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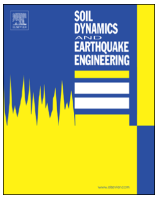

Small-strain shear modulus of volcanic granular soil: An experimental investigation

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ABSTRACT

While volcanic soils exist in many places around the world, their mechanical behavior is however less extensively studied as compared to the conventional soil type such as quartz sand and clay. This paper presents an experimental study investigating the small-strain shear modulus (G_0) and associated shear wave velocity (V_s) of a volcanic granular soil collected from the northeast of Japan that was affected by the devastating 2011 Tohoku earthquake. Reconstituted soil specimens were tested at different packing densities and confining stress levels by using the resonant column technique, and the pressure and density dependence of shear modulus was established for the soil. The study showed that under otherwise similar conditions, the G_0 value of the volcanic soil was markedly lower than that of clean quartz sands, but it tended to increase significantly when the fine particles in the soil were removed. This finding suggests that the presence of fines plays an important role in the mechanical behavior of volcanic soils. A practical model accounting for the influence of fines and the pressure and density dependence is proposed and it is shown to provide reasonable estimates of G_0 for both volcanic soils and clean quartz sands studied.

1. Introduction

The shear wave velocity (V_s) or associated small-strain shear modulus ($G_0 = \rho V_s^2$) is an important soil property needed in almost all earthquake geotechnical engineering problems, particularly in earthquake ground response analysis and liquefaction evaluation [1–3]. In the last few decades, a great number of laboratory studies have been conducted to determine G_0 and V_s values for quartz sands and clays by using the resonant column or bender element tests [1,4–15]. These studies have produced valuable data showing that the small-strain shear modulus is affected by various factors and among them the effective confining stress and void ratio are two most important ones. Compared with quartz sands and clays, volcanic soils can be regarded as a non-textbook type of soil. Available studies on their mechanical behavior are rather limited although they are found in many places around the world, particularly in the Pacific Rim region [16–18]. It has been frequently observed in recent years that natural deposits and earth structures composed of volcanic soils are susceptible to geohazards such as earthquakes and landslides [17,19], raising a pressing need for more comprehensive studies of the mechanical properties of this type of soils.

This paper presents an experimental study investigating the small-strain shear modulus of a volcanic granular soil collected from a site in the northeast of Japan, which suffered severe ground failures during the 2011 Tohoku earthquake (Fig. 1). A series of resonant column tests was performed on specimens of the soil at various packing densities and effective confining stress levels. Both the original volcanic soil samples and the sieved soil samples where fine particles (diameter < 63 μm) in the original soil were removed were studied, with the purpose of examining the influence of the fines on the small-strain property. In addition, the G_0 values of two clean, uniform quartz sands were also measured using the same method, and were compared with those of the original and sieved volcanic soil samples. Based on these comparisons, a predictive model is proposed that may be used as a first approximation to estimate G_0 values for both volcanic soils and quartz sands under a range of confining stresses and void ratios.

2. Experimental program

2.1. Material

The volcanic soil was collected from a site located in the County of Naganuma, Japan. The particle size distribution curve

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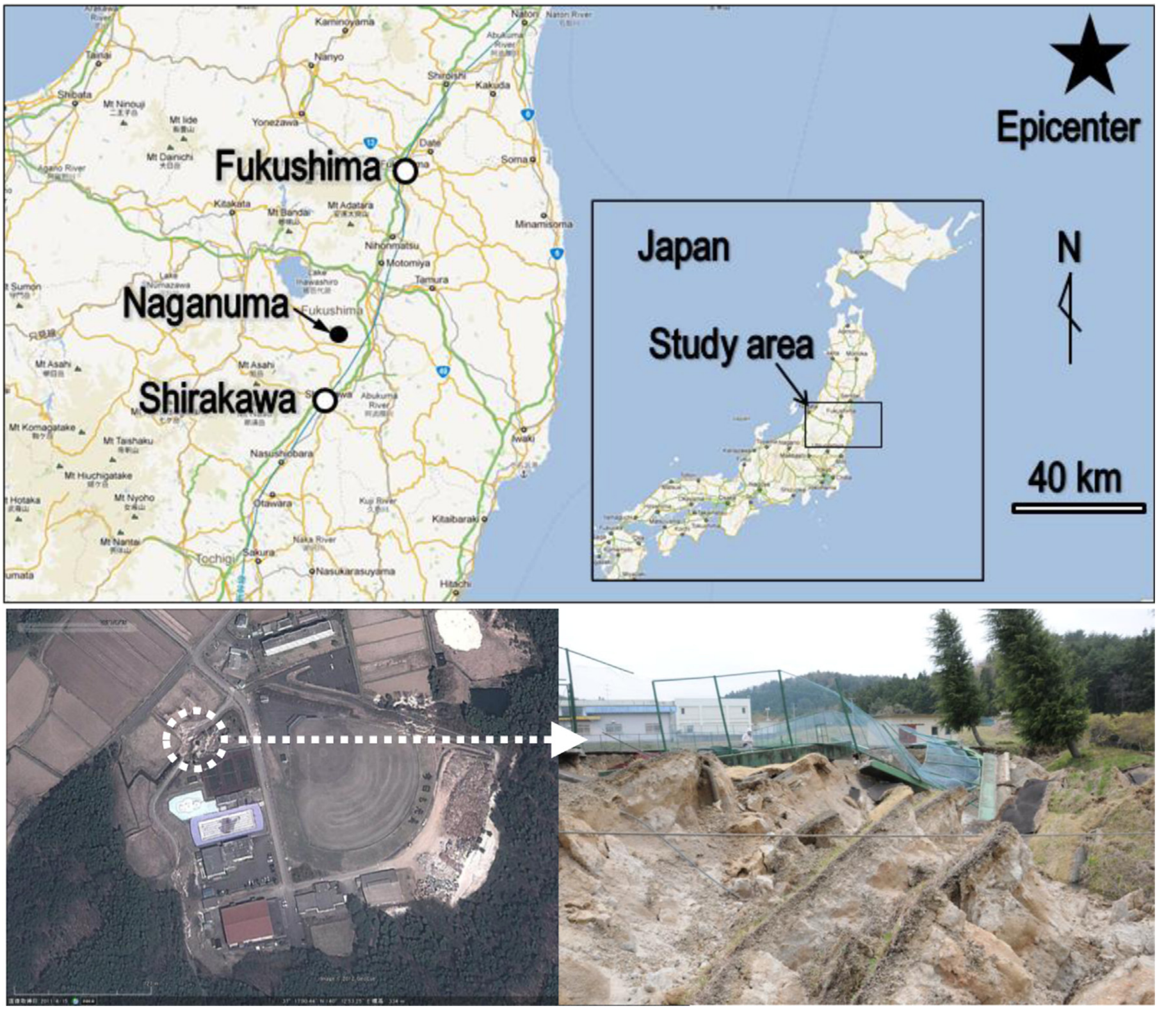


Fig. 1. Location of volcanic soil samples.

of the soil was determined by dry sieving and sedimentation tests, as shown in Fig. 2. For the purpose of comparison, the grading curve of Toyoura sand, a clean quartz sand that has been widely used in geotechnical engineering research [11,20], is also included in the plot. Apparently, the volcanic soil has a wider range of grain size, with a mean size of 982 μm and the coefficient of uniformity of 4.39. The percentage of fine particles (< 63 μm) in the soil was measured to be 5–7% by weight, which is significantly less than that (23%) of the volcanic soil at the Aratozawa landslide site in the prefecture of Miyagi, Japan [19], but is greater than the fines content (0.3%) of the volcanic soil in Mori prefecture of Japan [17]. The plasticity index of the fines was determined to be 26.2. The specific gravity of the volcanic soil was measured to be 2.56, which is slightly lower than that of Toyoura sand (2.65), but slightly larger than that of the volcanic soil at the Aratozawa landslides site (2.47). Compared to the volcanic soil in Mori ($G_s = 2.82$), its specific gravity is markedly smaller. More detailed information about index properties of the volcanic soil is summarized in Table 1.

