Effects of inherent anisotropy on $G_0$ of unsaturated sand

B. N. Le i), H. Toyota ii) and S. Takada iii)

i) Ph.D Student, Energy and Environment Science Course, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan
ii) Associate Professor, Department of Civil and Environmental Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan.
iii) Technical Staff, Department of Civil and Environmental Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan.

ABSTRACT

Inherent anisotropy, resulted from sediment process, is an important aspect when considering the behavior of sandy soils. Also, accurate initial shear modulus $G_0$ at very small strain is an essential parameter in many seismic designs and analyses of underground structures. In this research, the influences of inherent anisotropy on $G_0$ were investigated by conducting a series of triaxial tests employed both local small strain (LSS) measurement technique and bender element (BE) method. Specimens were prepared using air pluviation method in an inclined container at different angles to create the inherent anisotropy induced by orientation of sand particles. The experimental results obtained on both saturated and unsaturated sands indicate that $G_0$ was affected by depositional angle of the specimen. Moreover, those results showed greater $G_0$ on unsaturated sand than that on saturated sand because of the application of matric suction.

Keywords: inherent anisotropy, initial shear modulus, triaxial test, local small strain, bender element test

1 INTRODUCTION

Soils existed in nature are commonly formed in many kinds of depositional manner due to the influences of different factors from formation history. From this point, the inherent anisotropy was defined as the initial soil particle’s fabric and distinguished from the induced anisotropy related to the applied stress state to soils (Casagrande and Corrilo, 1944).

The inherent anisotropy on shear strength has been investigated widely in much previous research employed a variety of laboratory tests (Oda et al., 1972; Aurthur and Menzies, 1972; Lam and Tatsuoka, 1986; Guo, 2008; Tong et al., 2014; Razeghi and Romiani, 2015). On the other side, the inherent anisotropy on the shear modulus at small strain was also carried out by means of shear wave velocity $V_s$ determination (Pennington et al., 1997; Jovičić et al., 1998; Gasparre et al., 2007; Escribano and Nash, 2015) and direct measurement of $G_0$ using the local strain measuring instruments incorporated to testing apparatus (Hoque and Tatsuoka, 1998; Yamashita et al., 2003; Yamashita et al., 2005).

The shear stiffness at small strain, usually denoted as $G_0$, is an important parameter for solving many problems in geotechnical engineering related to underground structures such as analysis of ground response induced by the seismic/dynamic loading and prediction of the foundation settlement. $G_0$ is regarded to the linear elastic property responded at very small strain and can be obtained in different methods. In-situ test, $G_0$ is estimated indirectly from the correction results of penetration tests or determined via field seismic measurement of shear wave velocity. In laboratory tests, $G_0$ is usually assessed from resonant column tests (Iwasaki et al., 1978; Kumar et al., 2007; Khan et al., 2008), small strain triaxial tests (Hoque and Tatsuoka, 1998), bender element tests (Jamiolkowski et al., 2005; Viggiani and Atkinson, 2005), and small strain torsional shear tests (Iwasaki et al., 1978). In early studies (Hardin and Richart, 1963; Hardin and Drnevich, 1972), an empirical expression for the initial shear modulus $G_0$, accounted for the variation in mean effective stress and void ratio at the isotropic stress state, was suggested as follows:

$$ G_0 = AF(e) \left( \frac{\sigma'_m}{p_0} \right)^n $$

(1)

where $\sigma'_m$ is the confining stress; $p_0$ is usually taken the value as the atmospheric pressure of 100kPa and defined as the reference pressure; $A$ and $n$ are fitting parameters varied by soil types; $F(e)$ is the function of void ratio $e$ and normally determined from the expression suggested by Iwasaki and Tatsuoka (1997) for sands without fine fraction;

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\[ F(e) = \left(2.17 - e\right)^2 / \left(1 + e\right) \]  

The equation (1) indicates the initial shear modulus relates with effective stress and packing density. However, the influences of inherent anisotropy on \( G_0 \), an important property of sandy soil, are normally small matter.

For unsaturated soils, several factors such as particle size, compacted water content, degree of saturation, matric suction, hydraulic hysteresis were found to be influential on the shear wave velocity and initial shear modulus \( G_0 \) (Cho and Santamarina, 2001; Heitor et al., 2013; Oh et al., 2014; Khosravi et al., 2018). However, in those reports, the effects of inherent anisotropy on initial shear modulus of sand were less studied even for saturated sands.

In the current study, the inherent anisotropy on the initial shear moduli of both saturated sand and unsaturated sand were investigated using local small strain (LSS) test and bender element (BE) test.

