

Influence of the Sample Preparation on the Mechanical Characteristics of Hostun Sand

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ABSTRACT: The paper assesses the effect of sample preparation on the small and large strain characteristics of Hostun sand that has been widely used for many years in model tests and researches. For approaching to this goal, experimental efforts were conducted on fully saturated samples prepared using the dry air pluviation (AP) and moist tamping (with various initial water contents) (MT) methods. The experiments were conducted using bender elements for small strain level (e.g. the maximum shear modulus G_{max}) and triaxial device for large strain level. The results show that the initial fabric of specimens can be affected by sample preparation. For an example, loose specimens prepared by the AP method show larger maximum shear modulus in comparison with those prepared by the MT method. On the other hand, dense specimens compacted using the AP method show less maximum shear modulus in comparison with those compacted using the MT method. However, the experiments showed the negligible effect of sample preparation on the large strain characteristics of the adopted sand under drained condition. The experiments revealed that the dry deposition method provides samples with the more isotropic fabric in comparison with those prepared by the moist tamping. This effect can be obviously seen in dense samples.

KEYWORDS: Stiffness, Critical state line, Hostun sand, Triaxial device, Bender elements, Wave velocity.

1. INTRODUCTION

Numerous efforts have been conducted to assess the effect of various state parameters (e.g. stress state, density, particle characteristics) on the small and large strain characteristics of sands (i.e. wave velocity, shear stiffness and critical state line). For ease of discussion, these studies can be divided into two main groups: i) studies on the small strain properties (e.g. the maximum shear modulus, G_{max}) using piezoelectric elements (e.g. Bellotti et al., 1996; Zheng and Ni, 1998; Fioravante, 2000; Sadek et al., 2007; Wang and Mok, 2008; Ng et al., 2009; Ezaoui and Di Benedetto, 2009; Goudarzy et al., 2016a) or resonant column (e.g. Hardin and Black, 1966; Yanagisawa, 1983; Yu and Richart, 1984; Ishibashi et al., 1991; Santamarina and Cascante, 1996; Wichtmann and Triantafalydis, 2009; Wichtmann and Triantafalydis, 2013; Payan et al., 2016; Goudarzy et al., 2016b, 2018), and ii) studies at the large strain level, e.g. critical state line and state parameter (e.g. Been and Jefferies, 1985; Rahman et al., 2008; Azeiteiro et al., 2017). Some efforts have been also conducted to make a link between the small (G_{max}) and large strain properties (state parameter, ψ) of soils (e.g. Yang and Luo, 2015; Goudarzy et al., 2017; Guo and Yang, 2017). The main experimental efforts on these aforementioned parts are briefly described in following.

1.1 Small Strain Level, G_{max}

Numerous experiments can be found in literature on the effects of density, stress state and particle characteristic on the shear wave velocity, v_s , and the maximum shear modulus, G_{max} . These experiments revealed the significant effect of the density and mean effective stress (e.g. Hardin and Black, 1966; Hardin and Dernevič, 1972), shape of particles (e.g. Payan et al., 2016), grain size distribution (e.g. Wichtmann and Triantafalydis, 2009) and fine content (e.g. Salgado et al., 2000; Yang and Liu, 2016; Goudarzy et al., 2016a, 2016b) on the v_s and G_{max} .

Furthermore, studies were also conducted to describe v_s and G_{max} using empirical relationship. Hardin and Black (1966) proposed one of the most widely used empirical relations in space of e and p' to characterize G_{max} :

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

where, A is a material constant which depends on the type of soil, p_a is atmospheric pressure (≈ 100 kPa), p' is the mean effective stress, n

is the stress exponent and $f(e)$ is the void ratio function, commonly found in form of Eq. (2) (Hardin and Black, 1966):

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

where, c is a constant value and depends on the angularity of particles (e.g. $c = 2.97$ for angular sands and 2.17 for rounded sands). Eq. (1) and Eq. (2) were refined to assess the effect of shape of particles, grain size distribution and fines content on G_{max} (e.g. Payan et al., 2016; Wichtmann and Triantafalydis, 2009; Goudarzy et al., 2018).

The fabric of samples could be one of the parameters that may have a significant effect on the behaviour of soils, which is still interest of research. Magnanimo et al. (2008) and Goudarzy (2015) using DEM simulation showed that different sample preparations can change the number of contacts and the coordination number (number of contacts over 2 times of number of balls) in the specimens with the same density. This yields samples with the same density but different shear stiffness. Tatsuoka et al. (1979) conducted a series of resonant column and torsional shear tests on Toyoura sand. The specimens in their experiments were prepared by different methods with various initial water contents with relative density of 40.6 to 100%. They reported that the shear modulus is insensitive to the sample preparation after the second cyclic loading. However, in their study, the specimens tested under the fully dry or saturated conditions had the relative density in a range between 75 to 100%. The different mechanical behaviour was mostly observed for the loose specimens with relative density less than 40%. This difference is due to the fabric of the specimens formed with different methods and it is tried to interpret the influence on the fabric with the micromechanical characteristics. Yang et al. (2008) reported that the loose specimens prepared with dry deposition method possess obviously inherent anisotropy in the vertical plane, whereas those loose samples from moist tamping method tend to be more isotropic.

Based on the performed literature review, studies on the effect of sample preparation on the wave velocity and G_{max} as well as fitting parameters of their empirical relationships are rare and this seeks additional study that is one of the goals of this paper. Furthermore, the impact of initial water content in moist tamping method on the fabric of samples must be studied. This will show which sample preparation can provide specimens with the more isotropic fabric for the adopted sand.

1.2 Large Strain Level, Critical State Line (CSL) and State Parameter (ψ)

Stress and volume change of the sample with respect to the strain is the other mechanical characteristics of materials, which may be affected by the sample preparation. The critical state is defined as a final phase of the soil behaviour in which the soil deforms continuously without change in its volume and in the deviatoric stress (Roscoe et al., 1958). Extensive studies have been conducted in the previous works to describe the effect of particle characteristics (e.g. shape of particles and grain size distribution), packing properties (e.g. relative density) and boundary conditions (e.g. stress state) on the strain dependent properties of granular materials. For the large strain level, mostly vertical strain larger than 20%, sands will reach the critical state. The experiments were also conducted to assess the impact of particle and packing characteristics in the critical state of the sands (e.g. Ng, 2008; Vilhar et al., 2013; Ghafghazi et al., 2014; Yang and Luo, 2015; Phan et al., 2016). In parallel of these experiments, the relation between the void ratio and the mean effective stress of soils at the critical state can be described with a unique line named as the critical state line, CSL, (e.g. Rahman et al., 2008; Azeiteiro et al., 2017). The CSL can be expressed by the power function, as presented by Li et al. (1999):

$$e = e_{lim} - \lambda_{ss} \left(\frac{p'}{p_a} \right)^{\xi} \quad (3)$$

where, e_{lim} is the limiting value corresponding to $p' = 0$ kPa, p_a is the atmospheric pressure, λ_{ss} and ξ are the curve fitting parameters.