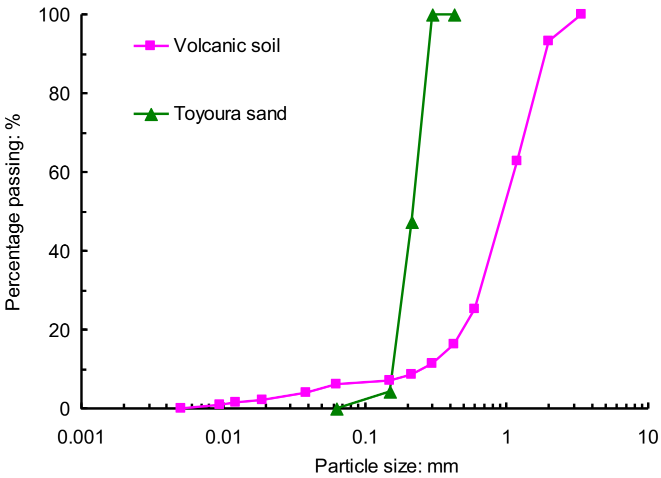


Fig. 2. Particle size distribution curves of volcanic soil and Toyoura sand.

Images were taken for soil grains sorted by size using a light microscope, as shown in Fig. 3. Generally, these grains are more angular and irregular than Toyoura sand grains. A careful examination of the images indicates that there are four major types of minerals in the volcanic soil, as shown in Fig. 4; they are amphibole (black and elongate), plagioclase (gray and blocky), quartz (colorless and translucent) and pumice (brown with rough surface). Among these minerals, pumice has been found in many volcanic soils; it is a lightweight porous material typically formed during explosive volcanic eruptions. Because of the existence of the intra-particle voids, pumice is prone to crushing when subjected to loading. In recent years pumice has been used as a construction material for producing lightweight concrete and subgrades of pavements [21].

Table 1
Physical properties of test materials.

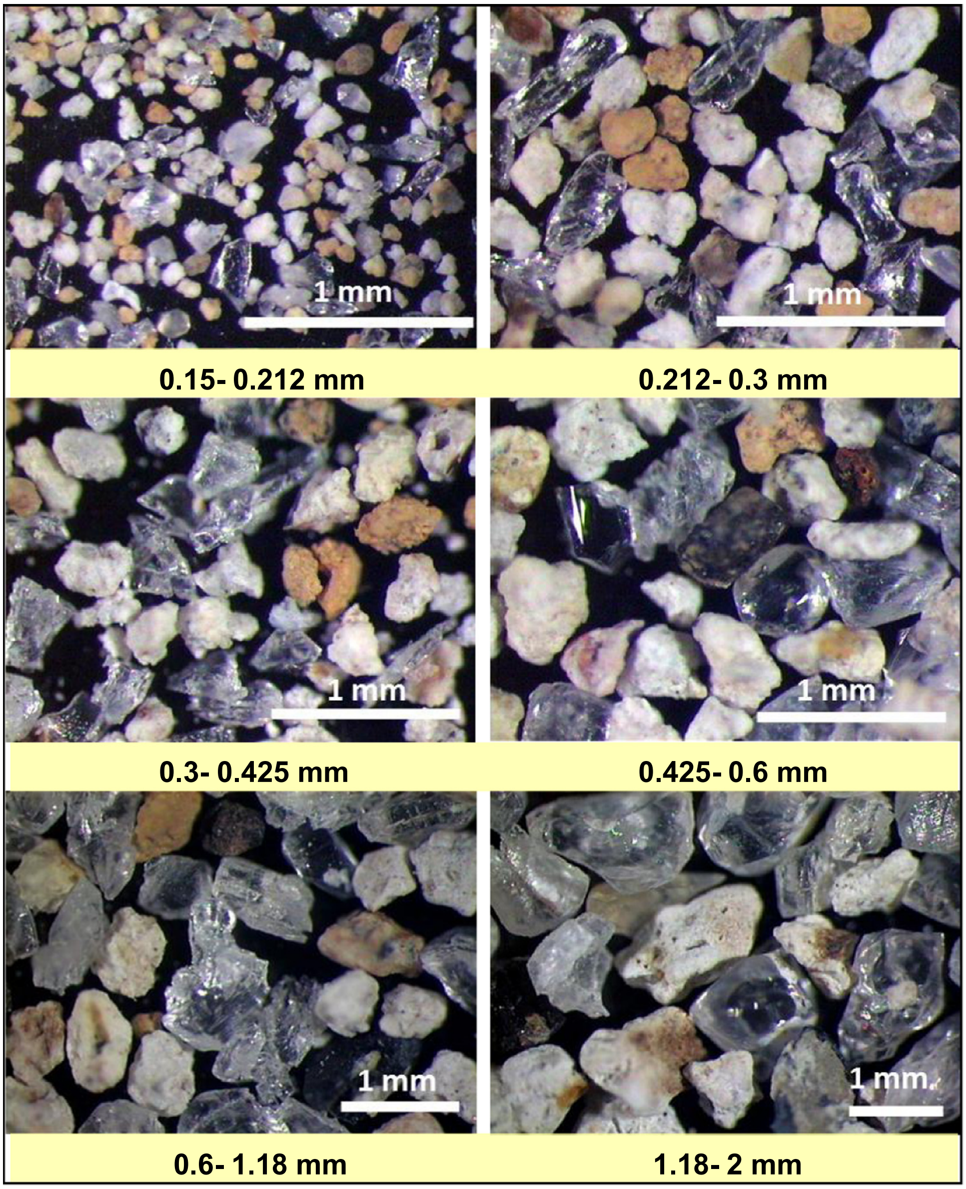
Soil sample	C_u	D_{50} (μm)	D_{60} (μm)	PI	G_S
Volcanic_O	4.39	982	1137	–	2.56
Volcanic_NF	3.00	1023	1170	–	2.57
Volcanic_X	2.98	971	1107	–	2.57
Fujian sand	2.92	982	1137	–	2.65
Toyoura sand	1.39	216	231	–	2.65

Note:
C_u=coefficient of uniformity; PI=plasticity index; G_s=specific gravity.
Volcanic_O: Original volcanic soil sample.
Volcanic_NF: Volcanic soil sample without fines.
Volcanic_X: Volcanic soil sample without fine and coarse particles.