2 EXPERIMENT

2.1 Testing material and specimen preparation

Toyoura sand, a Japanese standard sand with the sub-angular to angular poorly graded fine quartz-rich sand, was used in this research. The aspect ratio between length \((L)\) and width \((W)\) of Toyoura sand was 1.50 as reported by Le et al. (2018). The grain size distribution curves and physical properties are shown in Fig.1.

To investigate the inherent anisotropy of the sand, a rectangular container having a height of 250mm, length of 250mm and width of 100mm and consisted of six separated metal walls was designed and fabricated for making all reconstituted specimens. As shown in Fig. 2, six separated metal walls were connected together by fastening screws. Two movable walls were adjusted their positions to reach the different depositional angles \(\alpha\) of \(0^\circ\), \(22.5^\circ\), \(45^\circ\), \(67.5^\circ\) and \(90^\circ\), as shown in Fig.3.

Inherent anisotropy was resulted from the sediment process and can be considered as the fabric and initial state of soil particles. Therefore, the method of specimen preparation plays a crucial role in mechanical properties of sands. “Air pluviation method” used in the study was developed from the technique reported by Oda et al. (1978) and Miura and Toki (1982). As illustrated in Fig. 4, the soil was formed into the container through a sieve with a mesh size of 425μm opening diameter. The sieve was shaken cyclically in horizontal direction to accelerate the falling speed of the sand. The hanging weight with the length of 425mm was located in the center of the sieve and considered as the reference to maintain the constant height of falling. Then, the full of dry sand container was submerged slowly in water for 2 hours. Next, the water was removed naturally and the remained water inside the sand was pumped at -10kPa. The container was disassembled by each wall carefully so that the sand block can stand by itself. A cylindrical specimen with the dimensions of 125mm height and 50mm diameter was shaped from the sand block and placed to the triaxial apparatus. By controlling the constant height of falling, the desired relative density \(D_r\) about 85% (void ratio \(e\) of about 0.656) can be attained.
2.2 Testing apparatus and testing procedure

An automatic controlled triaxial apparatus integrated the local small strain (LSS) measuring devices and bender element (BE) equipment was employed to inquire the shear modulus at small strain, as illustrated schematically in Fig. 5.

The proximity transducers used in LSS test can capture the smallest strain of 10⁻⁴% accurately. Two metallic targets were attached directly on the specimen and a pair of proximity transducers were kept on two columns near the specimen. To avoid the influence of bedding error, the distance between two targets was 80mm compared to the total height of the specimen of 125mm. For radial strain measurement, the proximity transducer included target was hold in the middle part of the specimen by using a clamp device.

In this research, BEs with dimensions of 2.5mm length, 12mm with, and 1mm thickness are mounted in both top cap and pedestal to play the role as the transmitter and receiver respectively. The BE test conditions were based on the standard of Japanese Geotechnical Society (2011) and can be described as following:

1. Input frequency of 15kHz, 20kHz and 30kHz at the voltage ±10V were used to generate a single sinusoidal wave in the transmitter. Each frequency was carried out 10 times. The initial shear modulus \( G_0 \) was obtained from the average of those results at the three frequencies.
2. The start-to-start method was performed to identify the propagation time. The tip-to-tip \( L_{tt} \) (about 12cm) method was used as the wave propagation length.

A series of triaxial test was carried out following testing procedure below:

1. Saturation process for specimen: A cylindrical specimen was positioned into triaxial apparatus. Initially, suction of -20kPa was applied to the specimen and cell water was provided simultaneously. The double negative pressure of -100kPa inside specimen and -80kPa outside specimen was conducted to remove air inside the specimen. Degassed water was supplied into specimen in order to make it saturation. Maintaining suction of -20kPa, the cell water was removed from triaxial cell. Specimen’s height and diameter were measured carefully. The proximity transducers for LSS test were installed before triaxial cell was re-supplied by full of water. The internal suction was decreased while the cell pressure was increased gradually in order to maintain the isotropic effective stress constantly at 20kPa. Then, back pressure of 200kPa was applied to increase the degree of saturation of specimen. The pore pressure coefficient B (Skempton, 1954) was checked to make sure that it was greater than 0.97.
2. Isotropic consolidation process: The specimen was consolidated isotropically under an effective stress of 150kPa. The BE test was carried out to obtain the shear wave velocity.
3. Drying process: Providing the air pressure from the top of specimen, matric suction, \( s = (u_a - u_w) \) of 50 kPa, was applied to the specimen for dehydration under constant \( p_{net} = (p - u_a) \) in the axis-translation technique using a ceramic disk. This step may take a few days, until drainage volume from ceramic disc reached about 0.2cm³/day and the degree of saturation was equal to about 13%. This process was skipped in saturated sand. The BE test was conducted before shearing.