The term of state parameter, ψ , which is the difference between the current void ratio and the void ratio at the critical state corresponding to the same mean effective stress, was introduced by Been and Jefferies (1985) to describe the state of soils.

Vaid and Sivathayalan (2000) performed simple direct shear tests on the saturated sands, which were prepared with different sample preparation methods, under undrained condition. Comparing their results for strain level of 2 to 15% shows the significant effect of the sample preparation. This could be due to the impact of the sample preparation on the contact number and contact normal distribution from micro-mechanical point of view and from macro-mechanical point may be due to the different fabric.

Guo and Yang (2017) Conducted experiments using binder elements on Toyoura sand. They proposed that wave velocity can be written in form of Eq. (4).

$$v_s = (B - C\psi) \left(\frac{p'}{p_a} \right)^m \quad (4)$$

where B, C and m are fitting parameters. From this equation, it can be concluded that at the critical state ($\psi = 0$), the v_s can be predicted with a function of p' , only. Therefore, this seeks additional study to find an evidence for this hypothesis as well as to find the effect of sample preparation on the wave velocity at the critical state line.

The other goal of this paper is to assess the effect of sample preparation on the strain dependent properties of Hostun sand.

2. EXPERIMENTAL PROGRAM

The experimental program consists four sections: 1) physical characteristics of the adopted sand, 2) adopted equipment and the calibrations, 3) the adopted methods for sample preparation and 4) experimental procedure.

2.1 Tested Material

This study was carried out on Hostun sand, which is a quartz sand with the specific gravity, G_s , of 2.65 (Goudarzy et al., 2016b). The minimum and maximum void ratios of this sand, e_{min} and e_{max} , are 0.67 and 1.02, respectively. Figure 1 shows a microscopic image of random selected particles of this sand. It can be seen that this sand has subangular to angular grains. The grain size distribution of the

adopted sand was determined using DIN-18123 standard (Germany-standard). The determined grain size distribution of the adopted sand is presented in Figure 2 in comparison with the distributions from previous works on the similar sand. As can be seen, it is a uniform sand with the mean grain size $D_{50} = 0.30 - 0.38$ mm. The uniformity coefficient, C_u , of the sand adopted by this study is 1.68. The physical characteristics of the adopted sand are presented in Table 1 in comparison with those from previous works.

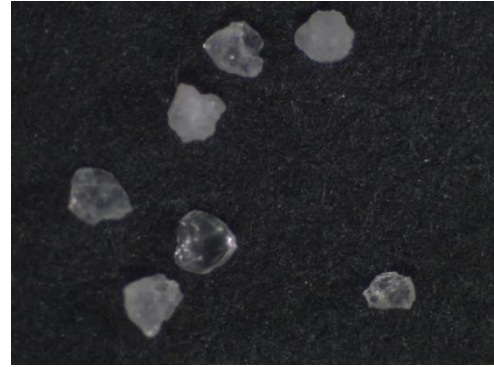


Figure 1 Microscope image of Hostun sand

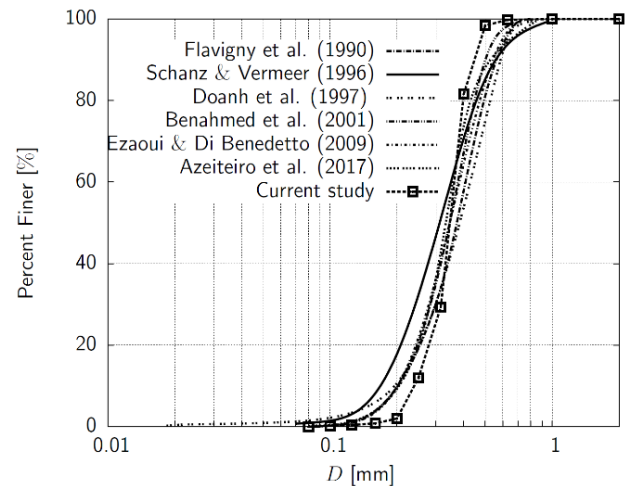


Figure 2 Grain size distribution of Hostun sand

Table 1 Comparison of the properties of Hostun sand

Reference	G_s [-]	D_{50} [mm]	e_{min} [-]	e_{max} [-]	C_u [-]
Flavigny et al. (1990)	2.65	0.30 - 0.35	0.62	0.96	1.7 - 1.9
Schanz and Vermeer (1996)	2.65	0.36	0.65	1.04	1.42
Doanh et al. (1997)	2.65	0.38	0.62 - 0.65	0.96 - 1.04	1.9
Benahmed (2001)	2.65	0.33 - 0.38	0.66	1.00	1.6 - 1.9
Sadek et al. (2007)	2.65	0.34	0.62	0.96	1.5
Ezaoui and Di Benedetto (2009)	2.65	0.36	0.62	0.96	1.42
Goudarzy et al. (2016b)	2.65	0.35	0.67	1.02	1.68
Azeiteiro et al. (2017)	2.64	0.33	0.66	1.00	1.4
Hostun sand (current study)	2.65	0.35	0.66	1.02	1.68

G_s is the specific gravity;

D_{50} is the mean grain size;

e_{min} is the minimum void ratio;

e_{max} is the maximum void ratio;

C_u is the uniformity coefficient.