2.2. Equipment and method

Resonant column tests have been widely used to determine the shear modulus of soils at small strains [1,13]. The resonant column apparatus in this study is of bottom-fixed and top-free configuration. Compared with the free-free configuration, the fixed-free configuration has the advantages of high available torque and convenient access to the specimen for control of effective stress. The apparatus can accommodate a soil specimen of 50 mm in diameter and 100 mm in height, with an air-filled cell pressure up to 1 MPa and an internal high-resolution LVDT for measurement of the specimen's deformation (Fig. 5(a)). A careful calibration of the equipment was carried out using aluminum bars of different dimensions to establish a calibration curve for the frequency-dependent mass polar moment of inertia of the drive head [22].

Specimens of volcanic soil were prepared using the dry tamping method, which is similar in principle to the methods used by several researchers in testing granular soils (e.g. [23,24]). A predetermined mass of soil was first oven-dried and then cooled down in an airtight container so that the potential influence of absorbed moisture was ruled out. Each soil specimen was prepared in five layers and compacted using a tamper after placing each layer (Fig. 5(b)). No obvious segregation was observed during sample preparation. After sample preparation, the drive head and the load cell were installed. As the suction inside the sample was gradually released, an initial confining stress of 30 kPa was applied. Isotropic confining pressures were applied in steps as 50,



0.15- 0.212 mm
0.212- 0.3 mm
0.3- 0.425 mm
0.425- 0.6 mm
0.6- 1.18 mm
1.18- 2 mm

Fig. 3. Microscope images of volcanic soil samples sorted by particle size.

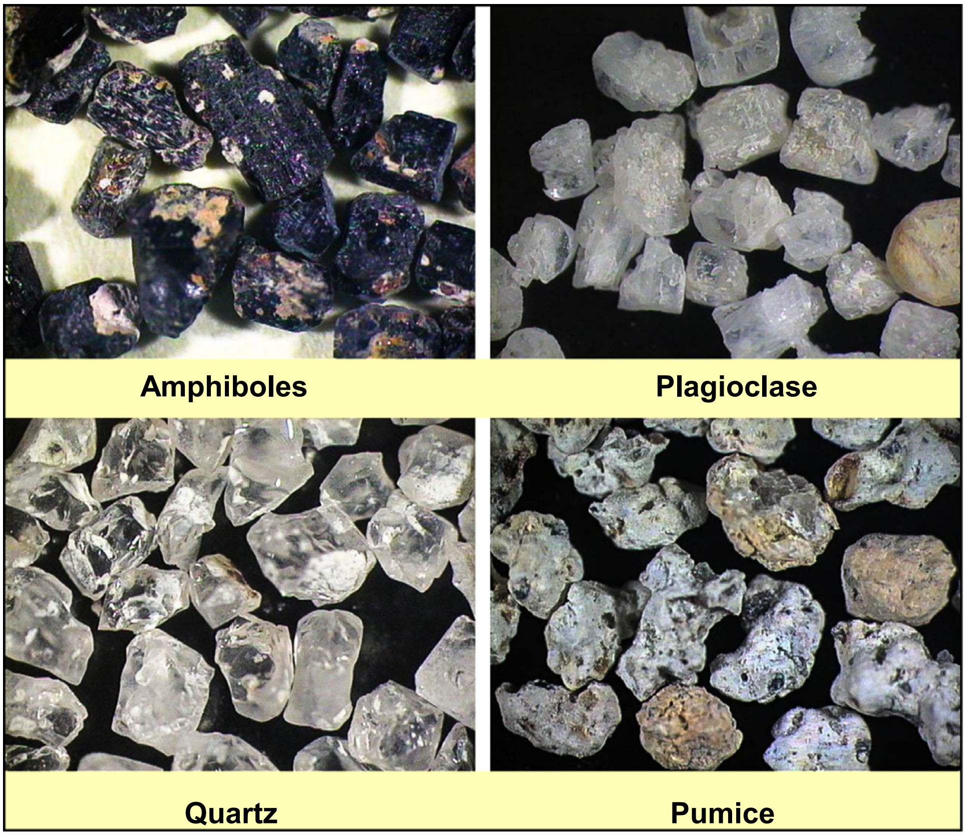


Fig. 4. Four types of minerals identified in volcanic soil samples. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

100, 200, 300 and 400 kPa. In bringing the specimen to a specific confining stress level, the specimen was first consolidated for 30 min at this stress level so that the readings of the internal LVDT became stable; this was then followed by resonant column testing. The strain level involved in all tests was in the order of 10^{-5}. All tests were conducted under dry conditions. For coarse granular soils, it has been commonly accepted that the value of G_0 in dry conditions is similar to that in water saturated conditions as water cannot sustain shear stress [11,13]. It is worth noting, however, that the compression wave velocity is highly dependent on the degree of saturation and this dependence can have a significant impact on the vertical ground motion during earthquakes [25,26]. In addition, the degree of saturation can also impose an impact on the liquefaction resistance of granular soils [27].

3. Results and discussion

3.1. Original volcanic soil

The measurements of V_s and G_0 at three different confining stress levels (100, 200 and 400 kPa) are shown as a function of void ratio in Fig. 6(a) and (b), respectively. Clearly, at a given confining stress the shear modulus decreases with increasing void ratio, and for a given void ratio the shear modulus increases with an increase in confining stress. A similar observation of the void ratio and confining stress dependence is obtained on Toyoura sand as well, and the trend curves are also included in Fig. 6 for ease of comparison. Typical frequency response curves of the two soils are shown in Fig. 7, from which the resonant frequencies of the soils at different confining stresses and void ratios can be clearly identified.

Of more interest here is the marked difference in the measured G_0 values of the volcanic soil and Toyoura sand. At a given confining stress, Toyoura sand has significantly larger G_0 values than the volcanic soil. Note that this marked difference is not attributable to the difference of void ratio for the two soils. Refer to test data in Fig. 6(b): at a void ratio around 0.85, the G_0 value of Toyoura sand under the confining stress of 400 kPa is about 158 MPa, which is over 30% higher than that of the volcanic soil under the same confining stress level and at a similar void ratio. At the confining stress of 100 kPa, the G_0 value of Toyoura sand at the similar void ratio is about 85 MPa, more than 70% larger than that of the volcanic soil. It is worth noting that a larger overlap in void ratio for the two soils is not attainable because of the differences in their grain size and grain shape. Compared with Toyoura sand, volcanic soil grains are more angular in shape and have a wider range of size, thus giving larger void ratios.

