Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

The combined effect of clay and moisture content on very small strain stiffness of compacted sand-clay mixture

L'effet combiné de la teneur en argile et de la teneur en eau sur la très faible rigidité de déformation du mélange compacté sable-argile

Vasileios Matziaris
VJTech Limited, Reading, UK, vasileios@vjtech.co.uk

Meghdad Bagheri
School of Energy, Construction, and Environment, Coventry University, Coventry, UK

ABSTRACT: The very small strain shear modulus (stiffness) of soils, G_{max}, is one of the most important parameters for predicting ground movements and dynamic responses of geo-structures. In this study, the combined effect of clay fraction and moisture content on shear stiffness of an unsaturated sand-clay mixture at very small strains was investigated using bender elements. Compacted soil specimens were prepared at three different clay contents of 10, 20, and 30%, and at four different initial moisture contents of 3, 6, 9 and 12%. Bender element tests were carried out under isotropic and constant moisture content conditions and inside a modified triaxial testing system equipped with a pair of piezoelectric bender-extender elements. G_{max} was calculated based on the velocity measurement of shear waves propagated through the specimen. The tests results showed that G_{max} decreases approximately linearly with an increase in moisture content, and non-linearly with an increase in clay content. A basic empirical equation was derived from an examination of trends in evolution of G_{max} with clay and moisture content. Additional empirical correlations were also derived for estimation of moisture content and degree of saturation based on the compression wave velocity measurements.

RÉSUMÉ : Le module de cisaillement (rigidité) à très petite déformation, G_{max}, est l'un des paramètres les plus importants pour prédire les mouvements du sol et les réponses dynamiques des géo-structures. Dans cette étude, l'effet combiné de la fraction d'argile et de la teneur en eau sur la rigidité au cisaillement d'un mélange de sable-argile insaturé à de très petites déformations a été étudié en utilisant un système de mesure d'ondes type «Bender Elements». Des échantillons de sol compactés ont été préparés à trois teneurs différentes en argile de 10, 20 et 30%, et à quatre teneurs en eau initiales différentes de 3, 6, 9 et 12%. Les essais «Bender Elements» ont été effectués dans des conditions isotropes et constantes de teneur en eau à l'intérieur d'un système triaxial modifié équipé d'une paire de «Bender Elements» piézoélectriques. G_{max} a été calculé sur la base de la mesure de la vitesse des ondes de cisaillement propagées à travers l'échantillon. Les résultats des tests ont montré que G_{max} diminue approximativement linéairement avec une augmentation de la teneur en eau, et de manière non linéaire avec une augmentation de la teneur en argile. Une équation empirique de base a été déduite d'une étude des tendances de l'évolution de Gmax avec l'argile et la teneur en eau. Des corrélations empiriques supplémentaires ont également été calculées pour l'estimation de la teneur en eau et du degré de saturation sur la base des mesures de la vitesse de l'onde de compression.

KEYWORDS: Small strain stiffness, Bender elements, Moisture content, Clay content

1 INTRODUCTION

Geotechnical engineering activities are often involved application of compacted soils as construction materials in a variety of earthworks. Compacted soils, comprised of sand, silt, and clay mixtures of different proportions, are typically used as fill materials behind retaining structures, beneath foundations, and in road embankments. The strain level behind these earth structures has been shown to be in the range of very small (0.001%) to small (1%) strains. Therefore, the small and very small strain stiffness (G_{max}) of the compacted soils generally governs the deformation characteristics of these geo-structures (Burland 1989).

Determination of G_{max} values of soils in laboratory is often done using bender elements technique. This technique enables estimation of G_{max} based on the measurement of shear (S) and compression (P) wave velocities (V_s and V_p) within a soil specimen. The magnitude of G_{max} has been shown to be influenced by several factors including stress history, current stress state and soils' physical and hydraulic properties. In particular, the impact of soils' hydraulic properties, mainly suction and degree of saturation (S_r), on G_{max} has received a significant attention in the literature. Qian et al. (1993) showed that for an unsaturated sand, starting from a completely dry state, the values of G_{max} increases with increase in degree of saturation to a peak value (optimum S_r) then decrease. Similarly, G_{max} was found to rapidly increase with increase in soil suction to a peak value then decrease or level off (Marinho et al 1995, Ng et al. 2009). Pagano et al. (2016) showed that for a well-graded sandy soil, stiffness increases with increase of suction (decrease of S_r) over the drying path of the soil water retention curve. However, at the same suction, the lower the degree of saturation (wetting path), the higher is the measured shear wave velocity and its corresponding magnitude of G_{max}. This indicates the dominant role of the degree of saturation on soil stiffness.