2.2 Apparatus

A triaxial device was used with specimens having a diameter of 100 mm and a height of 200 mm. In this device, a LVDT is externally mounted on the loading bar to measure the changes in the height of the specimen. The accuracy of the adopted LVDT was 0.0025 mm. The compression load was applied using strain control method with the rate of 0.1 mm per minute. The load cell was mounted in the bottom of the sample to measure the applied vertical load in the specimen. The back pressure is monitored using a sensor connected to the bottom of the specimen. The appropriate calibrations of load cell, LVDT and the other sensors were done precisely before performing the experiments. The top and bottom caps mounted in the triaxial device were modified for installing bender elements (Figure 3(a)). This pair of bender elements allow to determine the velocity of the shear wave propagated in the vertical direction in specimens. For the velocity of the shear wave propagated in the horizontal direction, four pieces of bender elements were mounted on the side surface of the specimen (Figure 3(b)). All elements were sealed using appropriate epoxy. The elements were connected with waterproof cables to an electric measuring system that comprises of a computer with the software of LabVIEW, two amplifiers, and a data logger. The schematic sketch of the system and the arrangement of bender elements are shown in Figure 4. The calibration and validation of the prepared elements were done using the Aluminium and plastic samples (Table 2). Furthermore, the existing delay time, due to the thickness of epoxy, was determined by measuring the traveling time when the couple of elements were directly contacted to each other. It is worthy to mention that the delay time for the elements mounted in the vertical and horizontal directions are 2×10^{-5} seconds. This value was subtracted from the traveling time. The sinusoidal signal, which is often used in the previous studies (Gajo et al., 1997; Pennington et al., 2001; Leong et al., 2005; Yamashita et al., 2009; Azeiteiro et al., 2017), was adopted in all of the experiments using bender elements in this paper. The traveling time was determined using the first deflection method that has been adopted in the previous works (e.g. Gajo et al., 1997; Yamashita et al., 2009; Goudarzy et al., 2016a).

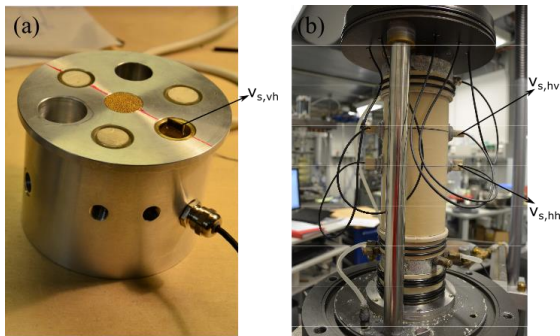


Figure 3 The device with the piezoelectric technique: (a) bender element coated with the epoxy in the bottom cap to measure the shear wave propagated in the vertical direction, $v_{s,vh}$ and (b) bender elements mounted on the side surface of the specimen to measure the two shear waves propagated in the horizontal direction, $v_{s,hv}$ and $v_{s,hh}$

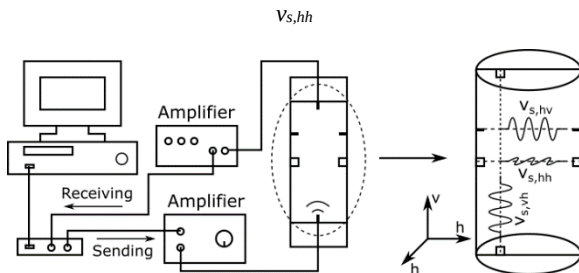


Figure 4 The schematic sketch of the measuring system with the piezoelectric technique (left) and the arrangement of the elements mounted in the specimen (right) to measure the shear wave velocities in different directions

Table 2 Calibration of the piezoelectric elements using the aluminium and plastic specimens, the delay time is 20 μ s

Sample	Aluminium	Plastic
Diameter d [mm]	5	5
Height h [mm]	200	200
Traveling time [μ s]	85	245
Velocity v_s [m/s]	3077	889
Density ρ [kg/m ³]	2700	1400
G_{max} [GPa]	25.6	1.1

2.3 Specimen Preparation

Two sample preparation methods were adopted in this research: i) dry air pluviation method and ii) moist tamping method with the initial water content of 5, 10 and 15%. However, the experiments were conducted on the saturated specimens.

2.3.1 Air Pluviation Method, AP

In this method, the oven dried sand was poured into a split model through a funnel from a certain dropping-height. The void ratio of the specimens constituted is controlled by the nozzle size of the funnel and the dropping-height from the funnel tip to the sand's surface. For the constitution of loose specimens, the sand fell through the nozzle having a diameter of 5 mm at the zero dropping-height above the surface of the deposition. In contrast, the nozzle size of 4 mm and the dropping-height of 20 mm were used to prepare dense specimens.

2.3.2 Moist Tamping Method, MT

In this method, the oven dry sand was mixed with a certain weight of water, which had been pre-calculated with a given water content (5, 10 and 15% in this study) about 16 hours before the sample preparation. So the water could be evenly distributed in the mixture for the homogeneity of the samples. The prepared moist mixture was compacted in 10 layers in the split mould to form a specimen with 100 mm in diameter and 200 mm in height. So each layer had a thickness of 20 mm to ensure the homogeneity of the specimen along its height. The amount of the moist mixture that was used for each layer was determined based on the desired density and the volume of each layer. Then the moist sand that was weighed for each layer was put into the split mould evenly with a spoon and was tamped to a height calculated with the number of the layers in the mould. In general, it takes much more energy to build a layer at a high density than to build one at a low density. The rest of the mixture was weighed before the dehydration in the oven as well as after that. The measurements were used to confirm the water content and the mass of sand in the specimen.

2.4 Experimental Procedure

Each specimen constituted by either the AP or MT method was constrained from deformation with a negative pressure of -50 kPa supplied by a vacuum. Then the vertical and horizontal dimensions of the specimen were measured to determine the initial volume of the specimen. When the cell was filled with water, the negative pressure was removed in steps of 10 kPa as well as the cell pressure was increased up to 50 kPa. During saturation, the specimen was flushed respectively with carbon dioxide gas and deaired water, and stayed overnight under the cell pressure of 250 kPa and the back pressure of 200 kPa to achieve a B-value of greater than 0.95. After assembling of the device and before inserting any water inside the cell and specimen, the program of the triaxial device was activated to record the change in the height of the specimens during all steps of the experiment. Since the recorded data show the negligible change in the height of the specimen during saturation, it can be considered that the void ratio obtained after the sample preparation is the initial void ratio, e_0 , in this study. Each specimen was consolidated sequentially under three isotropic effective stress states of 50, 100 and 200 kPa. At the end of each consolidation stage, the shear wave velocities in the

vertical and horizontal directions are measured using three couples of bender elements. For the calculation of the velocities, the travel length in the vertical and horizontal directions were updated based on the volume change of the specimen. Finally, a displacement controlled triaxial test (consolidated and drained) was performed under the cell pressure of 400 kPa and the back pressure of 200 kPa with a shear rate of 0.1 mm per minute. When the axial strain reached about 24%, the shear wave velocities were measured again. Later, the test was stopped at the axial strain of near to 25%.

