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Title: Deformation characteristics of cohesive soils at various stress condition

1. Introduction:

In recent years, the increased demand for extensive underground space utilization has led to large-scale deep excavations. Excavations involve a process of gradual stress release. Then upward ground movement occurs, which is known as rebound or heaving deformation. Ground rebound occurs when overburden pressure is removed during deep excavations for high-rise buildings with lower ground floor, tunnels, and underground structures. The rebound amount has been estimated using empirical approaches. For example, the deformation coefficients for rebound has been determined using an empirical multiple-fold number on results of conventional triaxial compression tests. However, these deformation coefficients are not appropriate for capturing the actual rebound phenomenon, where the soil swells in the extension direction. This study aims to investigate the effective methods to estimate the rebound deformation, which causes swelling deformation in the extension direction.

The initial stress state in the ground is reproduced through the K_0 consolidation. Bender element tests, local small strain tests, and shear strength tests with compressional and extensional loading are conducted to obtain the deformation coefficient for small and large strains using undisturbed and reconstituted specimens of four different layers 3De-8 (depth: 8.50 to 9.50 m), 3De-21 (depth: 21.50 to 22.50 m), 3Tr-13 (depth: 13.50 to 14.50 m) and 3De-30 (depth: 30.50 to 31.50 m) two are cohesive layers and two are sandy layers. The results obtained from the experiment can be used to evaluate the rebound phenomenon in the practical field. As a fundamental result, the strain dependent trends of the secant shear modulus are equivalent between undisturbed and reconstituted specimens under extensional loading. Therefore, reconstituted soils can be substitute for undisturbed soils to estimate the strain dependent trend under extensional loading. However, attention is needed in the larger strain because undisturbed soil exhibits higher shear strength and more brittle (less deformation to the failure) compared to artificial one. To evaluate the rebound amount in practical field, the use of the secant shear modulus from compressional loading will lead to overestimate rebound amount than the used of extensional results.

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2. Purpose of the Research:

K_0 consolidation simulates the **in-situ stress condition** of the horizontal ground (i.e. the stress condition that the soil naturally experiences in the ground without lateral strain). This is more realistic for analyzing **natural soil behavior**, especially in the initial condition of the ground before excavation. From K_0 consolidation, we can able to know the real soil phenomena.

The compression and extension tests are conducted to evaluate the deformation and rebound behavior of soils under different stress paths. Specifically:

- Compression tests simulate loading conditions (e.g. ground settlement under structures).
- Extension tests simulate unloading conditions (e.g. rebound after excavation).