This paper presents an experimental investigation of G_{max} of sand-clay mixtures with different clay contents under isotropic stress state and unsaturated conditions with the aim to identify the coupled and dominant role of clay fraction and moisture content (and corresponding S_r) on small strain stiffness. Basic empirical formulas correlating these variables are introduced.

2 TEST SETUP

In this study, a bender element setup for triaxial testing equipment by VJTech Ltd was used. The test setup is shown in Figure 1. A pair of bender-extender (BE) elements was used for measurement of S- and P-wave velocities. The BE elements enable transmitting and receiving both S- and P-waves using a single pair of piezoceramic elements and hence, measurement of S- and P-wave velocities over the same soil path. One benefit of using such hybrid elements is the ability to measure G_{max} based on S-wave velocity along with other properties such as porosity and degree of saturation based on P-wave velocity. The BE elements were accommodated in the loading cap and pedestal of the triaxial cell. The protrusion length of the BE elements was 3 mm which was also the penetration depth within the soil specimen. An interface unit (benderscope) was used to generate a driving signal through the specimen from the BE element in the top cap (transmitter) to the BE element in the base pedestal (receiver).

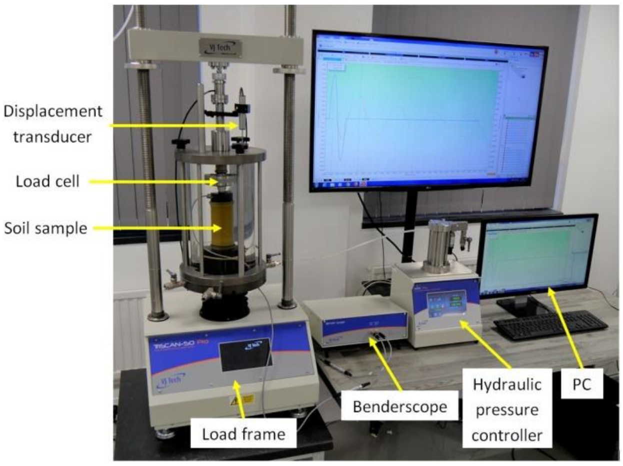

Figure 1. Bender element setup for triaxial testing equipment

3 MATERIAL PROPERTIES AND SPECIMEN PREPARATION

The soil material used in this study is a sand-clay mixture obtained from mixing of uniform Congleton sand with Speswhite kaolin clay. Consideration of this mixture enables better control over the amount of fine grains and therefore capturing the impacts that clay content may have on the stiffness. Triaxial soil specimens of 50 mm diameter and 100 mm height were prepared at three different clay contents (c_0) of 10, 20, and 30%, and at four different initial gravimetric moisture contents (w_0) of 3, 6, 9 and 12% using moist tamping method. A good contact between the BE elements and the soil specimen was achieved by sculpturing a small groove at each end of the specimen and filling it with a paste made of the same soil material but with higher moisture content. The properties for each soil specimen are given in Table 1. At the end of each test, the specimen was split into three equal parts (top, bottom and middle) and final moisture content (w_f) values were measured based on the mean value of the moisture contents obtained from oven drying these three parts.

4 EXPERIMENTAL PROGRAMME

To study the coupled effects of clay and moisture contents on soil stiffness, 12 tests were carried out under isotropic and constant moisture content conditions. Once the specimen was setup in the triaxial cell, a small seating load was applied. A confining pressure of 100 kPa was then applied and the specimen was left for a few hours to equalize. Single sinusoidal S and P pulses were triggered at an input frequency of f_{in} = 2 kHz and input voltage of V_{in} = 10 V. The transmitted and received waveforms were analysed using the VJTech software.