To take into account the influence of void ratio, the measured G_0 values of the two soils are normalized by a void ratio function [5] as follows:

$$F(e) = \frac{(2.17 - e)^2}{(1 + e)} \tag{1}$$

While a variety of void ratio functions have been used in the literature for sands and clays [20,28], the above one is found to be effective for a range of granular soils including the volcanic soil studied here. In Fig. 8 the void ratio-corrected G_0 values of Toyoura sand and of the volcanic soil are plotted against the confining stress that is also normalized by a reference pressure (98 kPa). For each soil a best-fit curve with a high coefficient of determination ($R^2 > 0.98$) can be derived, yielding a relationship as follows:

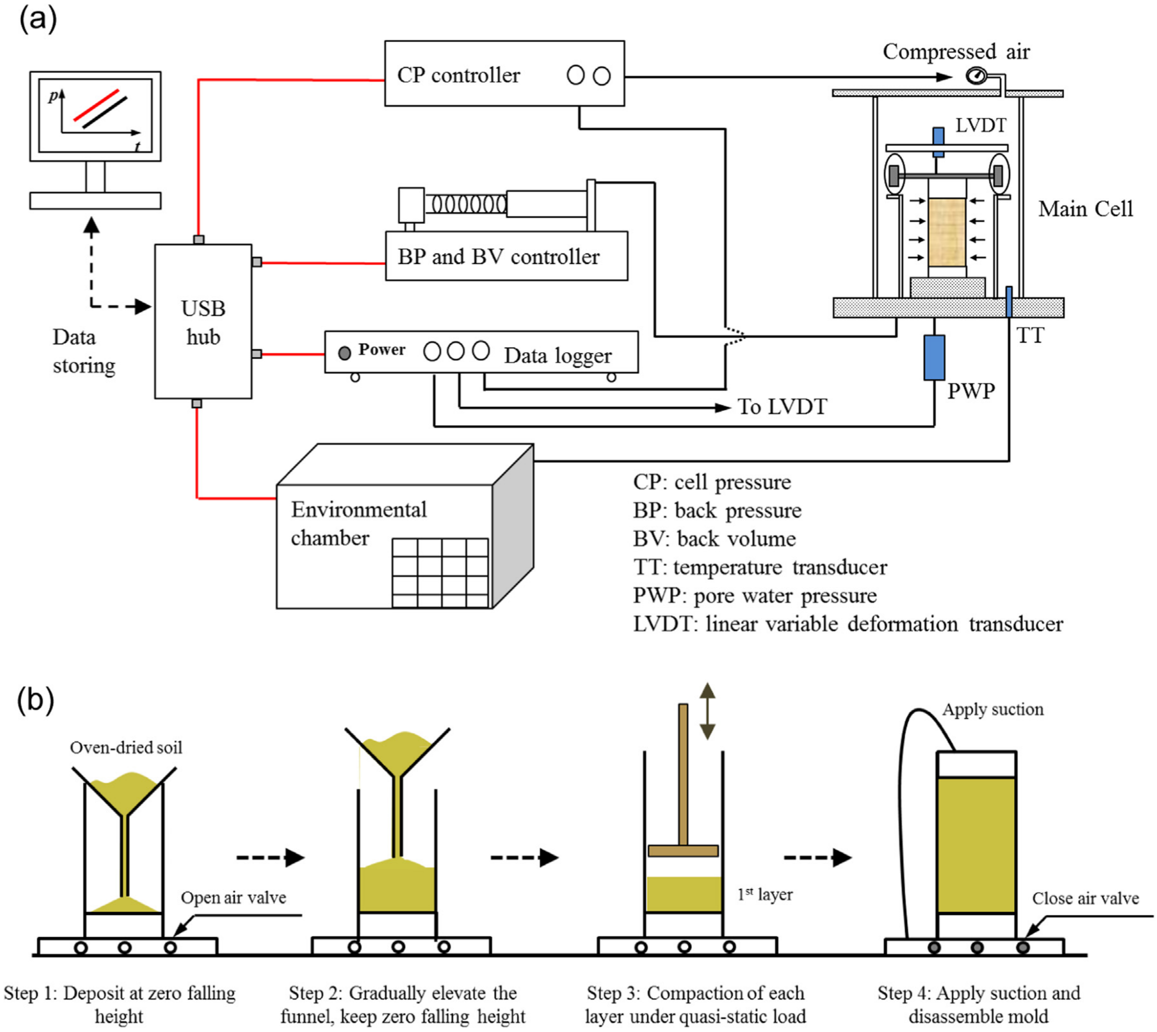


Fig. 5. Schematic illustrations for (a) experimental setup and (b) sample preparation.

$$G_0 = A\frac{(2.17-e)^2}{(1+e)}\left(\frac{\sigma}{p_a}\right)^n \tag{2}$$

where A (in MPa) is obtained to be 55.48 and 92.08 for the volcanic soil and Toyoura sand, respectively, and n is obtained as 0.60 for the volcanic soil and 0.41 for Toyoura sand.

The above relationship suggests that over the wide range of confining stresses applied, the normalized G_0 values of Toyoura sand are consistently greater than those of the volcanic soil. The stress exponents for both soils are greater than 1/3, a theoretical prediction derived for packings of spheres by using the classic Hertz contact law [29,30]. However, compared to Toyoura sand, the volcanic soil appears to be more sensitive to the mean effective stress, and this difference is considered to be due to their differing particle characteristics as will be discussed in the sections following.

3.2. Sieved volcanic soil

The difference in particle size gradation is considered to be a major contributor to the observed difference in shear modulus. In comparison with Toyoura sand, the volcanic soil contains a small amount of fine particles (see Table 1 and Fig. 2). To quantify the influence of gradation due to the presence of the fines, the fines in the original soil samples were removed by dry sieving to form samples without fines (denoted as Volcanic_NF). Furthermore, coarse particles with the diameter greater than 2 mm were removed to form samples without both fine and coarse particles (denoted as Volcanic_X). These two groups of sieved soil samples were then subjected to resonant column testing under similar conditions.

Interesting results are presented in Fig. 9, where G_0 values of the original volcanic soil samples (denoted as Volcanic_O) are compared with those of the sieved samples for three confining stress levels and for a range of void ratios. A marked feature here is that G_0 values of the sieved samples without fines become significantly higher than those of the original volcanic soil, and the increase due to removal of the fines tends to be more remarkable at high confining stresses. It is also of interest to note that further removal of the coarse grains does not result in a further increase of G_0; rather, the G_0 values of the sieved samples without fine and coarse particles (denoted Volcanic_X) are smaller than those of the sieved samples without fines but with coarse particles retained (Volcanic_NF). Nevertheless, both sieved samples exhibit higher stiffness than the original volcanic soil samples.

To remove the influence of void ratio, all G_0 values are normalized by the void ratio function in Eq. (1) and then plotted against the normalized confining stress, as shown in Fig. 10. It becomes clearer that over the range of confining stresses investigated, the original volcanic soil exhibits the smallest shear