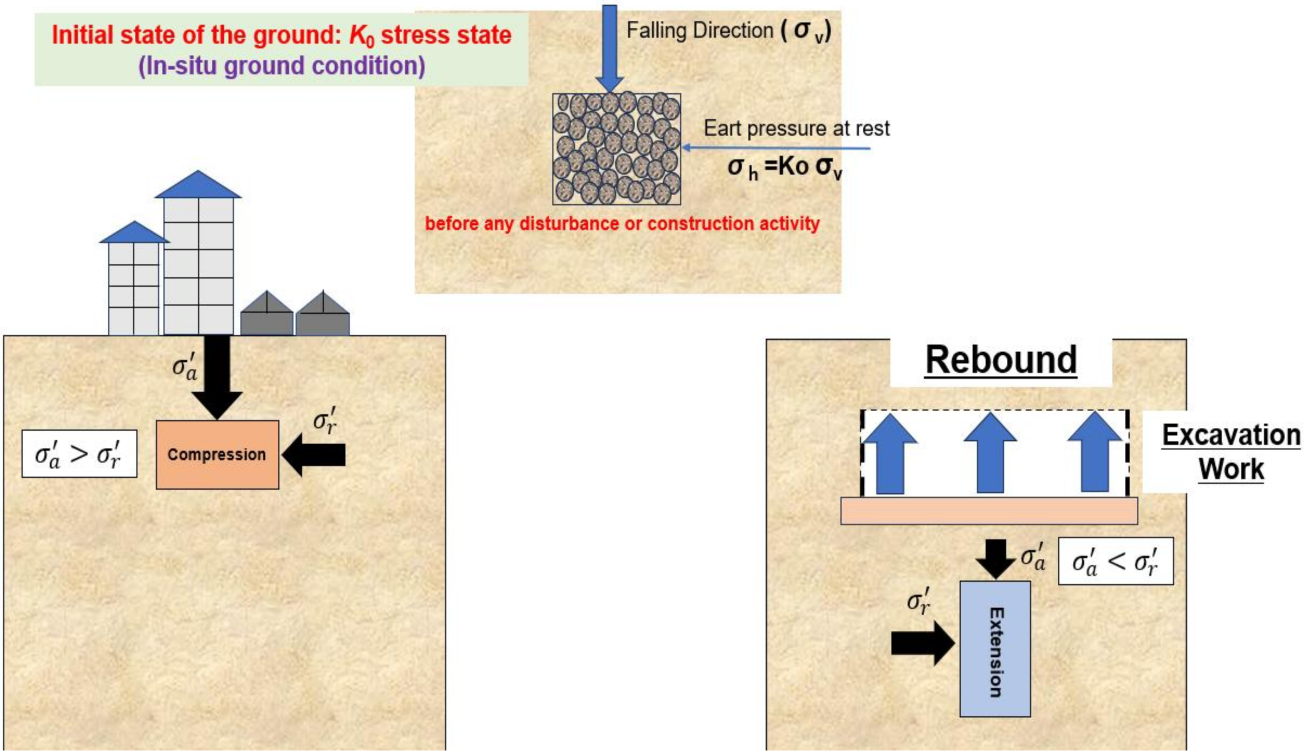

Fig.2.1. Purpose of the compression and extension loading test

3. Objectives:

Following items are objectives in the study.

- To find alternative method for extension tests using undisturbed samples.
- To comparative study between compressional (conventional) and extensional (uncommon) loading tests.
- To comparative study between undisturbed (expensive) and reconstitute (reasonable) samples.

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4. Testing Materials

Cohesive Samples: Undisturbed soil samples from two different layers 3De-8:(Depth: 8.50 to 9.50m) 3De-21:(Depth:21.50-22.50m) were examined (Fig. 4.1). For making reconstituted soil samples, the soil sample from the same layer was disturbed and prepared a slurry by mixing with water. Then the slurry was consolidated in a mold by applying 70 kPa to top and bottom of the specimen for 4 days. The physical properties for layer 3De-8 are soil particle density ρ_s of 2.60 (g/cm^3), liquid limit (W_L) of 60.18 %, and plasticity index (IP) of 27.14. The layer 3De-21 has ρ_s of 2.694 (g/cm^3), W_L of 72.163 %, and IP of 34.67. The grain size distribution curve is shown in Fig 4.2.

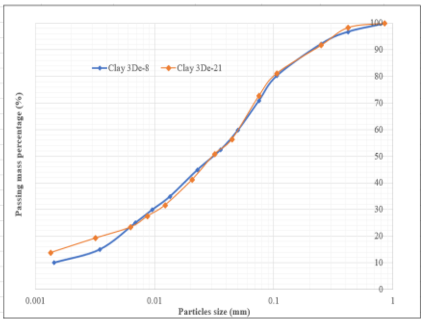


Fig.4.2. Grain size distribution curve (Cohesive layers)

Undisturbed 3De-8 | Final shape H:12.5, D:5cm | Undisturbed 3De-21 | Final shape: H:12.5, D: 5cm

Fig. 4.1 Undisturbed samples

Sandy Samples: Undisturbed soil samples from two different layers 3Tr-13:(Depth: 13.50 to 14.50m) 3De-30:(Depth:30.50-31.50m) were examined (Fig. 4.3). For making reconstituted soil samples, the soil sample from the same layer was disturbed and prepared by air pluviation method. 3Tr-13 samples were freezing sample with ρ_s of 2.789 (g/cm^3) and sand content of 85.12%. 3De-30 samples were nonfreezing sample with ρ_s of 2.735 (g/cm^3) and sand content of 55.03%. The grain size distribution curves are shown in Fig 4.4.