After the aforementioned procedure, 13 tests were conducted on the specimens prepared by the AP or MT method with different initial water content. The information of these tests is listed in Table 3.

Table 3 The adopted experimental plan for bender element and triaxial tests with their initial conditions

Sample preparation	w_0^* [%]	D_r [%]	B^{**} [-]	σ_3' [kPa]	$\varepsilon_{1,max}$ [%]	Comment
AP	0	92.0	0.96	200	24	No***
		64.9	0.97			No
		59.4	0.96			No
		39.4	0.96			No
		12.9	0.98			No
	0	69.2	0.97	100	24	No
MT	5	51.7	0.97	200	24	No
		32.0	0.97			No
		8.2	0.99			Yes
	10	72.0	0.98			No
	15	64.9	0.98			No
		14.6	0.99			Yes

*Initial water content for sample preparation

**B-value for saturation

***test doesn't reach to CSL

3. TEST RESULTS

3.1 Shear Wave Velocities and Shear Modulus after Consolidations

The sinusoidal waves with different frequencies were used for bender-element-testing. The traveling time was determined with the first deflection method, as shown in Figure 5. The determined traveling time has been marked with arrows in this figure. The input waves, sending signals, are the sinusoidal waves with the frequencies of 5, 10 and 15 kHz. This experiment was conducted on a specimen, which had the void ratio of 0.81 and was subjected to the isotropic effective stress of 200 kPa. Figure 5 shows the output signals, receiving signals, for this experiment. The location of the arrows shows that there is no obvious difference between the detected traveling times in Figures 5(a), 5(b) and 5(c) for this range of frequency. Note: the sinusoidal wave with the frequency of 10 kHz was adopted as the input signal, sending signal, for our experiments on the saturated specimens.

A series of experiments were conducted to measure the wave velocity and the maximum shear modulus, G_{max} . For an example, Figure 6 shows the recorded output signals from an experiment using bender elements to determine the $v_{s,sh}$. In this experiment, a specimen with the void ratio of 0.95 was prepared with the air pluviation (AP) method and subjected to the effective stress states of 50, 100 and 200 kPa as presented in Figures 6(a), 6(b) and 6(c), respectively. The main results of these experiments are described in this section. Figures 7(a) and 7(b) show the maximum shear modulus, G_{max} , versus void ratio for the specimens prepared by the moist tamping (MT) and air pluviation (AP) methods but subjected to the isotropic stress state of 50 and 200 kPa, respectively. The results show that the G_{max} increases with the decreasing void ratio, e , and the increasing mean effective pressure, p' , which is in agreement with the previous works. In these figures, the solid and open points show the measured stiffness

for the specimens prepared by the moist tamping (MT) and air pluviation (AP) methods, respectively. As can be seen, the results for both methods are located in a narrow band. The results show that there is no significant impact of initial water content on the G_{max} in specimens prepared by the MT method. However, the deviation between the measured G_{max} for the specimens prepared by the MT and AP methods increases by increasing or decreasing the void ratio. For instance, in the loose specimens ($D_r = 20\%$, $e = 0.95$) under isotropic effective stress of 200 kPa, the G_{max} in the specimen prepared by the AP method is about 15% larger than the G_{max} in the specimen prepared by the MT method. However, in dense specimens ($D_r = 76\%$, $e = 0.75$), the G_{max} in the specimen prepared by the AP method is about 5% less than the G_{max} in the specimen prepared by the MT method. This could be due to the applied energy to prepare dense specimens using the MT method that causes a significant inherent anisotropy in the specimens (this will be explained in the next section).

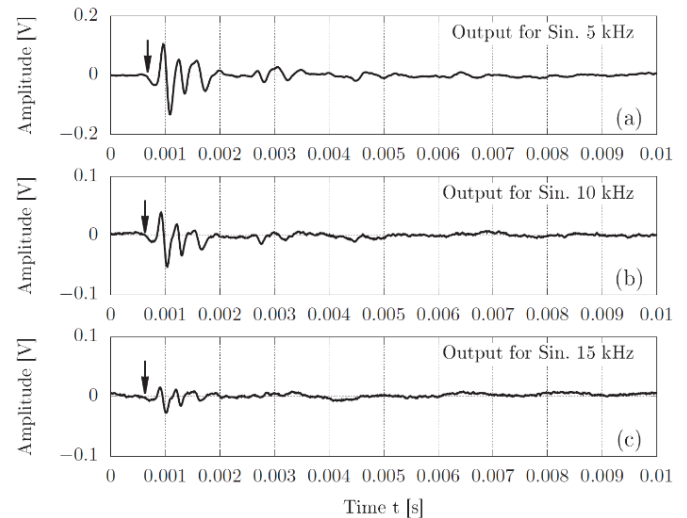


Figure 5 Recorded output signals from BE test and adopted arrival times for the specimen with the void ratio of 0.81 and subjected to the mean effective stress of 200 kPa. The input signals were sinusoidal with the frequency of: (a) 5 kHz, (b) 10 kHz and (c) 15 kHz

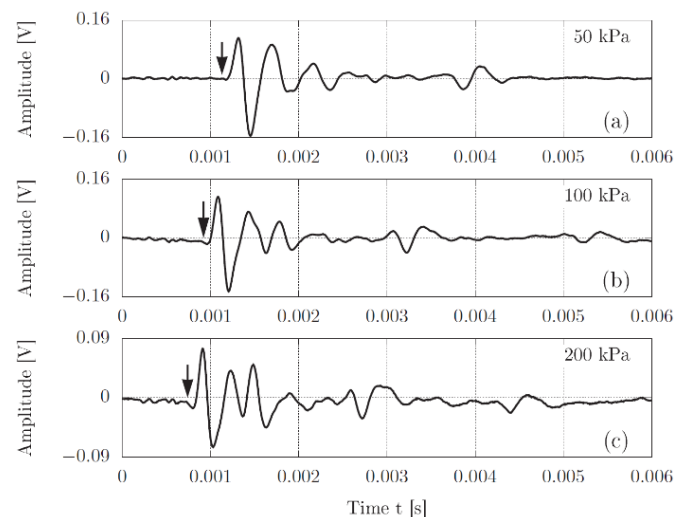


Figure 6 Recorded output signals from BE test and adopted arrival times for the specimen with the void ratio of 0.95 and subjected to mean effective stress of: (a) 50 kPa, (b) 100 kPa and (c) 200 kPa. The input signals are sinusoidal with the frequency of 10 kHz

