small strains

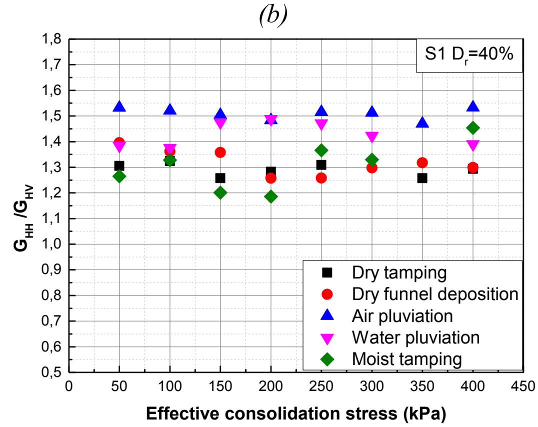
In order to assess the stiffness anisotropy, the shear moduli G_{HH} and G_{HV} , measured on the same plane, are calculated with equation (1). The ratio G_{HH}/G_{HV} for different SPM samples are plotted in Figure 5 against the effective consolidation stresses. It is seen that the air pluviation sample exhibits the highest anisotropy ratio as well as for S1 as Mol sand. The lowest anisotropy ratio is measured in the moist tamping sample, with an average of 1.27 and 0.93 for S1 sand and Mol sand at 60 % relative density. A low anisotropy ratio of 1.26 is also found in the dry funnel deposition sample for the S1 sand at D_r=60%, however, this is not observed in the Mol sand sample.



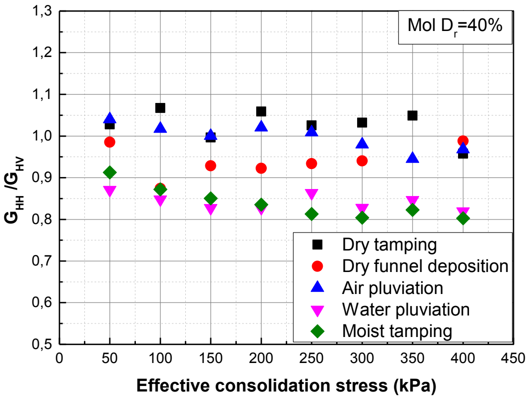
(a)



(b)



(c)



(d)

Figure. 5. Anisotropy ratio versus effective consolidation stress: (a) S1 sand, D_r=60% ; (b) Mol sand, D_r=60% ; (c) S1 sand, D_r=40%; (d) Mol sand, D_r=40%

These results show that the effect of SPM on the stiffness anisotropy of sand at small strains is significant. It is known that the long side of an irregular grain tends to move parallel to the horizontal direction during its deposition process, resulting in an anisotropic fabric. Therefore, the degree of the horizontal alignment depends on the time and space provided in the different sample preparation methods. In this study, the particle orientation in the air pluviation method is sufficient due to its free drop without any restriction. In contrast, in the moist tamping method, the particles are tightened by the capillary forces and the movement is insufficient, resulting in a more random particle orientation. For the dry funnel deposition sample, the low anisotropy ratio is due to the vertical aligned elongated grains after the vibration induced by tapping, as reported by Börzsönyi and Stannarius (2013). For samples prepared in the water pluviation method, the lack of drop energy counteracted by the buoyancy and the vibration required for densification afterwards lead to a slightly less anisotropic fabric than in the air pluviation sample. For dry tamping samples, the absence of capillary force reduces the randomness of the particle orientation compared with the moist tamping samples. However, the almost zero drop height limits the space and time for particle movement, resulting in a more isotropic structure in the sample. In addition,it is noted that the anisotropy ratio of Mol sand in moist tamping is lower than 1, showing that the shear modulus polarized in the horizontal direction (G_{HH}) is higher than that polarized in the vertical plane (G_{HV} and G_{VH}). This difference in anisotropic behavior is ascribed to the particle shape since the rounded and subrounded grains dominating in Mol sand lead to a more isotropic fabric and reduce the sensitivity to the SPM. Also the tamping force in the moist tamping method produces stronger force chains in vertical direction, which results in a higher stiffness in the vertical plane.

4 CONCLUSIONS

The effect of the sample preparation method on the stiffness anisotropy of both S1 calcareous sand and Mol silica sand at small strains is investigated by conducting isotropic consolidation tests with bender elements. The air pluviation method produces the highest anisotropy ratio. A low stiffness anisotropy is found in moist tamping samples for both S1 calcareous sand and Mol silica sand as well as in the dry funnel deposition sample for S1 sand. The difference in anisotropic behavior between calcareous sand and Mol sand is attributed to the difference in particle shape.

5 ACKNOWLEDGEMENTS

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