The wave velocity (V) and the corresponding stiffness modulus (G_{max}) were calculated using the following equations;

$$V = \frac{L_{tt}}{\Delta t} \tag{1}$$

$$G_{max} = \rho_b \times V^2 \tag{2}$$

$$\rho_b = \left(\frac{G_s + S_r e}{1+e}\right)\rho_w = \left(\frac{G_s(1+w)}{1+e}\right)\rho_w \tag{3}$$

where L_{tt} is the tip-to-tip distance between the sender and receiver BE elements, Δt is the wave travel time, ρ_b is the bulk density of the soil, G_s is the specific gravity of the soil, e is void ratio, and ρ_w is the density of water. Different methods can be found in the literature for determination of Δt including; (1) first arrival time, (2) travel time between characteristic points (peaks and troughs), (3) travel time by cross-correlation of input and output signals, and (4) travel time by cross-power of transmitted and received signals (Leong et al. 2005). There are errors and uncertainties in measurement of travel time using each of these four methods. In this study, the arrival time Δt was determined based on the method of characteristic points and travel time to the first bump maximum. However, where the first bump was not visible, the first deflection was considered for determination of Δt as suggested by Leong et al. (2005).

Table 1. Properties of the soil specimens

Sample ID	c_0 (%)	w_0 (%)	w_f (%)	ρ (Mg/m^3)	ρ_d (Mg/m^3)	e_0 (-)
M10-3	10	3.0	3.3	1.80	1.74	0.503
M10-6	10	6.0	5.8	1.94	1.83	0.429
M10-9	10	9.0	8.6	2.03	1.87	0.402
M10-12	10	12.0	11.2	2.01	1.80	0.449
M20-3	20	3.0	3.0	1.63	1.58	0.656
M20-6	20	6.0	6.1	1.68	1.58	0.655
M20-9	20	9.0	8.9	1.92	1.77	0.486
M20-12	20	12.0	10.8	2.11	1.90	0.376
M30-3	30	3.0	3.8	1.48	1.43	0.830
M30-6	30	6.0	6.1	1.73	1.63	0.601
M30-9	30	9.0	9.0	1.80	1.65	0.581
M30-12	30	12.0	12.0	1.98	1.77	0.477

ρ_b: Bulk density, ρ_d: Dry density, e_0: Initial void ratio

5 RESULTS AND DISCUSSIONS

5.1 *Shear wave velocity*

Graphs of Figure 2 present the variation of shear wave velocity (V_s) with w_f, S_r, and c_0. As it is seen in Figure 2a, the values of V_s measured in specimens with c_0 = 10% increase with increase in moisture content to a peak value then decrease. This is not, however, the case for specimens with 20 and 30% clay content where the values of V_s appear to decrease approximately linearly with increase in moisture content. At a given clay content, the lower moisture content implies lower degree of saturation and available bulk water in the specimen. With increase in moisture content, and hence degree of saturation, a decrease in suction, and hence mean effective (skeleton) stress and shear wave velocity was expected (Mancuso et al. 2002, Xiaoqiang et al. 2015) as shown in Figure 2b. Furthermore, as shown in Figure 2c, the values of V_s measured in specimens with w_0 = 3% increase with increase in clay content at a decreasing rate. This is not, however, the case for specimens with 6, 9, and 12% moisture contents where the values of V_s decrease non-linearly with increase in clay content. At a given moisture content, the higher clay content resulted in higher void ratios and lower degrees of saturation. The higher void ratio at a constant moisture content implies lower bulk density and inter-particle contact forces and hence, lower shear wave velocity.