The cross anisotropy of the specimens was assessed by measuring the wave velocities in the different directions. As can be seen in Figure 4, the wave velocity with the vertical propagation and the

horizontal polarization, $v_{s,vh}$, and the wave velocity with the horizontal propagation and the vertical polarization, $v_{s,hv}$, can be considered as the in plane wave velocities. And the wave velocity with the horizontal propagation and polarization, $v_{s,hh}$, is the out of plane wave velocity. Then the $v_{s,vh}$ and the $v_{s,hv}$ have been compared to describe the fabric of two dense specimens prepared by the MT and AP methods in this plane, the vertical cross section, (Figure 8). Figure 8(a) shows the measured wave velocities for the specimen prepared by the AP method with the relative density of 76%. As can be seen in this figure, the $v_{s,vh}$ and the $v_{s,hv}$ are the same. This may confirm that the fabric of the dense specimens prepared by the AP method is the same in the vertical and horizontal directions. On the other hand, Figure 8(b) shows the $v_{s,vh}$ and the $v_{s,hv}$ measured for the specimen prepared by the MT method with the relative density of 72%. This figure shows a deviation between the measured wave velocities. This means that the fabric of the specimen prepared by the MT method in the vertical and horizontal directions is not the same. For ease of discussion, the three wave velocities were normalized with respect to the $v_{s,vh}$ in Figure 9. Figure 9(a) presents the normalized wave velocity for the specimen prepared by the AP method and shows that the $v_{s,vh}$ and $v_{s,hv}$ obtained from this specimen are similar. On the other hand, Figure 9(b) presents the normalized wave velocities for the specimen prepared by the MT method and shows that the $v_{s,vh}$ is larger than the $v_{s,hv}$. This shows the effect of the sample preparation on the fabric of specimens.

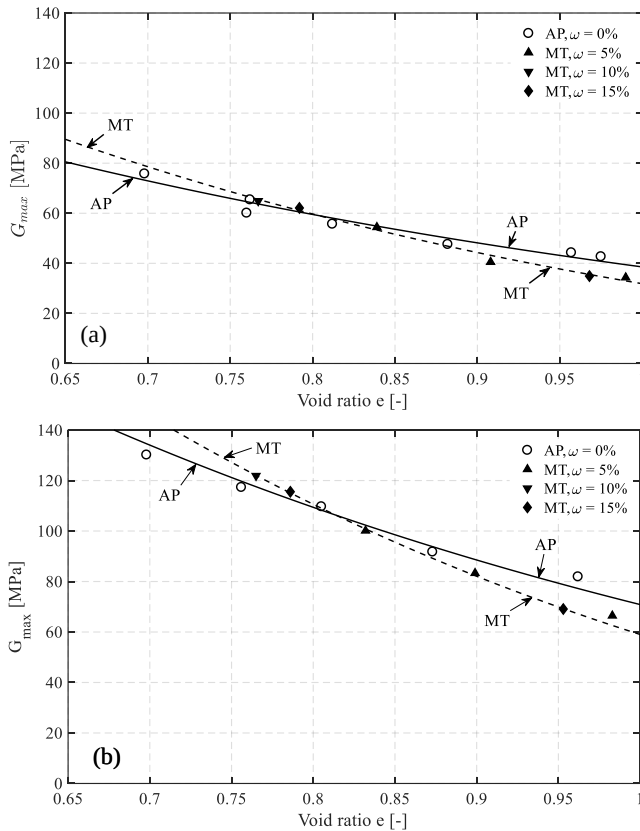


Figure 7 G_{max} versus void ratio for mean effective stress, p' : (a) = 50 kPa, (b) = 200 kPa

3.2 Compressional Triaxial Tests under the Drained Condition

A series of compressional triaxial tests were conducted on fully saturated specimens up to 24% of the axial strain (due to the limitation of the device) after the isotropic consolidation stage under drained condition.

Figure 10(a) shows deviatoric stress, q , versus vertical axial strain for specimens with relative density, D_r , of about 74% and prepared by the air pluviation (AP) and moist tamping (MT) methods. This figure shows that the q - ε_1 curve for the MT specimen is located above the curve for the AP specimen up to the axial strain of 5%. This means

that the initial stiffness of the specimens prepared by the MT method is more than the one of the specimens prepared by the AP method. Furthermore, this figure shows that the peak of the deviatoric stress, q -peak, for the specimen prepared by the MT method ($\omega = 10\%$) is located at the axial strain of 3%, where the q -peak for the specimen prepared by the AP method is located at the axial strain of 7.5%. However, the results for loose specimens ($D_r = 18\%$) in Figure 10(b) show that the q - ε_1 curve for the AP specimen is above those for the specimens prepared by the MT method ($\omega = 5$ and 15%). As it is apparent from this figure, the q -peaks of the three curves are all located in the same strain level.