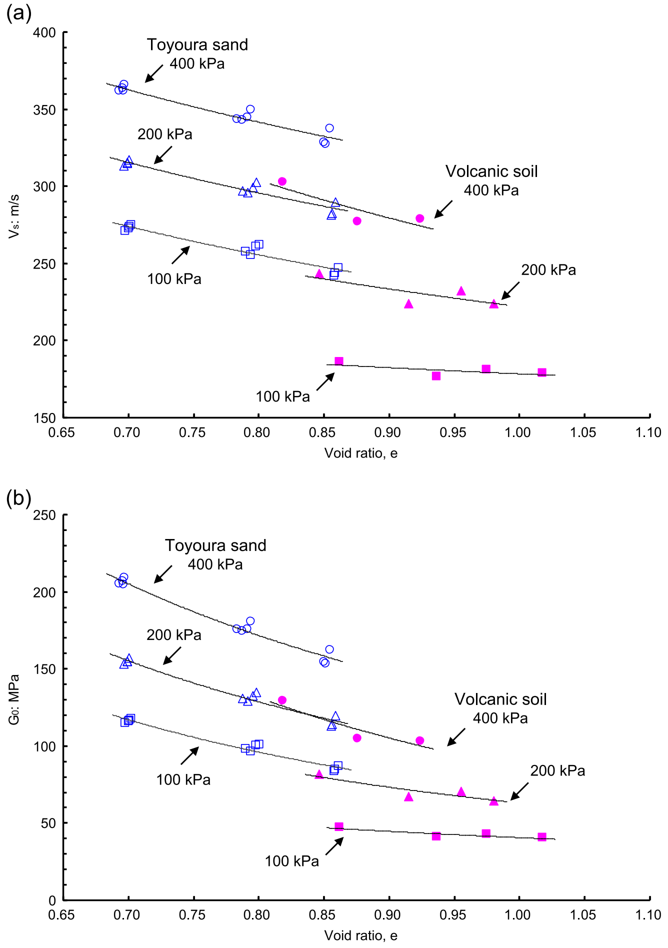


Fig. 6. Variation of (a) shear wave velocity and (b) shear modulus with void ratio at different confining stress levels: volcanic soil versus Toyoura sand.

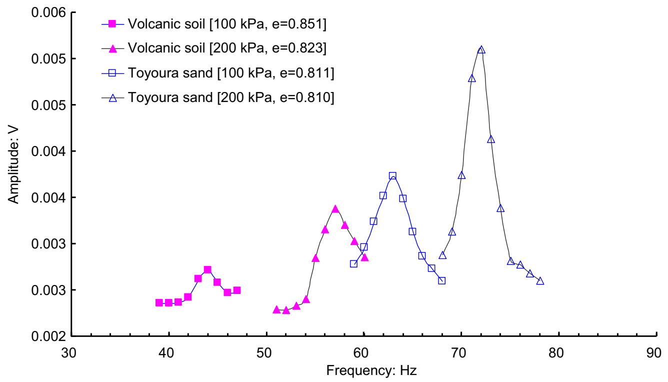


Fig. 7. Frequency response of volcanic soil and Toyoura sand at various confining stresses and void ratios.

modulus, whereas the sieved soil samples without fines have the largest shear modulus and shear wave velocity. For all three groups of soil samples, the relationship in Eq. (2) can be used to describe the confining stress and packing density dependence of G_0. The best-fit values for A and n for these soils are summarized in Table 2. Compared to the original volcanic soil samples, the stress exponent for samples of Volcanic_NF is 0.52 and for samples of Volcanic_X it is 0.55, both being less than the value for the original volcanic soil samples (0.6). The implication of this result is that removal of the fines tends to reduce the sensitivity of G_0 to the confining stress.

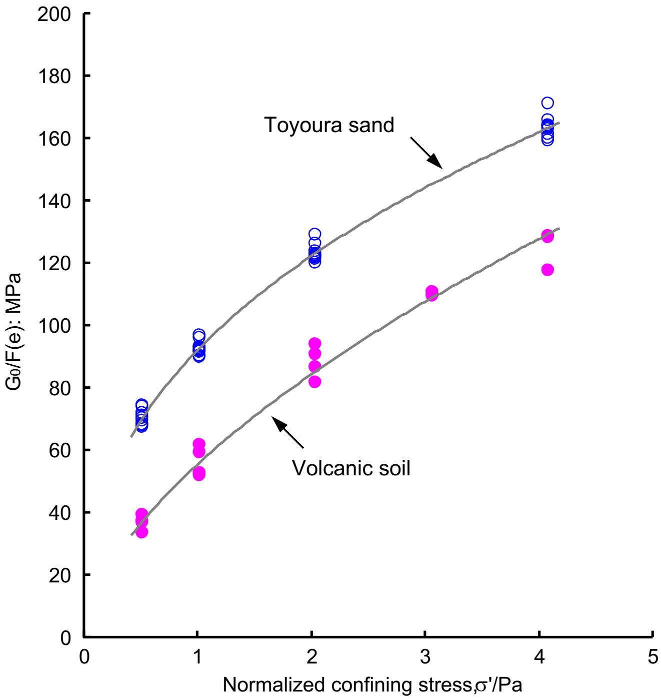


Fig. 8. Void ratio-corrected shear modulus as a function of normalized confining stress: volcanic soil versus Toyoura sand.

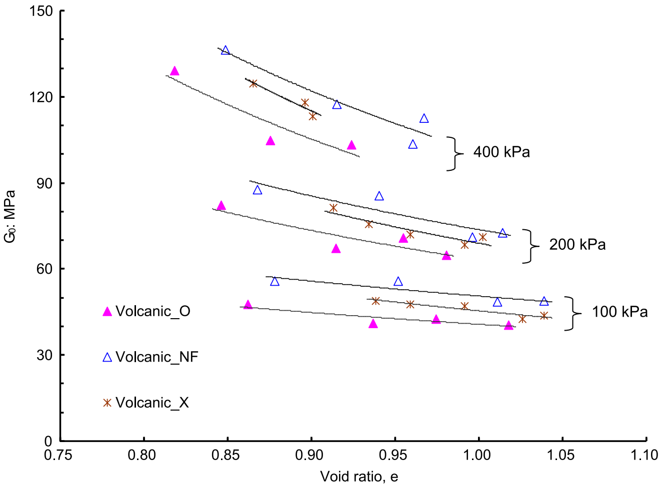


Fig. 9. Variation of shear modulus with void ratio at different confining stress levels: original and sieved volcanic soil samples.

3.3. Effect of mineralogy

It has been found that the existence of fines in the volcanic soil causes a significant decrease in shear modulus. This can be a main reason for the experimental result shown in Figs. 6 and 8 that G_0 values of the volcanic soil are markedly lower as compared with Toyoura sand. Nevertheless, one may speculate that the difference in G_0 may also be contributed by the difference in mineralogy of the two soils. As discussed before, four major types of minerals have been found in the volcanic soil while the predominant mineral of Toyoura is quartz. To investigate the potential influence of mineralogy, a quartz sand named Fujian sand, which has a larger coefficient of uniformity than the standard Fujian sand used by Yang and Wei [31] and than Toyoura sand, was subjected to sieving in the laboratory to produce samples with a gradation similar to that of the sieved volcanic soil samples without fine and coarse particles (i.e. Volcanic_X samples). The purpose of this treatment

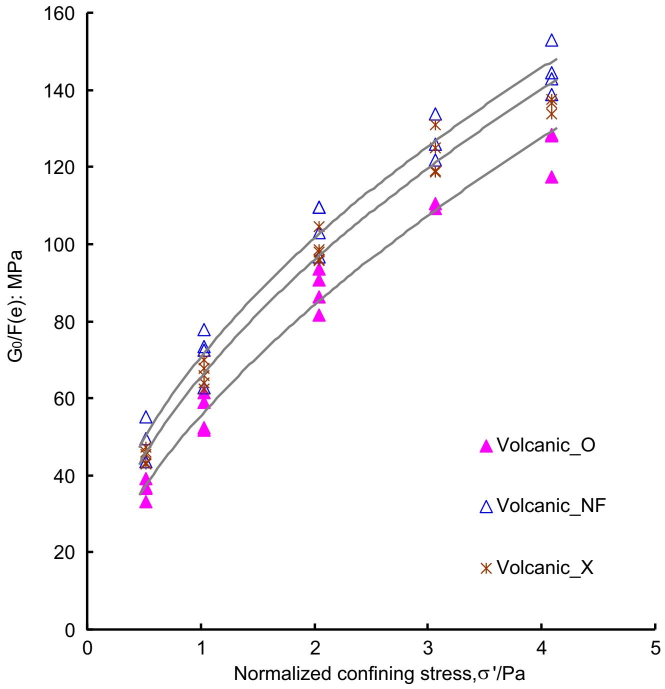


Fig. 10. Void ratio-corrected shear modulus as a function of normalized confining stress: original and sieved volcanic soil samples.