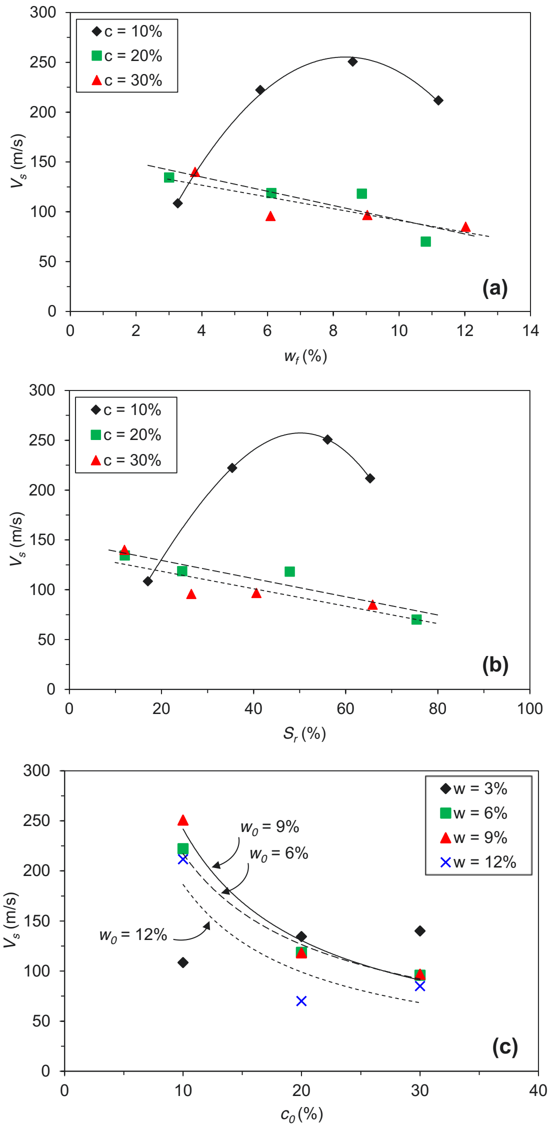

Figure 2. Variation of V_s with: (a) w_f, (b) S_r and (c) c_0.

5.2 *Compression wave velocity*

Graphs of Figure 3 present variation of compression wave velocity (V_p) with w_f, S_r, and c_0. As it is seen in Figures 3a and 3b, an increase in moisture content and hence, available bulk water and degree of saturation, generally results in higher V_p values as the compression wave travels faster in water. Discarding the deviated data points, it is observed that the variation of V_p with w_f and S_r is approximately linear for the range of moisture contents considered in this study. Furthermore, the rate of increase in V_p with w_f and S_r decreases with increase in clay content. Zhao et al. (2017) showed that an increase in clay content leads to an increase in void ratio and a decrease in water retention capacity. This may explain the observation of lower V_p values with increase in clay content (Figure 3c). For specimens with c_0 = 30%, variation of V_p with moisture content is minimal. This observation may suggest the minimal influence of moisture content at higher clay contents (> 30%).

As discussed earlier, the values of V_p can be used for determination of soils' hydraulic properties. The below empirical equations were derived for estimation of moisture content and degree of saturation of the compacted sand-clay mixtures used in this study;

$$w_f = 0.65\left(\frac{V_{p_0}-V_p}{c_0-28.7}\right) \tag{4}$$

$$S_r = 4\left(\frac{V_{p_0}-V_p}{c_0-28.4}\right) \tag{5}$$

In above equations, V_{p0} is the compression wave velocity measured in a completely dry state (zero moisture content). These correlations, although may not be generalized, can be used as the basis for development of other more comprehensive empirical correlations based on a wider tests results on different soil types, compositions, and stress states.

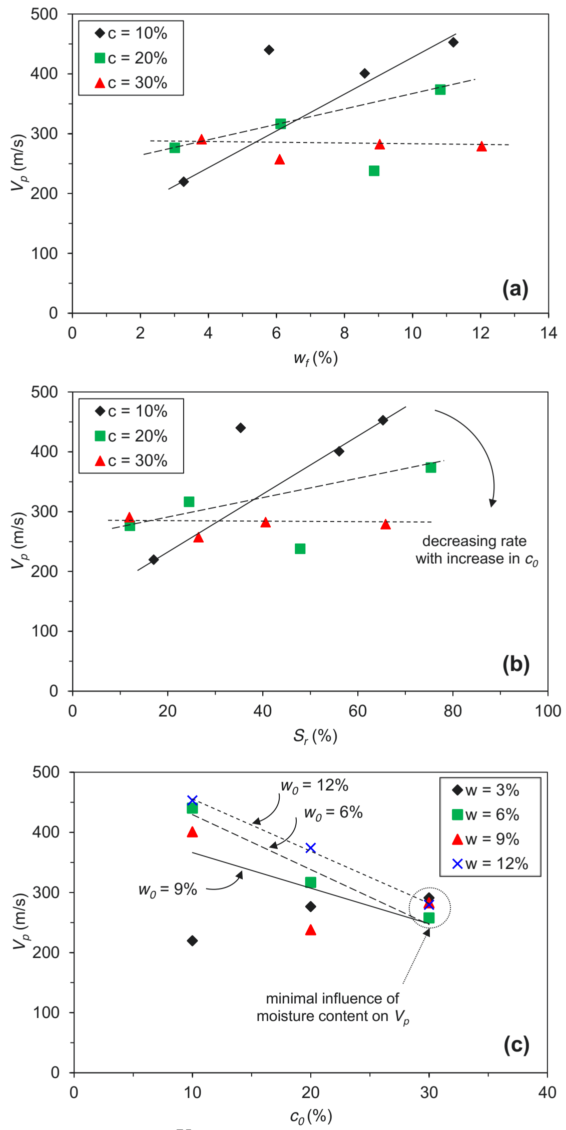

Figure 3. Variation of V_p with: (a) w_f, (b) S_r and (c) c_0.