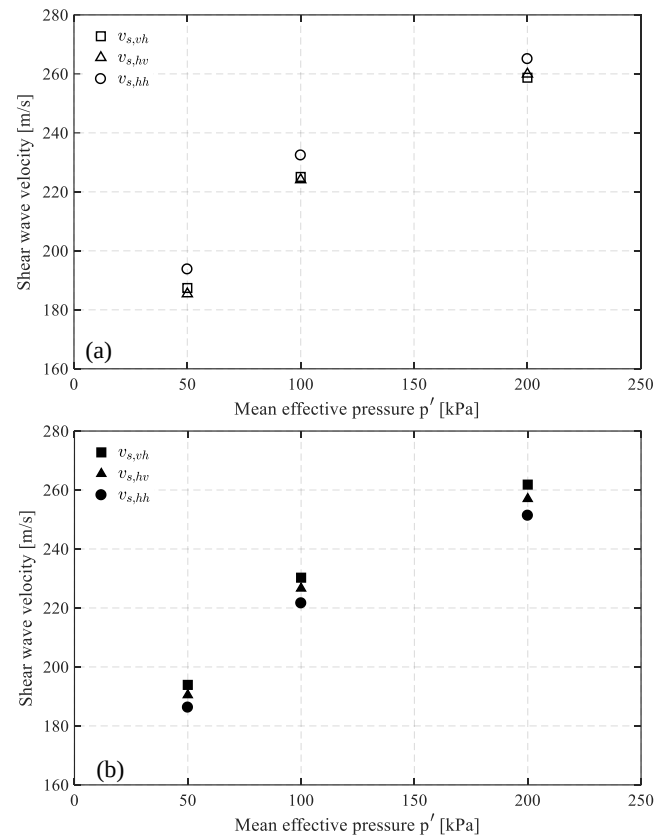


Figure 8 Shear wave velocities in different directions versus mean effective stress: (a) at the specimen prepared by the dry pluviation method at the void ratio of 0.75 ($D_r = 76\%$), (b) at the specimen prepared by the moist tamping method at the void ratio of 0.77 ($D_r = 72\%$)

These observations for the q - ε_1 curves can be explained through the effect of the sample preparation on the behaviour of soils. It means, due to the applied energy for increasing the density of specimens, the fabric of the dense specimen prepared by the MT method is completely different from those prepared by the AP method or the loose specimens. Figure 10(b) shows that the water content at the sample preparation doesn't have obvious impact on the q - ε_1 curve for the loose specimens, although the initial slope of the q - ε_1 curve for the specimen prepared with $\omega = 5\%$ is slightly more than the one with $\omega = 15\%$.

In Figure 11, the void ratios of the specimens prepared by the AP and MT methods measured at the last isotropic stress level, denoted as the open points, are compared with those measured at the axial strain of 24%, denoted as the solid points. It can be seen that the void ratios measured at the axial strain of 24% were close to each other regardless of the initial value and the sample preparation.

3.3 Shear Wave Velocity at the Axial Strain of 24%

The shear wave velocity, $v_{s,vh}$, was measured at the axial strain of 24% during the compressional triaxial tests. These tests were performed with the low strain rate of 0.1 mm per minute. During this process,

the variation of the height of the specimens was measured using a calibrated LVDT and recorded in a computer with respect to Time. Before performing the bender element test, the time of the triaxial test was recorded to obtain the height of the specimen. After that, the bender element test was immediately performed, and the input and output signals were saved in the computer. However, due to the quality of signals from the bender element test, this is not easy to get clear signals with one try. Therefore, these experiments, measuring wave velocity at large strain, was successful only for some of our experiments that have been presented in Figure 12.

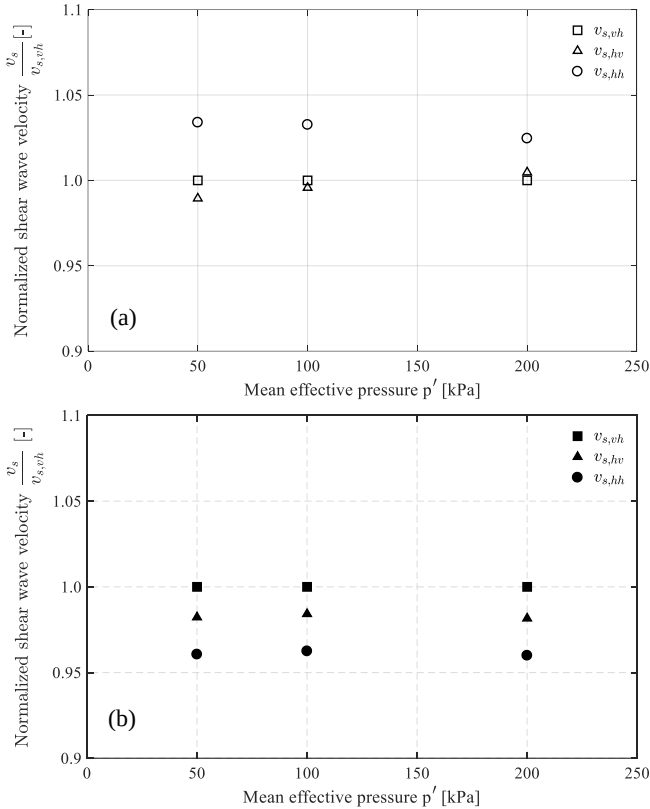


Figure 9 Normalized shear wave velocities versus mean effective stress: (a) at the specimen prepared by the dry pluviation method at void ratio of 0.75 ($D_r = 76\%$), (b) at the specimen prepared by the moist tamping method at void ratio of 0.77 ($D_r = 72\%$)

Figure 12 shows the shear wave velocity with respect to the mean effective pressure, p' . This figure compares the measured $v_{s,vh}$ for all of the specimens prepared by the AP and MT methods with different relative densities. In this figure, the open points show the measured wave velocity after the isotropic consolidation and the solid points show the measured wave velocity at the axial strain of 24%. The significant scatter can be seen from the measurements of wave velocity at the initial condition with respect to the p' in Figure 12, which is due to the significant impact of density and slight impact of the sample preparation on the wave velocity. However, as can be seen in this figure, the wave velocity obtained at the axial strain of 24% is independent of the sample preparation and the density of the specimens. This means that the wave velocity at this strain can be written in form of $v_s = Ng(p')$, and it is only dependent on the p' .

4. ANALYSIS OF EXPERIMENTAL RESULTS

4.1 Shear stiffness

The goal of this section is to find the effect of sample preparation (initial fabric of specimens) on the fitting parameter of Hardin's relationships (Eq. (1) and Eq. (2)). For approaching to this goal, the plots of G_{max} - e for mean effective stresses of 50, 100 and 200 kPa were employed (Figure 7). This figure was used to find the fitting

parameters of Eq. (2). The procedure of the determination of the fitting parameters is similar to the method described by Goudarzy et al. (2018). Firstly, lines in form of $kf(e)$, where $f(e)$ is Eq. (2) and k is a fitting parameter, were fitted to the experimental data points in the G_{max} - e space for each stress level (Figures 13(a) and 13(b)). This analysis will give us the best value for the parameter c in Eq. (2) for the adopted sand (more details in Goudarzy et al., 2018). Then, the G_{max} was normalized with respect to the $f(e)$. At the next step, the normalized G_{max} was drawn with respect to the p' to determine the other fitting parameters of Eq. (1) using the power regression of data for getting the maximum R^2 .