Table 2
Fitting parameters of test materials.

Soil sample	Fitting parameters in Eq. (2)		
	A (MPa)	*n*	R^2
Volcanic soil_O	55.48	0.60	0.98
Volcanic soil_NF	70.75	0.52	0.97
Volcanic soil_X	65.6	0.55	0.99
Fujian sand	75.21	0.45	0.99
Toyoura sand	92.08	0.41	0.99

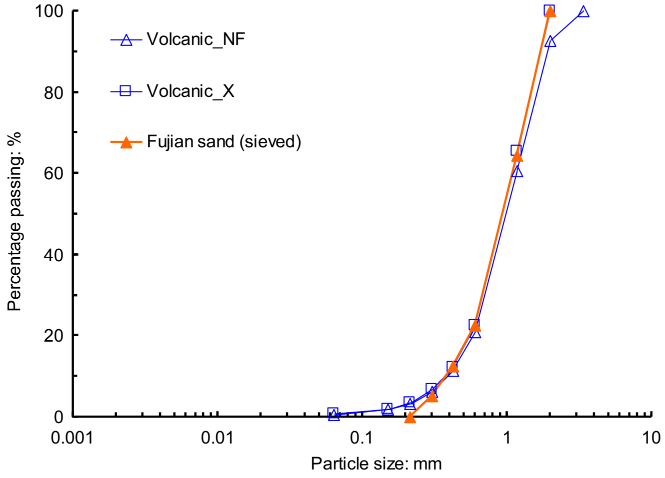


Fig. 11. Particle size distribution curves of sieved volcanic soil samples and sieved Fujian sand samples.

was to remove any possible influence of particle size and grading [22] and hence to approximately isolate the influence of mineralogy. Fig. 11 compares the grading curves of the two sieved volcanic soil samples with that of Fujian sand. As can be seen, Fujian sand and the volcanic soil without fine and coarse particles have a similar mean size and a similar coefficient of uniformity.

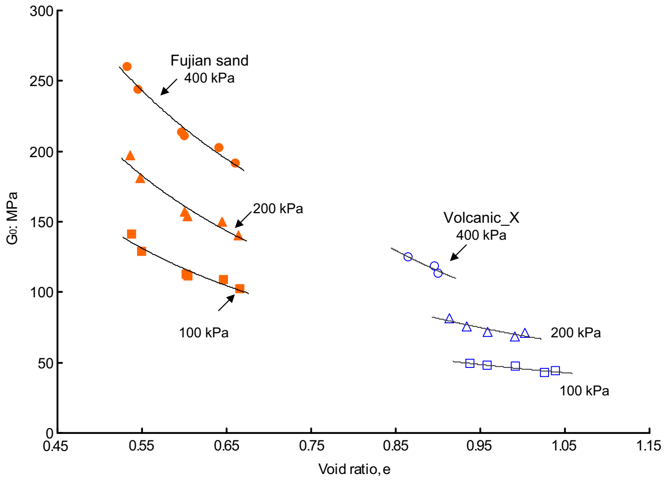


Fig. 12. Variation of shear modulus with void ratio at different confining stress levels: sieved volcanic soil versus Fujian sand.

For these two soils, the variations of G_0 values with void ratio are compared at three different confining stress levels in Fig. 12. A first glance seems to suggest that G_0 of Fujian sand remains to be significantly higher than that of the sieved volcanic soil, although the two soils have similar grading. However, this apparently big difference is considered to be mainly attributable to the difference in void ratio. Note that the values of void ratio for Fujian sand samples are significantly smaller than those for the volcanic soil samples. To remove the influence of void ratio, the void ratio function in Eq. (1) is used to normalize G_0 values, and the normalized G_0 values are plotted against the normalized confining stress in Fig. 13.

It becomes evident from Fig. 13 that if correction is made for void ratio, the two soils tend to have comparable G_0 values, particularly at large confining stresses (300 and 400 kPa). At lower confining stresses (50 and 100 kPa), the normalized G_0 values of Fujian sand are approximately 10–15% greater than those of the

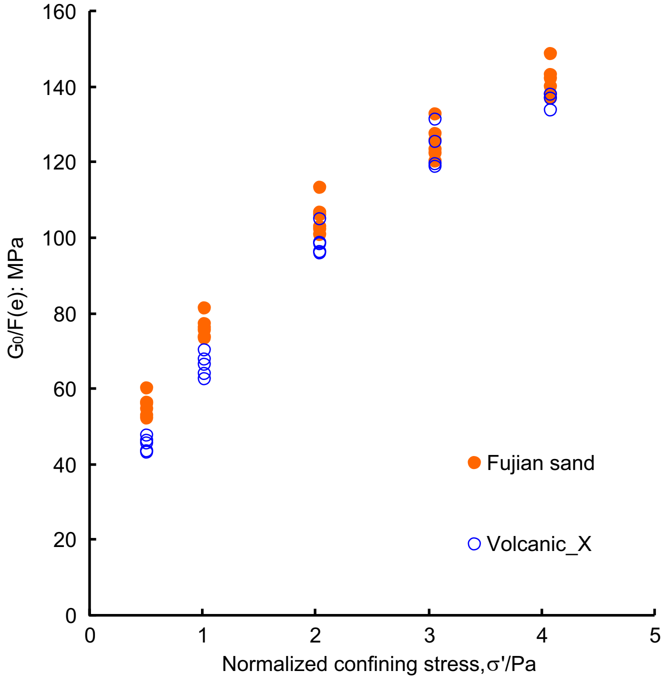


Fig. 13. Void ratio-corrected shear modulus as a function of normalized confining stress: sieved volcanic soil versus Fujian sand.

sieved volcanic soil. The observed difference is considered to be mainly related to different minerals of the two materials. The other factor that might also contribute to the difference in G_0 values is grain shape: compared with the shape of Fujian sand grains [31], the volcanic soil grains appear to be more angular. However, the influence of grain shape may have been largely reflected by the range of attainable void ratios [5]: For the volcanic soil with more angular grains the attainable void ratios are markedly larger, whereas for Fujian sand with more rounded grains the void ratios are much smaller (Fig. 12). In this connection the influence of grain shape is considered to be a secondary factor.

It is perhaps worth noting that the stress exponent for Fujian sand is derived to be 0.45, which is less than that for the sieved volcanic soil (0.55). The change of the stress exponent is likely to reflect that quartz sand grains are stronger and stiffer than volcanic soil grains which are more susceptible to deformation at contacts because of their mineralogy and angularity. From a micromechanics viewpoint [32–34], the stress dependence of modulus is closely associated with the contact conditions between grains.

