Title of Thesis: Effects of anisotropic stress states on deformation characteristics of sand in small strain range
（砂の微小ひずみ変形特性に与える異方応力状態の影響）

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1. Introduction

The real ground formed by sands and/or clay has usually anisotropic mechanical behavior. Two types of anisotropy, as shown in Fig. 1, are defined in Geotechnical Engineering: inherent anisotropy which develops from orientation of soil particles during sedimentation, and induced anisotropy which arises when anisotropic stress is applied to the soil. A deep understanding about the anisotropy and the effects on deformation characteristics of soils are very important when analyzing ground deformation in engineering earthworks. Accurate initial shear modulus of soils is a key parameter to design and construct the underground structures rationally.

The purpose of this research is to study the effect of anisotropic stress states on deformation characteristics of sand in small strain range (represented by the stiffness = initial shear modulus G_0).

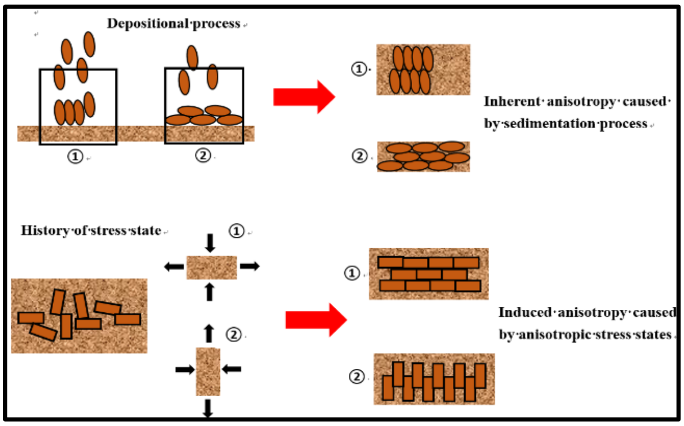


Figure 1: Definition of two types of anisotropy

2. Experiments

2.1. Testing material and specimen preparation

Toyoura sand, a Japanese standard sand, was used for this study. The particle size distribution shows that Toyoura sand is a sub-angular to angular poorly graded fine quartz rich sand (Fig. 2). The physical parameters of the sand are shown in Table 1. A container with movable walls (Fig. 3) was employed to create a soil fabric at different deposition angle (0, 45 and 90 degrees). Air pluviation method was used to make the specimen. The processes of making the specimen (Fig. 4) are: 1. to pour the sand into the container, 2. To immerse it into water. Then the water was dehydrated from the soil bloc and then a specimen of 125 mm and 50 mm respectively in height and diameter was trimmed to conduct the experiment.