Table 4 shows the summary of the determined fitting parameters for the specimens prepared by different methods. As can be seen in Table 4, there is a difference between the average of the fitting parameters for the specimens prepared by the AP and MT methods.

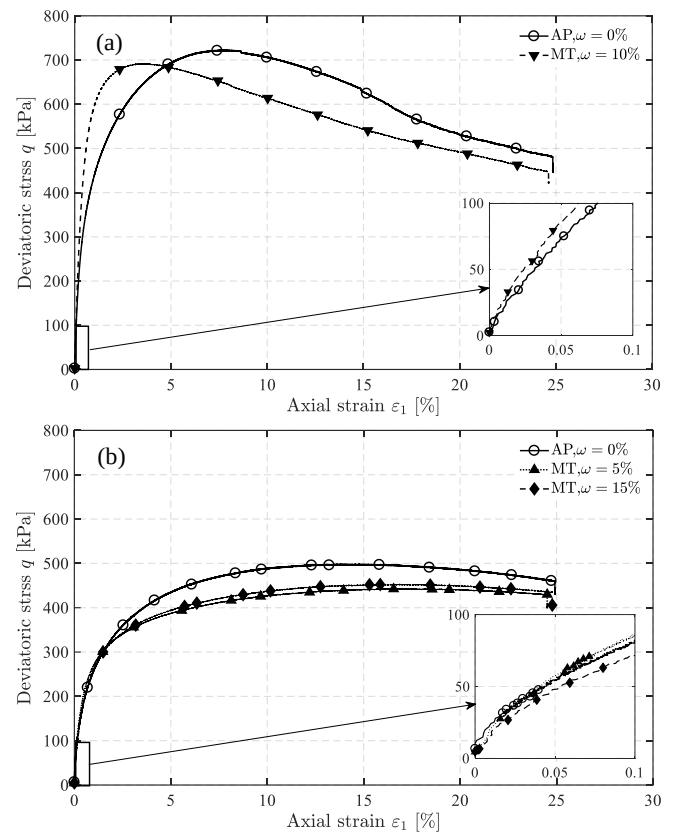


Figure 10 Deviatoric stress q versus axial strain with a detail up to the axial strain of 0.1%: (a) for the specimens prepared at void ratio of 0.76 (at the relative density D_r of 74%), (b) for the specimens prepared at void ratio of 0.96 (at the relative density D_r of 18%)

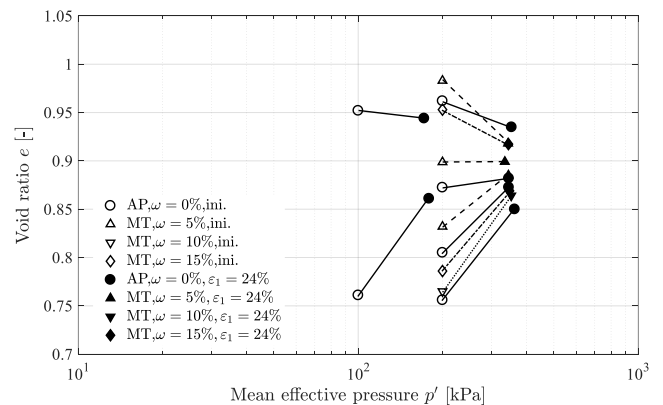


Figure 11 Void ratio e versus mean effective stress. Void ratios after isotropic consolidation are denoted as the open points, and those measured at the axial strain of 24% by shearing, $\epsilon_1 = 24\%$, are denoted as the solid points

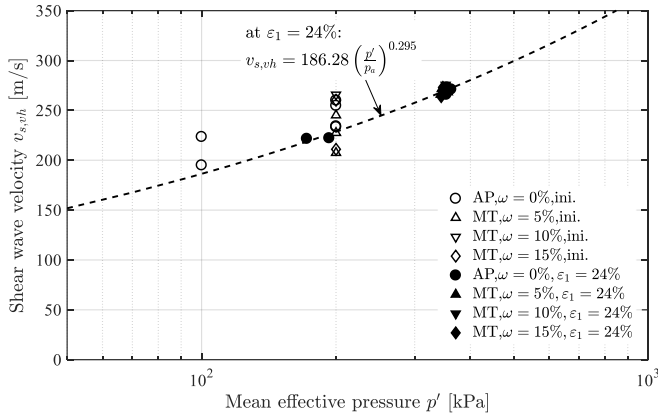


Figure 12 $v_{s,vh}$ versus mean effective stress. Void ratio after isotropic consolidation are denoted as open points, and those measured at the axial strain of 24% ($\varepsilon_1 = 24\%$) are denoted as solid points. Dashed line shows the best fitting line on the solid points for $v_{s,vh}$ at the axial strain of 24%

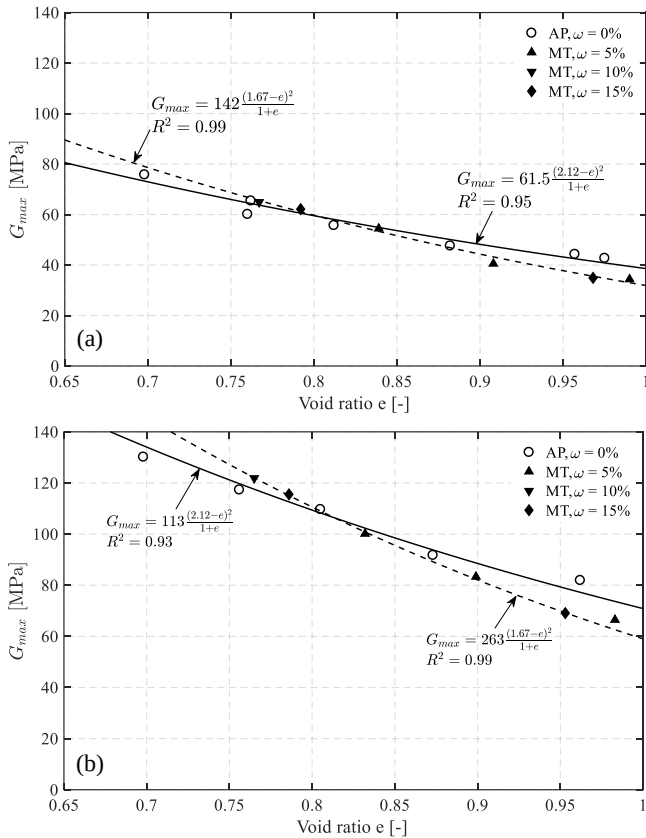


Figure 13 G_{max} versus void ratio e under the different mean effective stress p' . The fitting line are in form of $G_{max} = k \frac{(c-e)^2}{1+e}$, for specimens prepared by the dry pluviation method $c_{ap} = 2.12$ (the solid line), for specimens prepared by the moist tamping method $c_{mt} = 1.67$ (the dashed line): (a) $p' = 50$ kPa, (b) $p' = 200$ kPa