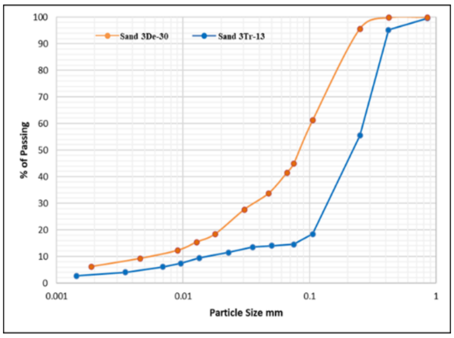
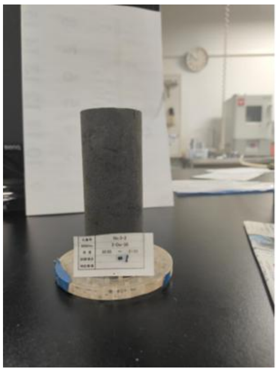


Fig.4.4. Grain size distribution curve (Sandy layers)

Undisturbed 3Tr-13 (Final shape H:12.5, D:5cm)



Undisturbed 3De-30 (Final shape: H;12.5, D: 5cm)

Fig. 4.3 Undisturbed samples

5. Experimental Methods

In this study, three distinct methods were used to measure shear strain at different levels as shown in Figure 5.1. Specimen with a dimension of 125 mm in height and 50 mm in diameter was used. Initial shear modulus G_0 was obtained from both LSS and BE tests, During K_0 consolidation, axial stresses are set to σ'_a = 300 kPa and 158 kPa for cohesive samples 3De-8 and 3De-21, respectively. Axial stresses are set to σ'_a = 95 kPa and 218 kPa for sandy samples 3Tr-13 and 3De-30, respectively. The lateral strain is controlled automatically. After doing the K_0 consolidation and getting the coefficient K value, we continured the K-consolidation with the same K_0 value. Then, we performed the bender element test. After that, we conducted the shearing of samples both extensional and compressional loadings to reproduce the loading and rebound phenomenon as shown in Fig 5.2. We obtained the result for a shear strain of up to 1% using the local small strain devices. For large shear strain, we continued the shear strength test until the sample reached to the failure.

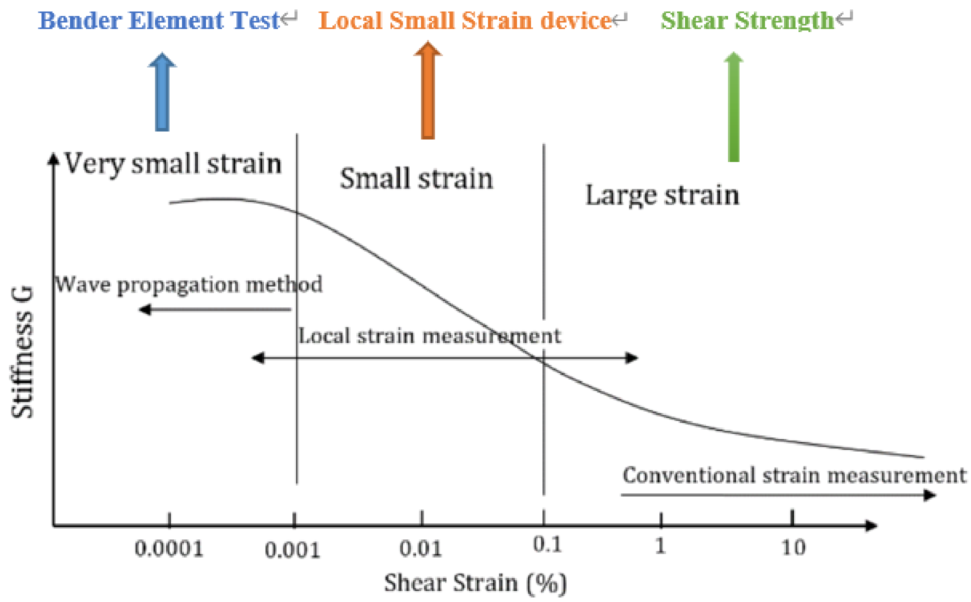


Figure 5.1 Methods for measuring shear strain at different strain levels.