4. Drained shearing process: The monotonic compression under a drained condition for saturated sand and constant suction (CS) for unsaturated sand was conducted at the axial strain rate of 0.0025%/min and constant cell pressure. The shearing process was continued until shear strain reached value of 0.1%.

3 TESTING RESULTS AND DISCUSSIONS

3.1 Results on the LSS test

Figures 6 and 7, respectively, indicate the secant shear modulus, calculated as equation (3), plotted against the shear strain of saturated sand and unsaturated sand in different depositional angles \( \alpha \).

\[
G_{secant} = \frac{q}{3\varepsilon_s} \tag{3}
\]

It was found that \( G_{secant} \) in shear strain smaller than 10³% is the largest at the \( \alpha \) of 90° and the smallest at \( \alpha \) of 0°. This trend tend to be reversed when the shear strain is greater than 10³%. These results are in agreement with observation conducted by Yamashita et al. (2003 and 2005). The authors made specimen as pluviation direction of 0° (V-specimen) and 90° (H-specimen). The elastic shear moduli \( E_H \) on H-specimen are slightly larger than \( E_V \) on V-specimen.

The elastic region was appeared and observed from secant shear modulus of saturated sand and unsaturated sand as shown in Figs. 6 and 7. Saturated sand exhibits the elastic region in the range of shear strain smaller than 10³%. On the other side, unsaturated sand creates the elastic region up to slightly greater shear strain of 10³%. Therefore, matric suction applied on unsaturated sand attribute to maintain elastic region up to greater shear strain than that on saturated sand.

Figure 8 presents how the initial shear modulus varies through the depositional angle \( \alpha \). The results on both saturated sand and unsaturated sand exhibit the same changing trend; \( G_0 \) become larger with the increasing of \( \alpha \). These results depend on the inherent anisotropy of both saturated sand and unsaturated sand. However, \( G_0 \) of unsaturated sand is greater than that of saturated sand because of the application of matric suction.

Toyota et al. (2018) investigated the effects of inherent anisotropy on shear strength at large shear strain of about 10% and found that drained shear strength of both saturated sand and unsaturated sand tended to decrease with the increase of depositional angle. That is interesting because inherent anisotropy of shear strength behaves reversely to the inherent anisotropy of shear modulus.

3.2 Results on BE test

Figure 9 shows an example of the typical received signal obtained in BE test on saturated sand and unsaturated sand. Because of the application of matric suction, the selected point for arrival time on unsaturated sand become shorter than that on saturated sand. As a result, the shear wave velocity \( V_s \) of
unsaturated sand is greater compared to \( V_s \) of saturated sand.

Figure 10 shows the shear wave velocity \( V_s \) versus different frequencies at three representative depositional angles \( \alpha \) on both saturated sand and unsaturated sand. \( V_s \) increases with not only the increase of frequency but also the changing of \( \alpha \) from 0° to 90°. The shear wave velocity determined in unsaturated sand are higher than \( V_s \) obtained in saturated soil because of application of matric suction.

![Fig. 9. An example of received waves on saturated sand and unsaturated sand in BE test at frequency of 15kHz.](image)

![Fig. 10. Variation of shear wave velocity plotted against frequency in BE test.](image)

The variation of initial shear modulus \( G_0 \) plotted against the depositional angle \( \alpha \) is illustrated in Fig.11. The data were collected more than one time at some depositional angles to confirm the repeatability of results. The matric suction induced the greater values of \( G_0 \) on unsaturated sand than those values on saturated sand. The inherent anisotropy is also appeared on both saturated sand and unsaturated sand in BE test. Almost the same tendency is obtained compared between saturated sand and unsaturated sand.

![Fig. 11. Initial shear modulus of saturated sand and unsaturated sand in BE test.](image)

### 3.3 Comparison between LSS and BE tests

Figures 12 and 13, respectively, summarize the comparison between the initial shear modulus obtained from LSS and BE tests of saturated sand and unsaturated sand. Results are similar between LSS and BE tests, depending on the depositional angle \( \alpha \). However, stronger inherent anisotropy, which is steeper inclination in relation between \( G_0 \) and \( \alpha \), was obtained in LSS test than that in BE test.