ρ_s (g/cm^3)	e_{max}	e_{min}	U_c	D_{50} (mm)
2.65	0.990	0.597	1.48	0.2

Table 1: Physical parameters of Toyoura sand

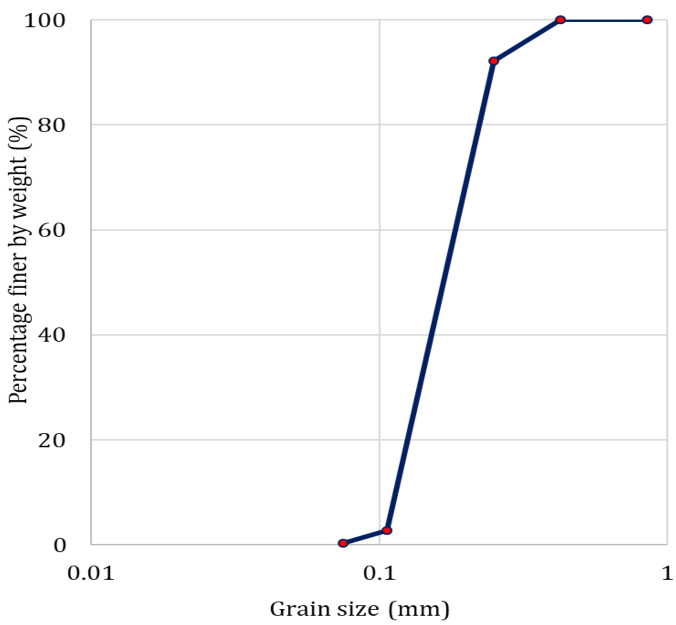


Figure 2: Particle size distribution of Toyoura sand

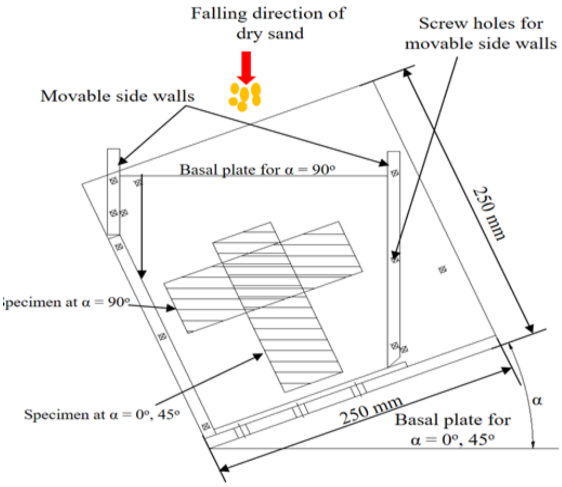


Figure 3: Container with movable walls

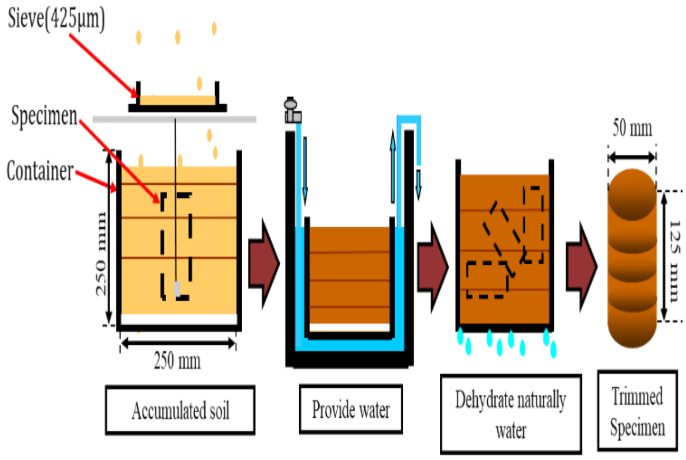
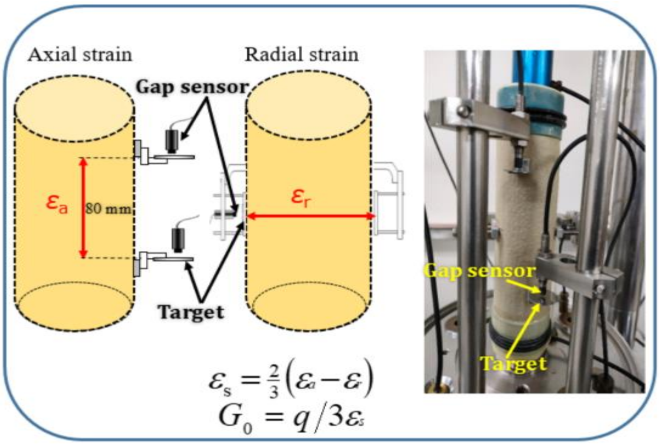
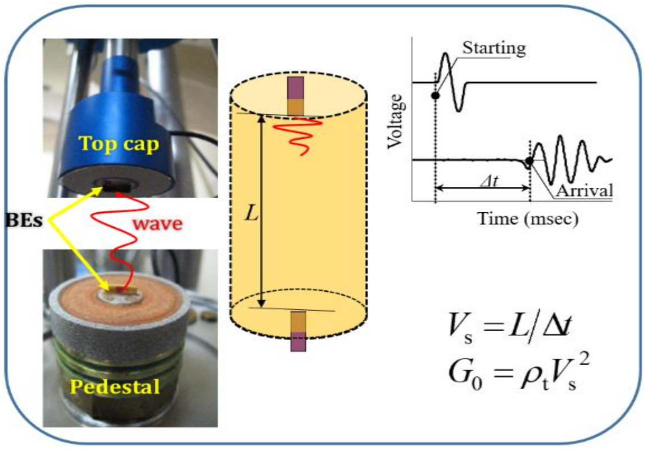