4.2 Critical State

Figure 14 shows the state of the specimens at the axial strain of 24% (the solid points) from our experiments (see Table 3). The existing data to show the state of Hostun sand at the critical state, have been gathered from the previous literatures and added to this Figure as the open points for comparing with our data. As can be seen, all of data are located in a narrow band, which could be due to the maximum applied vertical strain in the triaxial experiments, i.e. in our study, experiments have been done up to the axial strain of 24%. The regression analysis was also performed on our data to fit a curve in form of Eq. (3) (for the maximum R^2) to our data. From the performed

regression, the values of e_{lim} , λ_{ss} and ζ are 1.023, 0.094 and 0.254, respectively, from our experiments on Hostun sand.

Table 4 Determined fitting parameters of Eq. (1) and Eq. (2) for the specimens prepared using: (a) AP method, (b) MT method. G_{max} is in MPa.

(a)				
P' [kPa]	k [MPa]	c [-]	A [-]	n [-]
50	60	2.13	0.82	0.441
100	84	2.11		
200	111	2.12		
Average	-	2.12	0.82	0.441
(b)				
P' [kPa]	k [MPa]	c [-]	A [-]	n [-]
50	142	1.66	1.96	0.441
100	184	1.65		
200	249	1.70		
Average	-	1.67	1.96	0.441

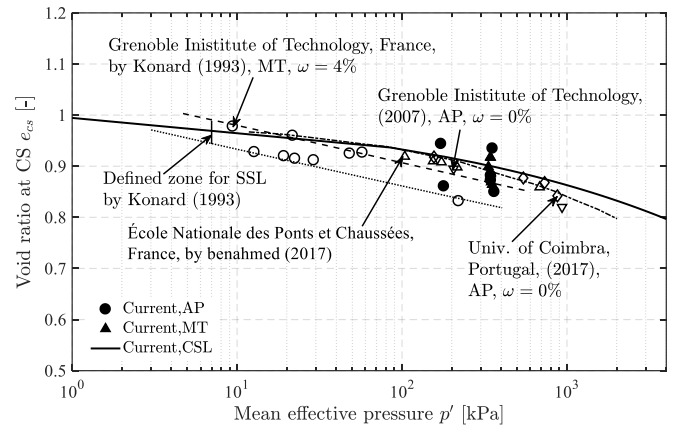


Figure 14 Void ratio, e , versus mean effective stress, p' . The solid line shows the best fitted to our data and the dashed lines shows the CSL from previous works on the same sand

4.3 Empirical Equations for Shear Wave Velocity at the Large Strain Level

As it was observed in Figure 12, the $v_{s,vh}$ at the axial strain of 24% was independent of the e and the sample preparation. Therefore, if the $v_{s,vh}$ at the axial strain of 24% was presented with respect to p' , an unique curve in form of $v_{s,vh} = K(p'/p_a)^m$ can be used to fit the data, as shown in Figure 12. This shows that wave velocity measured at the axial strain of 24%, which could be close to or at the CSL, is only a function of the mean effective stress.

5. COMPARING WITH PREVIOUS WORKS

The maximum shear modulus, G_{max} , of the specimens prepared by the AP method in this study were compared with those from the previous researches (Ezaoui and Di Benedetto, 2009; Sadek, 2006; Azeiteiro et al., 2017; Goudarzy, 2016b) in Figure 15 to confirm the results. For the comparison, the G_{max} were all normalized with the function of void ratio, $f(e)$ in Eq. (2), and the constant parameter c of 2.12. The constant parameter and the stress exponent used to draw the line were calculated with the results from this study. It can be seen that the results from this study are consistent with those previous.

6. CONCLUSIONS

In this study, a set of compression triaxial tests was conducted out on the specimens prepared with the desired void ratio using the AP and MT methods with different initial water content. The shear modulus

was measured using piezoelectric element technique after the consolidation under the isotropic stress states and at the axial strain of 24% during shearing. Comparing the results from the specimens prepared by different methods showed the effect of sample preparation at small and large strain level:

- (1) The sample preparation has effect on the initial fabric of specimens. Loose specimens prepared using the AP method show larger maximum shear modulus than those prepared using the MT method while the dense specimens compacted using the AP method show less maximum shear modulus than those compacted using the MT method due to the applied energy for sample preparation and the contact condition between particles (dry or wet). However, the effect of the sample preparation on the initial fabric of specimens is less significant than the void ratio and the effective confining stress.
- (2) Experiments under drained condition on the adopted sand showed the negligible effect of the sample preparation on the critical state line, *CSL*.
- (3) For the axial strain about 24%, the measured shear wave velocities depend on the mean effective pressure, p' , only.

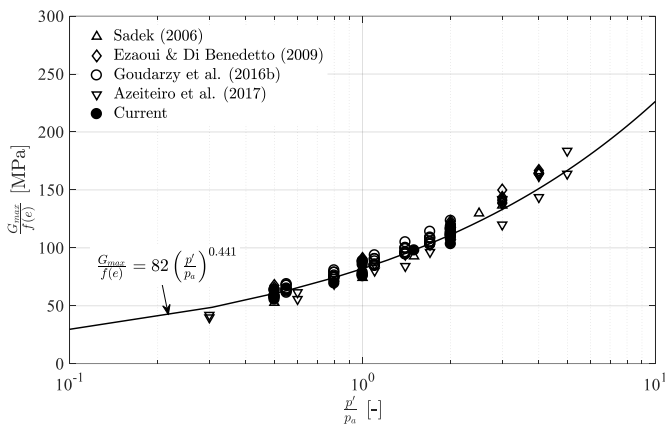


Figure 15 Normalized shear modulus $\frac{G_{max}}{f(e)}$ versus stress ratio $\frac{p'}{p_a}$ comparing to the results from the previous literatures

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