![Fig. 12. Comparison of the initial shear modulus in saturated sand between LSS test and BE test.](image)

![Fig. 13. Comparison of the initial shear modulus in unsaturated sand between LSS test and BE test.](image)
The possible reason for this difference seem to be induced by the degree of the uniformity or homogeneity of the specimen. Choi et al. (2010) used a rainer system with a porous plate to make specimen in a 1.0m split mold. By conducting three uniformity tests including measurement of the relative density of 20 small molds along the height of split mold, the shear wave velocity from BE test and the cone resistance from cone penetration test along the depth were observed. They found that the relative density increased with the depth. Tabaroei et al. (2017) proved that, even in the horizontal direction, the density differences were ranged from 2.3% to 5.0%. Although the small scale container, 250mm in height and width, was used to make specimen, it is difficult to produce a perfectly homogenous specimen. Moreover, the different lengths applied in LSS test (80mm) and BE test (120mm) indicates that two testing methods will create a different condition of specimen in the point of void ratio. According to the equation (1), $G_0$ is varied with the changing of the void ratio $e$. Thus, the effect of the heterogeneous specimen can generate the difference between LSS and BE tests.

Yamashita et al. (2005) assumed that the higher results on elastic modulus obtained from BE test than those results from triaxial test might be affected by the different strain level in $10^{-3}\%$ (triaxial test) and smaller than $10^{-3}\%$ (BE test). The bedding error in triaxial test also might be taken account for the difference between LSS and BE tests.

Although there is a slight difference in the results obtained between two kinds of tests, the inherent anisotropy reaches the same tendency in both saturated sand and unsaturated sand. Further experiments need to conduct to clarify the consistency of the results from different measuring methods.

### 3.4 The degree of anisotropy

The degree of anisotropy was expressed as $G_{hh}/G_{hv}$ or $E_h/E_v$, which is the ratio of between $G_{hh}$ or $E_h$ in the horizontal plane and $G_{hv}$ or $E_v$ in the vertical plane, to estimate the inherent anisotropy of soils in previous research. In this study, the similar way was applied for normalized method using the ratio between the initial shear modulus at the given depositional angles and that at the depositional angle of $0^\circ$.

As shown in Fig. 14, the normalized line increases with the increase of depositional angle. In LSS test, the ratio of $(G_{0(\alpha=90^\circ)}/G_{0(\alpha=0^\circ)})$ reaches 1.19 and 1.15 for the unsaturated sand and saturated sand, respectively. This result implies that the sand specimen with depositional angle of $90^\circ$ is stiffer than that with depositional angle of $0^\circ$. Moreover, slight stronger inherent anisotropy shows in unsaturated sand than in saturated sand. In BE test, although the results show the same trend compared to the results of LSS test, the inherent anisotropy in BE is slightly weaker than those in LSS test. The ratios of $(G_{0(\alpha=90^\circ)}/G_{0(\alpha=0^\circ)})$ are 1.14 and 1.12 for unsaturated sand and saturated sand, respectively.

Bellotti et al. (1996), Pennington et al. (1997), Yamashita et al. (2005), Hight et al. (2007), and Teng et al. (2013) demonstrated that the shear moduli in the horizontal plane were higher than those in vertical plane. Ng and Yung (2008) proved that the increase of matric suction from 0 kPa to 50 kPa induced the increase of the shear modulus ratio $(G_{0(\alpha=0^\circ)}/G_{0(\alpha=90^\circ)})$ from 1.03 to 1.05. It is noted that the term of horizontal plane and vertical plane respectively correspond to depositional angles of $90^\circ$ and $0^\circ$ in this research.

![Fig. 14. The degree of anisotropy in saturated sand and unsaturated sand obtained from LSS test and BE test.](image)

### 4 CONCLUSIONS

A series of triaxial tests was performed on Toyoura sand in order to investigate the effects of inherent anisotropy on initial shear modulus in both saturated sand and unsaturated sand. The inherent anisotropy was created using the inclined container having the movable walls to reconstitute the specimen with different depositional angle. The initial shear modulus was obtained from local small strain test and bender element test. From the experimental results, the following conclusions are summarized as follows:

1. At small strain ($10^{-3}\%$ to $10^{-4}\%$), the secant shear modulus of both saturated sand and unsaturated sand were obtained. The reversed tendency in the relation of $G_{sec}$ and $\alpha$ was obtained between in smaller shear strain than $10^{-1}\%$ and in greater shear strain than $10^{-1}\%$.

2. The initial shear moduli of both saturated sand and unsaturated sand increased with the increase of depositional angle $\alpha$. Matric suction induced the higher results on the shear modulus of unsaturated sand under constant suction condition than that of saturated sand under drained condition.

3. The elastic regions appeared on both saturated soil and unsaturated sand. Moreover, elastic region on unsaturated sand exhibited up to a larger shear strain than that for saturated sand because of application of matric suction.

4. Initial shear modulus in LSS test exhibited stronger inherent anisotropy than that in BE test.
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