Figure 4: Process of making the specimen



(a): Local small strain



(b): Bender element

Figure 5: Tests conducted and parameters obtained with the triaxial testing apparatus

2.2. Tests conducted with the triaxial apparatus

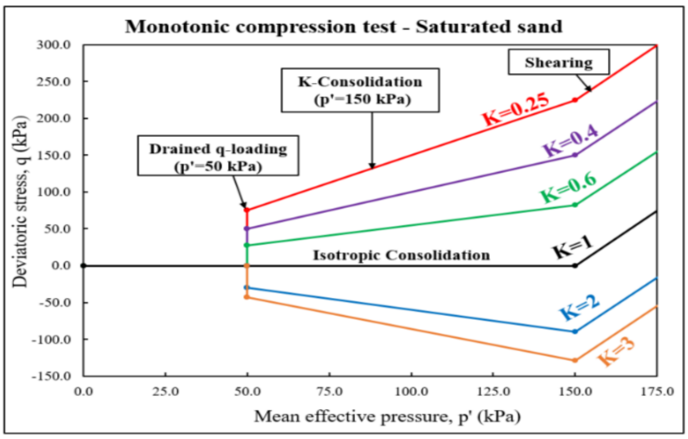
The monotonic triaxial compression/extension test on small strain triaxial apparatus was used for this study. Two tests namely local small strain (LSS) and bender element (BE), shown in Fig. 5, were conducted to determine the deformation characteristic of the sand represented by the stiffness (or initial shear modulus, G_0).

Parameters of axial strain (ε_a) and radial strain (ε_r) were obtained with the LSS test. Then shear strain (ε_s) and initial shear modulus (G_0) were calculated from these two parameters.

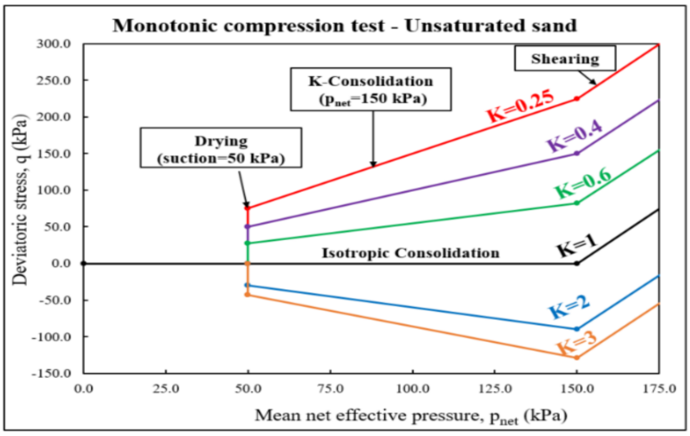
In BE test, the parameter of wave travel time (Δt) was obtained. Then the shear wave velocity (V_s) and initial shear modulus (G_0) were calculated.

2.3. Representative stress paths

Monotonic compression loading and monotonic extension loading tests were conducted to carry out this study. Figures 6 and 7 show the differerent stress paths of the tests.