3.4. A simple predictive model

Given the importance of G_0 in geotechnical engineering practice, a number of empirical models for predicting G_0 values have been proposed in the literature (e.g. [10,35]). These predictive models were derived mainly from experimental data on clean uniform quartz sands for which the variation of the coefficient of uniformity (C_u) is insignificant and hence the effect of C_u is ignored. Most recently an empirical model accounting for the effect of grain size distribution was suggested by Wichtmann and Triantafyllidis [12], based on a well-structured resonant column testing program on quartz sands. In this model the small-strain shear modulus is given as:

$$G_0 = A\frac{(a-e)^2}{(1+e)}p_a^{(1-n)}\sigma^n \tag{3}$$

where e is void ratio, σ is mean confining stress, and p_a is a reference pressure (taken as 100 kPa). The parameters A, a and n are all expressed as a function of the coefficient of uniformity (C_u) as follows:

$$a = c_1 \exp(-c_2 C_u) \tag{4}$$

$$n = c_3 (C_u)^{c_4} \tag{5}$$

$$A = c_5 + c_6 (C_u)^{c_7} \tag{6}$$

where the parameters c_1 to c_7 were given the following values: $c_1=1.94$, $c_2=0.066$, $c_3=0.4$, $c_4=0.18$, $c_5=1563$, $c_6=3.13$, and $c_7=2.98$.

It is of interest to examine whether the above empirical model is applicable to the volcanic soil studied here. In doing that, G_0 values of the original and sieved volcanic soil samples are calculated using Eqs. (3)–(6) and the C_u values given in Table 1, and then plotted against laboratory measurements in Fig. 14(a). The predictions and measurements for the two quartz sands of different C_u values (Toyoura sand and Fujian sand) are also included in the same plot. It can be seen that the empirical relationship in Eq. (3) significantly underestimates G_0 values of volcanic soil samples. While the empirical relationship appears to perform better for the two quartz sands, it still yields G_0 values that are 10–15% less than the measurements.

The empirical model in Eq. (3) is also used to predict G_0 values for several volcanic soils reported in the literature for which laboratory measurements are available. A comparison of the predictions and measurements is shown in Fig. 14(b), where the volcanic soil of Sahaphol and Miura [17] is a natural soil sampled from the prefecture of Mori, Japan and the material tested by Senetakis et al. [36] is crushed volcanic rock of sand size. It can be seen that the model also underestimates G_0 values for these two soils. A relatively significant scatter is observed on data of Sahaphol and Miura [17]; it is not clear whether this scatter was caused by uncertainties involved in the bender element tests used to determine V_s and then G_0 values. A number of studies have shown the variability in bender element test results associated with interpretation of shear wave signals [11,13,22].

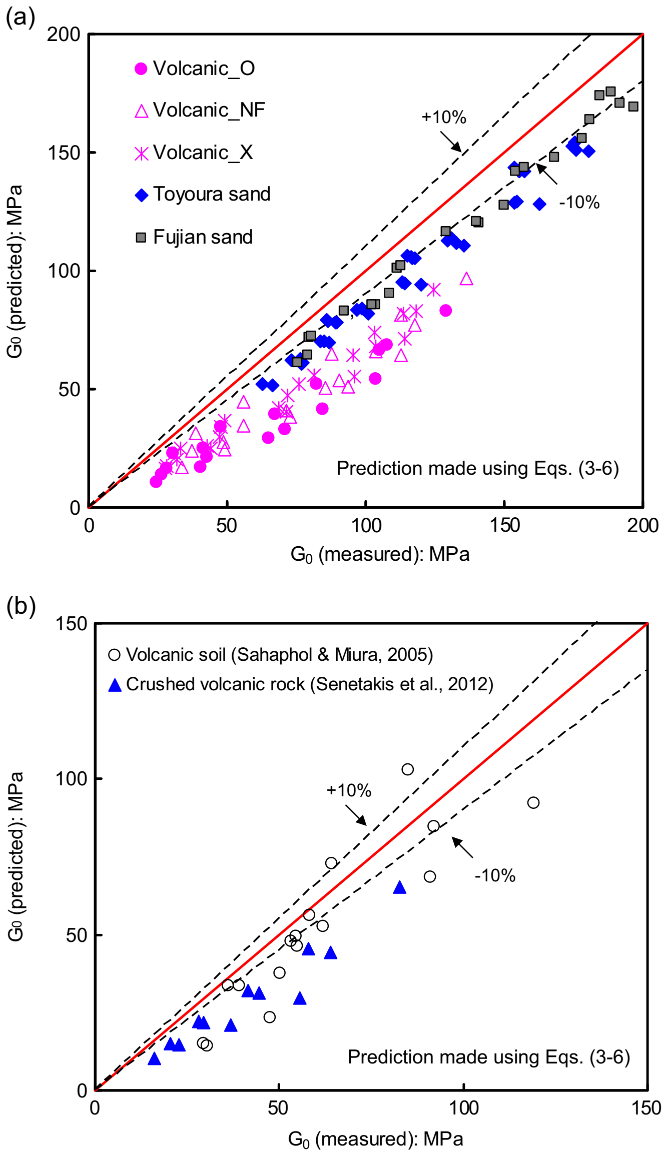


Fig. 14. Predicted and measured values of shear modulus: (a) original and sieved volcanic soils and quartz sands tested; (b) volcanic soils in literature.

The comparisons shown in Fig. 14 suggest that the empirical equations derived from experiments on clean quartz sands may not be well suited to volcanic soils. To facilitate practical applications, there is a need for a predictive model that can be used as a first approximation to provide acceptable estimates of G_0 values for volcanic soils as well as for quartz sands. In doing that, the general form expressed in Eq. (2) for G_0 is adopted, but the coefficient A and the stress exponent n are treated as functions of the coefficient of uniformity as follows:

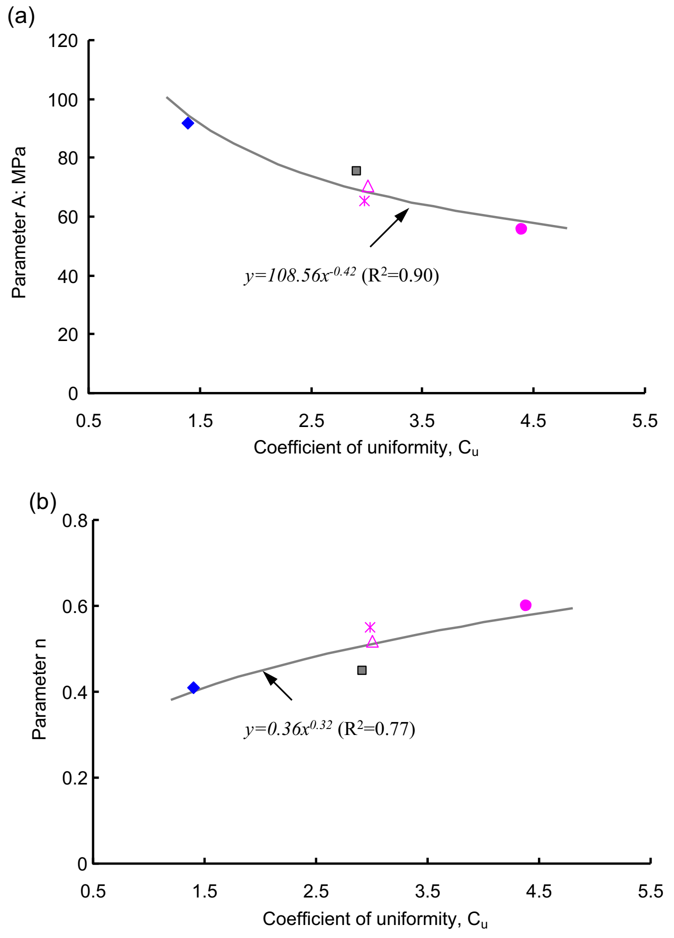


Fig. 15. Variation of shear modulus parameters with the coefficient of uniformity for tested soils: (a) parameter A; (b) parameter n.