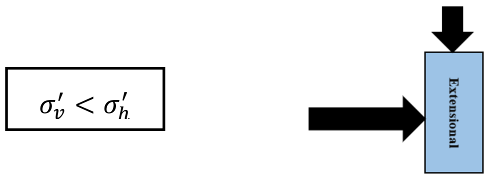


Fig.5.2 (a) Extensional loading condition (reducing σ_v' under constant σ_h')

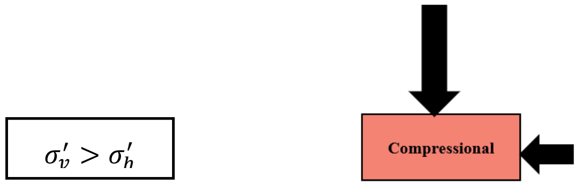
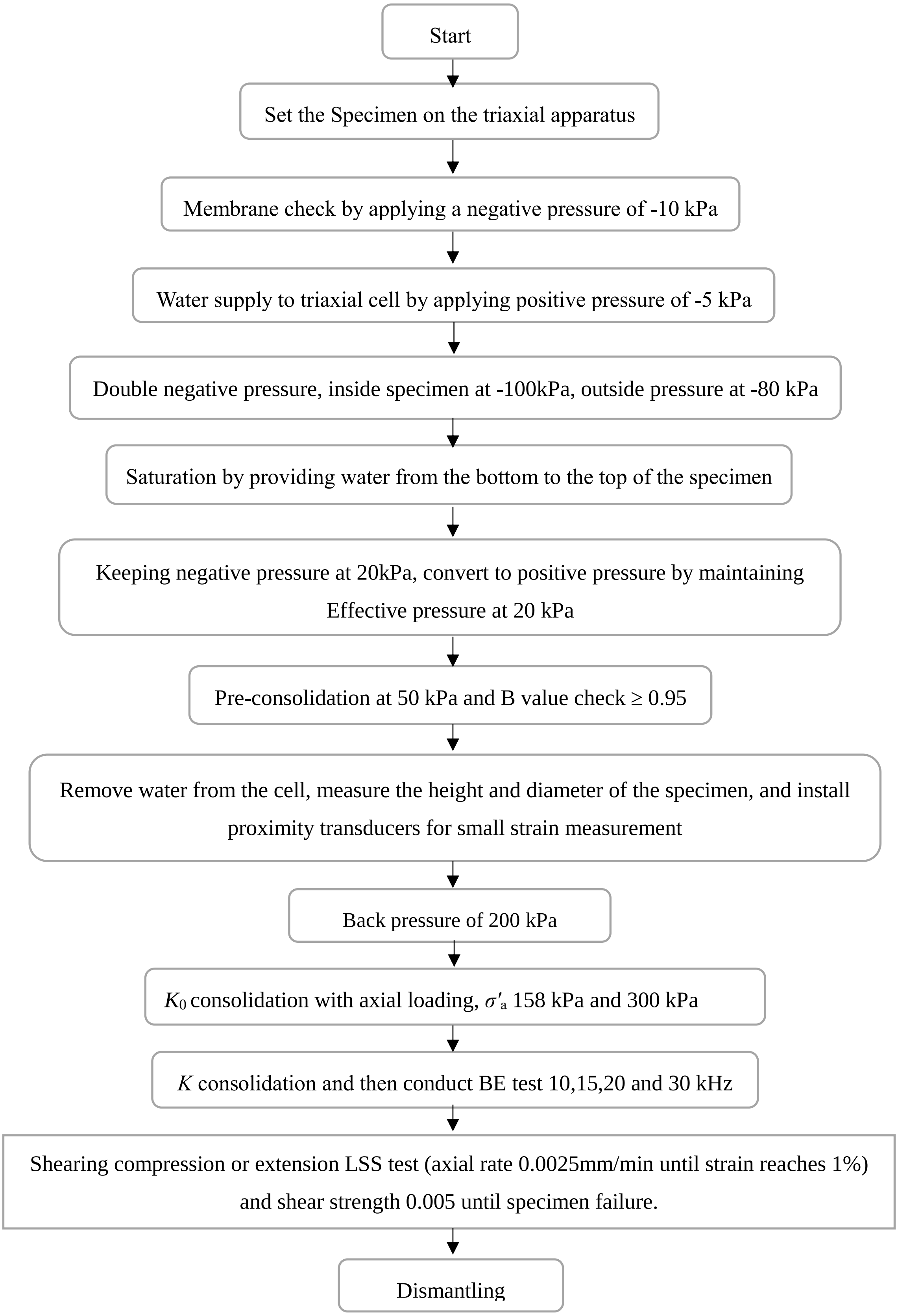


Fig.5.2 (b) Compressional loading condition (increasing σ_v' under constant σ_h')

Experimental procedure is shown as the next flowchart.