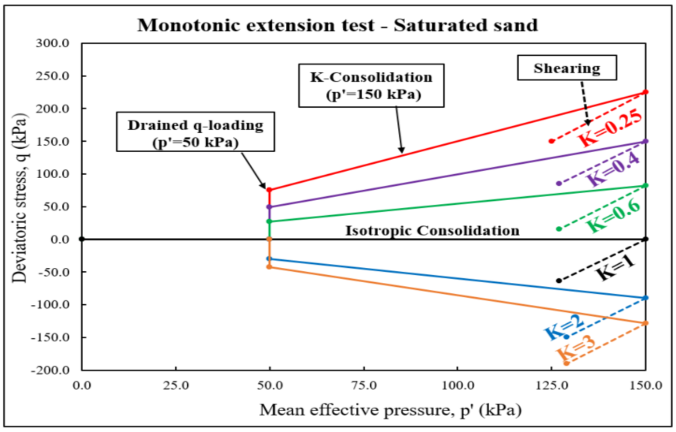


(a): Saturated sand

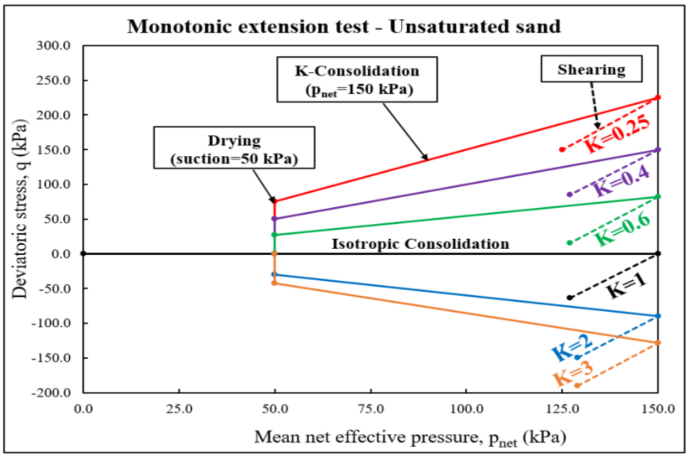


(b): Unsaturated sand

Figure 6: Stress paths of compression tests



(a): Saturated sand



(b): Unsaturated sand

Figure 7: Stress paths of extension tests

Drained q-loading was conducted for saturated sand at effective pressure of 50 kPa while drying was conducted for unsaturated sand by applying suction of 50 kPa. Then for both saturated and unsaturated sand, specimens were consolidated at effective pressure of 150 kPa. The stress ratio, K, was defined as the ratio between the radial stress and the axial stress ($K = \sigma_r/\sigma_a$). The conditions of the anisotropy during consolidation were defined as follows:

- K=1: isotropic consolidation;
- K<1: Compressional anisotropic consolidation (K=0.25, 0.4, and 0.6 in this study);
- K>1: Extensional anisotropic consolidation (K=2 and 3 in this study).

The difference between the compression and extension tests is recognized as the shearing process shown in Fig. 8. In compression shearing, the lateral stress (σ_r) was constant, the axial stress (σ_a) increased and the specimen was expanding laterally. In extension shearing, the lateral stress (σ_r) was constant, the axial stress (σ_a) decreased and the specimen was expanding vertically.