5.3 *Small strain shear modulus*

Graphs of Figure 4 present variation of G_{max} with w_f, S_r, and c_0. As it is seen in Figures 4a and 4b, variation of G_{max} with w_f and S_r follows similar trends as those observed for shear wave velocity in Figures 2a and 2b. The values of G_{max} measured in specimens with c_0 = 10% increase with increase in moisture content (or degree of saturation) to a peak value then decrease. This behavior is in agreement with the experimental findings of G_{max} variations in an unsaturated sand as reported by Qian et al. (1993). However, such peak values are not observed for specimens with 20 and 30% clay contents, and G_{max} appears to decrease approximately linearly with increase in w_f or S_r. This observation may suggest the minimal influence of clay content in the lower range (< 10%). In general, the inverse relationship between the clay content and the degree of saturation implies lower soil stiffness with increase in clay content. Specimens with 30% clay content exhibit lower G_{max} than those with 20% clay content. For these specimens, variation of G_{max} with moisture content is minimal for $w_f \geq 6\%$. This observation may suggest the minimal influence of moisture content at higher clay contents (> 30%). Inspection of Figure 4c also reveals a non-linear relationship in the form of a power law between the small strain shear modulus and clay content for specimens with 6, 9, and 12% initial moisture contents;

$$G_{max} = a{c_0}^{b} \tag{6}$$

where, a is a soil constant that depends on the value of G_{max} at zero clay content, and b is given as;

$$b = -0.24 \ln w_0 - 1.29 \tag{7}$$

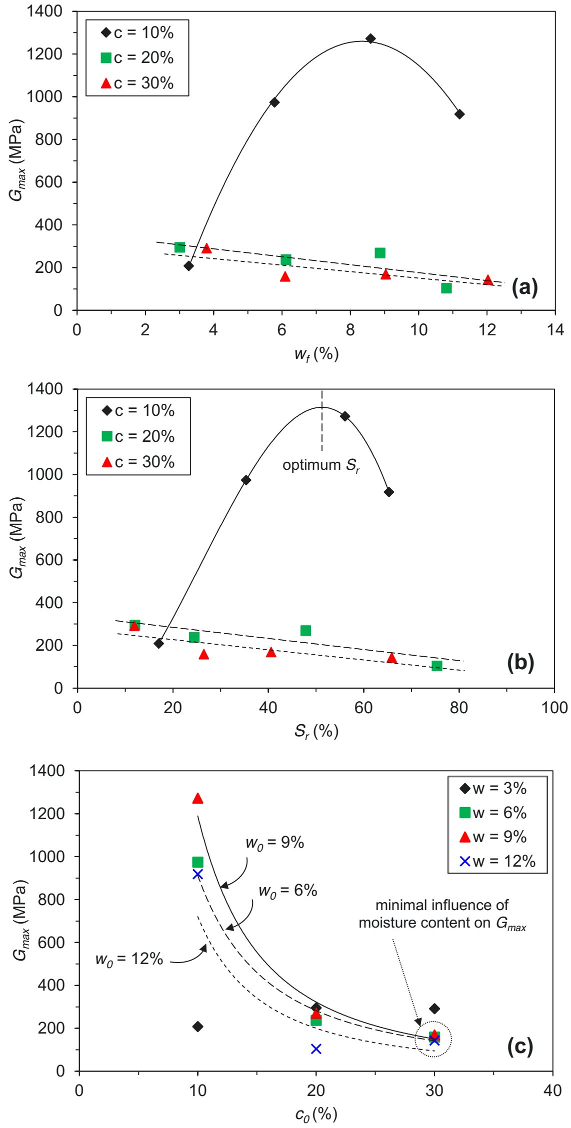

Figure 4. Variation of G_{max} with: (a) w_f; (b) S_r and (c) c_0.

It must be mentioned here that the above equations have been derived based on limited data and in the absence of suction measurements which can have a controlling influence on the stiffness. Therefore, their accuracy is subject to validation with a wider range of datasets in general, and consideration of soil suction measurements in particular for the tested mixture in this study.