6. Experimental results and discussions.

6.1. Representative stress path.

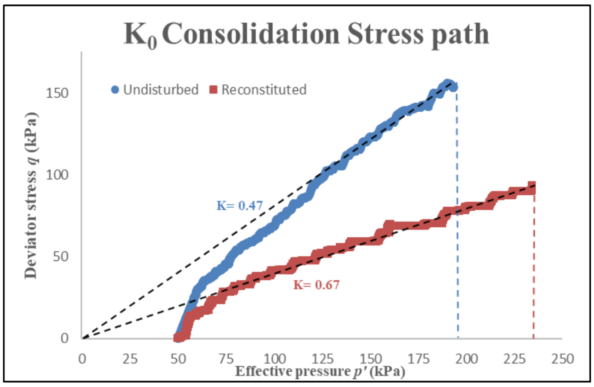


Fig. 6.1(a) K_0 consolidation stress path for clay soil.

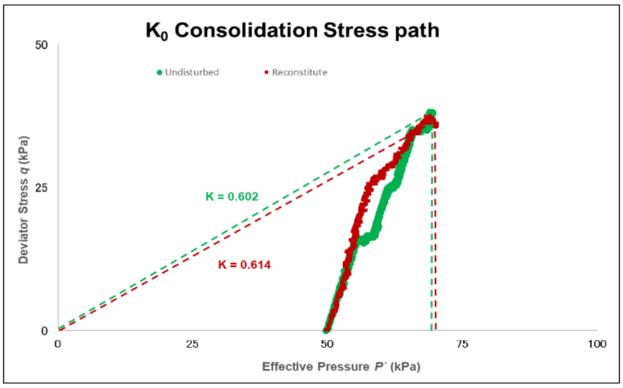


Fig. 6.1(b) K_0 consolidation stress path for sandy soil.

K_0 consolidation can be considered as the same stress conditions with the original ground. Figure 6.1(a) graph shows K_0 consolidation stress path in $q=\sigma_v-\sigma_h$ and $p'=(\sigma_v'+2\sigma_h')/3$ plane for undisturbed and reconstituted specimens of layer 3De-8: (depth:8.50 to 9.50m) where σ'_a is set at 300 kPa, which is about six times greater than overburden pressure in the real ground. The undisturbed sample (blue line) finally reaches a lower stress ratio ($K=\sigma_h'/\sigma_v'=0.47$) and effective mean stress p' of 194.2 kPa. On the other hand, the reconstituted sample reaches K=0.67 and p' of 232.0 kPa. Figure 6.1(b) shows K_0 consolidation stress path for undisturbed and reconstituted specimens of layer 3Tr-13: (depth:13.50 to 14.50m) where σ'_a is set at 95 kPa, which is the overburden pressure in the real ground. The undisturbed sample (green line) reaches a lower K of 0.602 and p' of 69.3 kPa. On the other hand, the reconstituted sample reaches K=0.614 and p'= 69.7 kPa.

6.2. Cohesive soil samples (Comparison between compressional and extensional loadings)

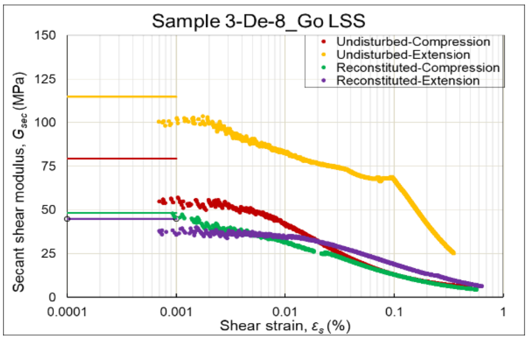


Fig. 6.2(a) 3De-8 soil LSS and BE results.

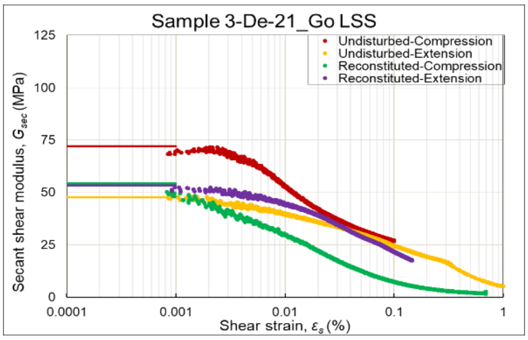


Fig. 6.2(b) 3De-21 soil LSS and BE results.