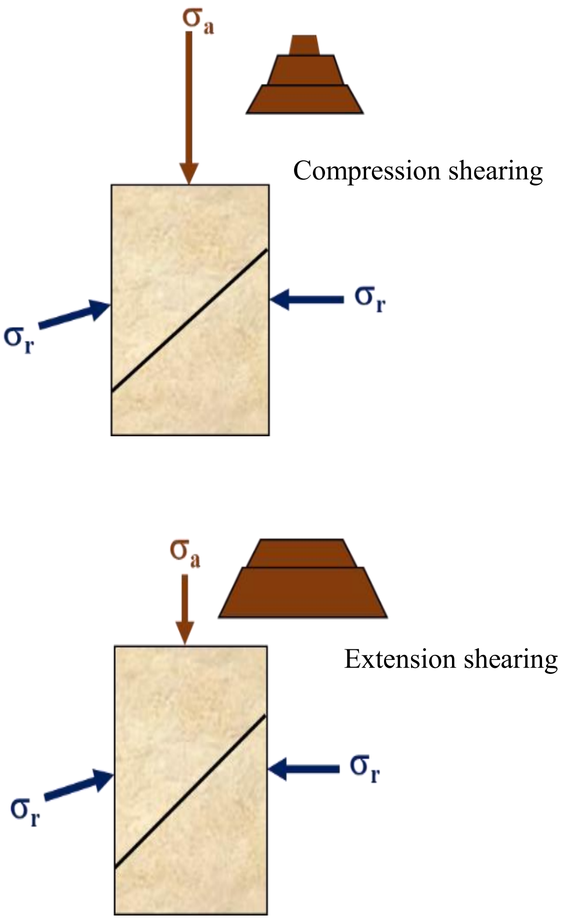


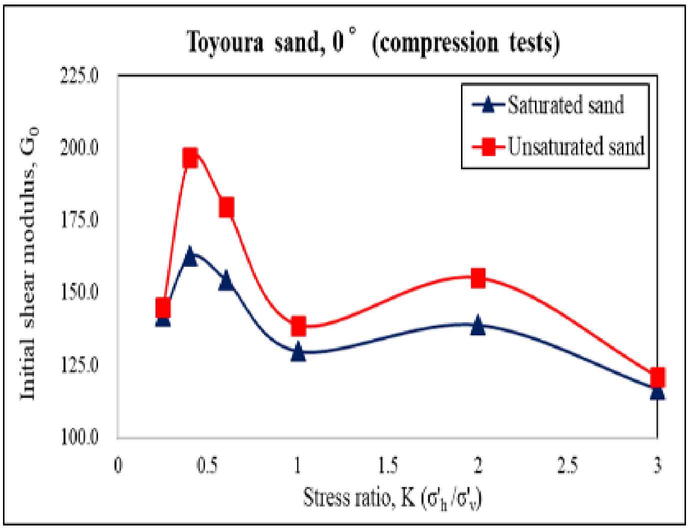
Figure 8: Shearing process

3. Results and discussion

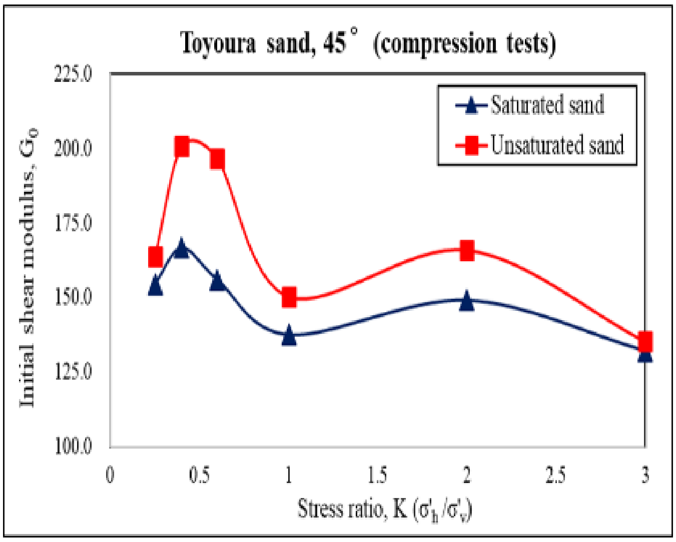
3.1. Bender element results

Bender element results of compression tests, presented in Fig. 9, show that the same tendency is observed on saturated and unsaturated sands for both depositional angles (0°, 45°, and 90°).

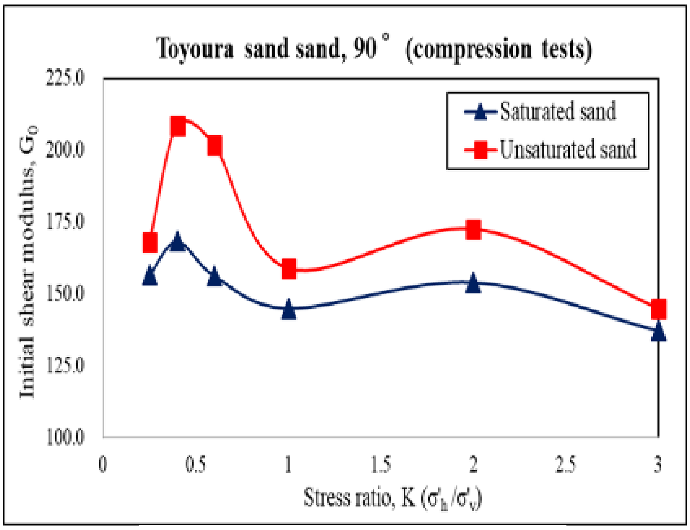
Under compressional anisotropic consolidation (K<1), the initial shear modulus (G_0) decreases when the stress ratio becomes larger from K=0.4 to K=1. Then, under extension anisotropy consolidation (K>1), it increases from K=1 to K=2. However, from K=0.4 to K=0.25 and K=2 to K=3, G_0 decreases. G_0 of unsaturated sand is greater than those obtained on saturated sand.