The obtained results demonstrate that G_{max} generally decreases with increase in both moisture content and clay content. However, the influence of clay content on G_{max} is more pronounced. At a given moisture content, with increase in clay content, the degree of saturation decreases (Figure 5), suggesting a possible increase in shear wave velocity and hence, G_{max}. However, a parallel reduction in bulk density with increase in clay content not only offsets the possible degree of saturation-induced increase in G_{max}, but also further lowers the estimated G_{max}. This might be an indication of the dominant role of clay content over the moisture content. It should be mentioned here that, the slight discrepancies in measured V_s and calculated G_{max} values could be attributed to the small differences in the measured w_f values.

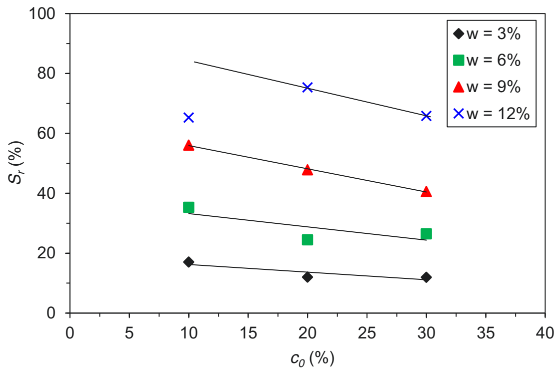

Figure 5. Variation of degree of saturation with clay content

6 CONCLUSIONS

In this study, the role of clay fraction and moisture content on small strain stiffness of a sand-clay mixture was experimentally investigated. The following conclusions are drawn:

- In general, G_{max} decreases approximately linearly with increase in moisture content, and non-linearly with increase in clay content.
- Although decrease in moisture content and the corresponding degree of saturation lead to an increment in soil stiffness, clay content appears to have a dominant role.
- The impact of clay content is minimal for $c_0 < 10\%$ and the response in terms of V_s and G_{max} are relatively similar to the samples with no fine grains as reported in the literature.
- Compression wave velocity increases approximately linearly with water content and degree of saturation, and decreases approximately linearly with clay content.
- The empirical formulae presented in this study were driven based on the limited experimental data and for the ranges of c_0 and w_0 considered in this study. Further investigations are required for validation of these correlations, where possible by consideration of suction measurements and the key role suction plays in determination of stiffness. Such empirical correlations, once validated, can be used as a reference for estimating the G_{max} of compacted sand-clay mixtures used in engineering practice and where the test data have not yet been obtained.

7 REFERENCES

Burland, J.B. 1989. Ninth Laurits Bjerrum Memorial Lecture: "Small is beautiful" – the stiffness of soils at small strains. *Canadian Geotechnical Journal* 26(4), 499-516.

Leong E.C., Yeo S.H. and Rahardjo H. 2005. Measuring shear wave velocity using bender elements. *Geotechnical Testing Journal* 28(5), 488-498.

Mancuso C., Vassallo R., and d'Onofrio A. 2002. Small strain behaviour of a silty sand in controlled-suction resonant column torsional shear tests. *Canadian Geotechnical Journal* 39(1), 22-31.

Marinho E.A.M., Chandler R.J. and Crilly M.S. 1995. Stiffness measurements on an unsaturated high plasticity clay using bender elements. *Proc. 1st Int. Conf. Unsat. Soils*, Paris, France, AA Balkema, 2, 535-539.

Ng C.W.W., Xu J. and Yung S.Y. 2009. Effects of wetting-drying and stress ratio on anisotropic stiffness of an unsaturated soil at very small strains. *Canadian Geotechnical Journal* 46, 1062-1076.

Pagano A., Tarantino A., Bagheri M., Rezania M. and Sentenac P. 2016. An experimental investigation of the independent effect of suction and degree of saturation on very small-strain stiffness of unsaturated sand. *E3S Web of Conferences*, 9, 14015.

Qian X., Gray D.H. and Woods R.D. 1993. Voids and granulometry: effects on shear modulus of unsaturated sands. *Journal of Geotechnical Engineering* 119(2), 295-314.

Xiaoqiang G., Jun Y., Maosong H. and Guangyun G. 2015. Bender element tests in dry and saturated sand: Signal interpretation and result comparison. *Soils and Foundations* 55(5), 951-962.

Zhao Y., Cui Y., Zhou H., Fend X. and Huang Z. 2017. Effect of void ratio and grain size distribution on water retention properties of compacted infilled joint soils. *Soils and Foundations* 57(1), 50-59.