$$A = a(C_u)^{\alpha} \tag{7}$$

$$n = b(C_u)^{\beta} \tag{8}$$

where parameters a, b, α, and β are derived from calibration of test data in the way shown in Fig. 15, where data for both the original and sieved volcanic soil samples as well as for Toyoura sand and Fujian sand are used. The calibration yields the following: $a=108.56$ (MPa), $\alpha=-0.42$, $b=0.36$, $\beta=0.32$. Note that the coefficient of uniformity is selected here as a controlling factor because both the original and sieved volcanic soil samples are continuously graded (Figs. 2 and 11). This differs from the case of sand-fines mixtures formed by mixing fines of varying quantities with base sand [37,38], for which the fines content appears to be a more appropriate factor to account for the influence of fines because these mixtures are generally gap graded.

Predictions for all the soils tested are then made using this simple model and compared with laboratory measurements in Fig. 16(a). Expectedly a much improved performance as compared with that shown in Fig. 14(a) is achieved. Furthermore, the performance of this new model is also examined against test data of Sahaphol and Miura [17] and Senetakis et al. [36], as shown in Fig. 16(b). Note that these literature data were not used to calibrate the model and hence the comparison can give an independent evaluation of the performance of the model. In comparison with that shown in Fig. 14(b), it is encouraging to note that the predictive performance is reasonably good. When more data become available, calibration of the parameters of the model expressed in Eqs. (7) and (8) can be improved and hence an improved performance can be yielded.

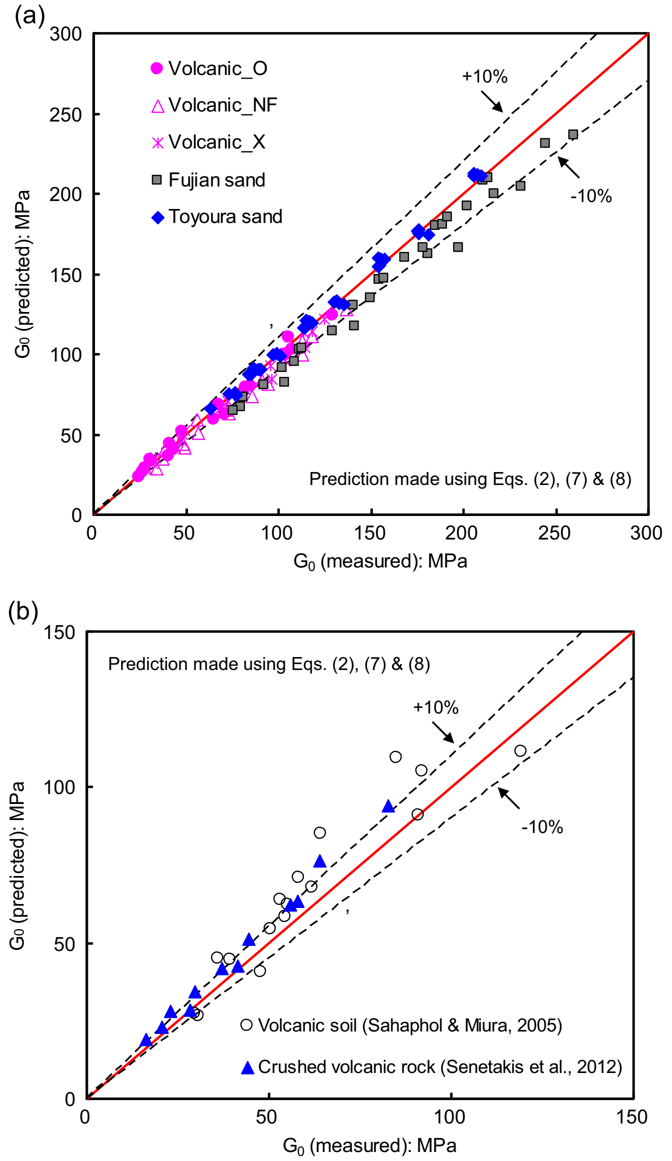


Fig. 16. Predicted and measured values of shear modulus: (a) original and sieved volcanic soils and quartz sands tested; (b) volcanic soils in literature.

Of final note is that several interesting issues on shear modulus of volcanic soils, such as the anisotropy and creep effects, are not discussed here because of the scope of the study, but further investigation is worthwhile.

4. Summary and conclusions

The mechanical properties of volcanic soils are of considerable interest from both academic and practical points of view. While numerous studies on conventional soils such as quartz sand and clay exist in the literature, available studies on natural volcanic soils are however very limited. This paper presents an experimental study focusing on the small-strain shear modulus (G_0) of a volcanic granular soil collected from a site in northeastern Japan where abundant evidence of ground failures due to the 2011 Tohoku earthquake was observed. Parallel tests have also been conducted on two quartz sands (Toyoura sand and Fujian sand) so as to give an insightful comparison. The main results and findings are summarized as follows.

(a) Compared with Toyoura sand, the volcanic soil exhibits markedly lower G_0 values over a wide range of confining stresses. This marked difference is caused mainly by the presence of fines (<63 μm) in the soil. It was shown that removal of the fines leads to a significant increase in shear modulus under otherwise similar testing conditions.
(b) The volcanic soil samples formed by removing both fines and coarse particles (>2 mm) exhibit G_0 values that are slightly smaller than those of Fujian sand. Given that the volcanic soil without fines and coarse particles has a similar grading with that of Fujian sand, the observed difference in G_0 values is attributable mainly to different mineral compositions of the two materials and the effect of grain shape is a secondary factor.
(c) The stress exponent derived for the original volcanic soil is markedly larger than that for quartz sands, but removal of the fines in the soil causes a notable decrease in the stress exponent. This finding suggests that the presence of fines and associated changes in particle size gradation play a role in the stress dependence of G_0.
(d) For the sieved volcanic soil with similar grading as Fujian sand, its stress exponent remains to be higher than that of Fujian sand. From a micromechanics viewpoint, this difference is likely to be attributable to volcanic soil grains being more susceptible to deformation at contacts because of their mineralogy and angularity.
(e) The predictive model developed from experimental data on quartz sands does not appear to work well for volcanic soils. The proposed model, which accounts for the influence of fines in terms of size gradation as well as the pressure and density dependence of G_0 in a simple way, shows an acceptable performance in estimating G_0 values for both volcanic soils and quartz sands. Further refinement of the model is needed when more test data on volcanic soils become available.

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