(a): Deposition angle 0°



(b): Deposition angle 45°



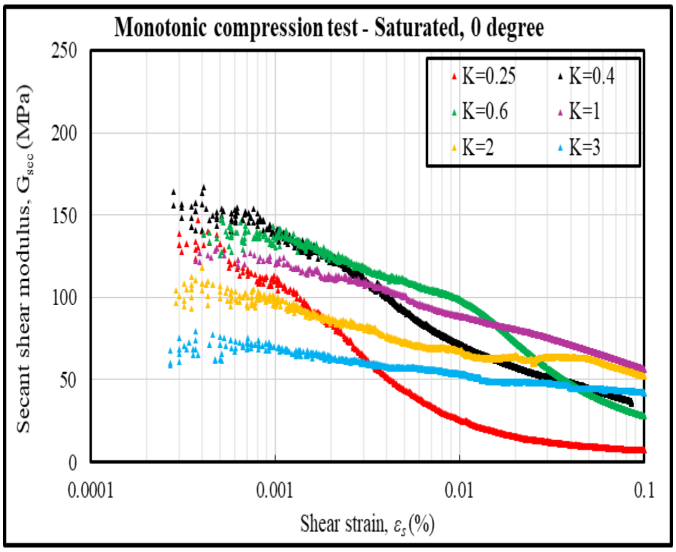
(c): Deposition angle 90°

Figure 9: Bender element results

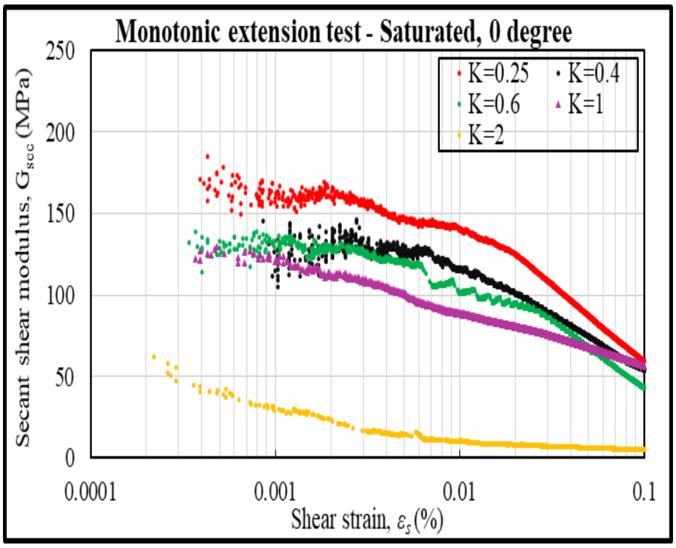
3.2. Local Small Strain results

Local small strain (LSS) results are presented in Fig. 10. The compression tests show that the secant shear modulus (G_{sec}) becomes greater when the stress ratio is larger, from K=0.25 to K=0.4. Then it decreases from K=0.4 to K=3.

LSS results of extension tests show that the secant shear modulus (G_{sec}) is decreasing when the stress ratio becomes larger from K=0.25 to K=2.



(a): Compression tests



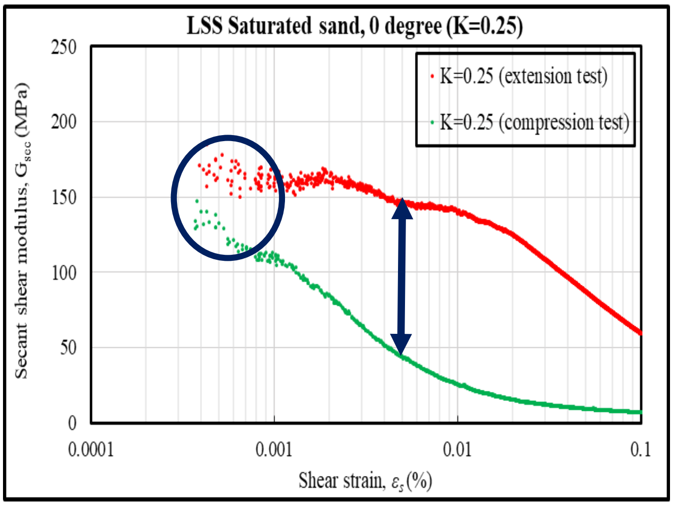
(b): Extension tests

Figure 10: Local small strain results

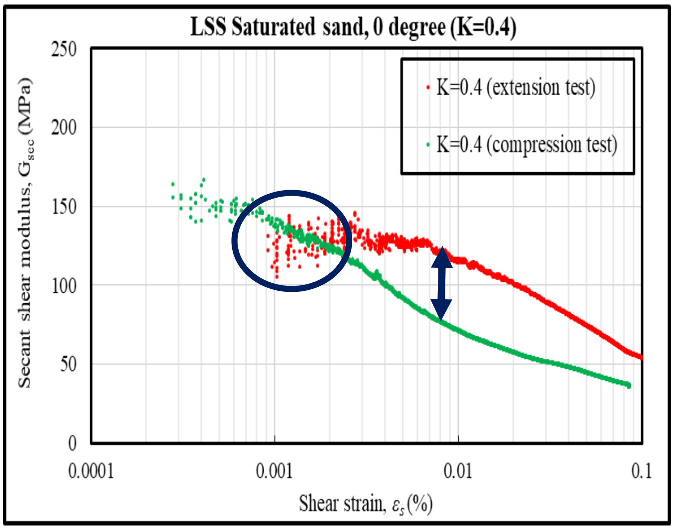
3.3. Comparison between compression and extension testing results

The comparison between the results obtained in compression and extension tests are shown in Fig. 11. The secant shear modulus is almost same for compression and extension tests at very small strain (smaller than 0.001%). From the strain of 0.001% to 0.1%, the secant shear modulus of extension tests is greater than that obtained in compression tests.

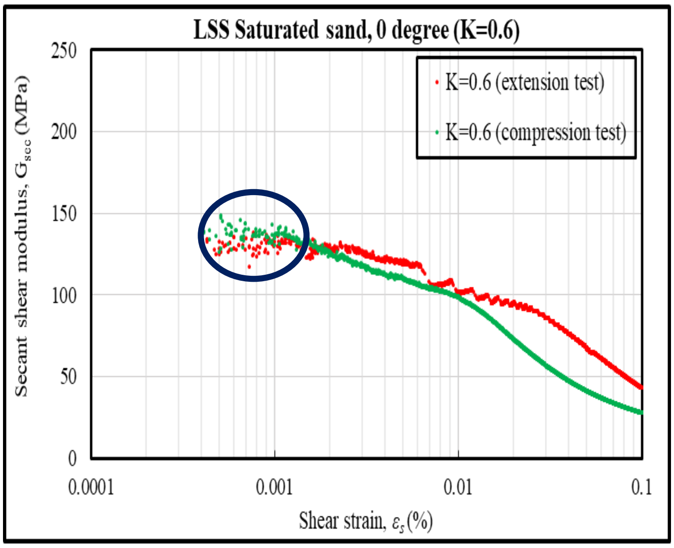
The difference between compression and extension becomes smaller when the stress ratio increases and reaches K=1.



(a): *K*=0.25



(b): *K*=0.4



(c): *K*=0.6

Figure 11: Comparison between compression and extension testing results

4. Conclusions

The following conclusions are made for this study:

- Bender element results of compression tests show that the initial shear modulus (G_0) on unsaturated sand is greater than those obtained with the saturated sand. Under compressional anisotropic condition (K<1), G_0 decreases when the stress ratio becomes larger from K=0.4 to K=1. Then, under extensional anisotropic condition (K>1), it increases from K=1 to K=2. Local small strain results show that the secant shear modulus, G_{sec}, becomes greater when the stress ratio increases from K=0.25 to K=0.4. Then it decreases from K=0.4 to K=3.

- In extension tests, local small strain results show that the secant shear modulus (G_{sec}) is decreasing when the stress ratio becomes larger from K=0.25 to K=2.
- The comparison shows that the shear modulus of extension tests is greater than that obtained in the compression tests when the strain increases. The difference becomes smaller when the stress ratio reaches K=1.