In Figs. 6.2(a) and 6.2(b), x-axis represent shear strain $\varepsilon_s=2/3(\varepsilon_v-\varepsilon_h)$ (%) and y-axis represent secant shear modulus G_{sec} (MPa) also the horizontal lines show the G_0 value obtained from the bender element (BE) tests. Good agreements in G_0 values are obtained between LSS and BE tests in Fig. 6.2(b). However, a large difference in G_0 apppears between BE and LSS tests in Fig. 6.2 (a). The considerable reason is as follows: In the natural ground, cementation might be engendered not homogeneously but locally. The shear wave created by BE can be transmitted through local cemented region with greater velocity. Then, G_0 estimated from V_s becomes greater than that obtained from loading tests, in which load is applied in overall area of the specimen.

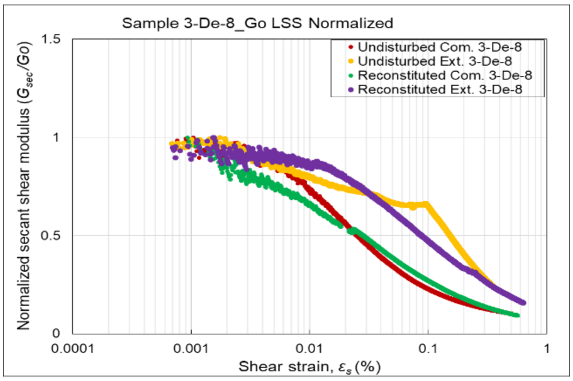


Fig. 6.2(c) Normalized LSS result for sample 3De-8

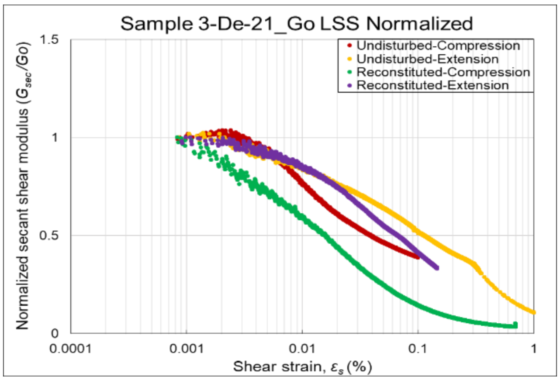


Fig. 6.2(d) Normalized LSS result for sample 3De-21

The G_0 in each sample is largely different. To examine the strain dependent trend of secant shear modulus G_{sec}, each G_{sec} was normalised by G_0 of the same sample. Figures 6.2(c) and 6.2(d) show the normalization of LSS results to remove the difference of G_0. Degradation of G is smaller in extensional loading than in compressional loading. Therefore, extensional loading tests are necessary to evaluate the rebounding behavior. In Fig. 6.2(c), similar trend appears in compressional loading between undisturbed and reconstituted samples. However, different trend is exhibited in Fig. 6.2(d) because of strong soil structure (cementation) in undisturbed sample. Concerning extensional loading, similar degradation trends between undisturbed and reconstituted samples are obtained in both types of cohesive soils (Figs. 6.2(c) and 6.2(d)).

6.3. Sandy soil samples (Comparison between compressional and extensional loadings)

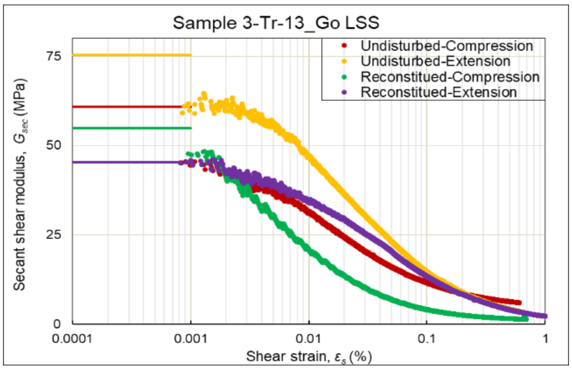


Fig. 6.3(a) 3Tr-13 soil LSS and BE results.

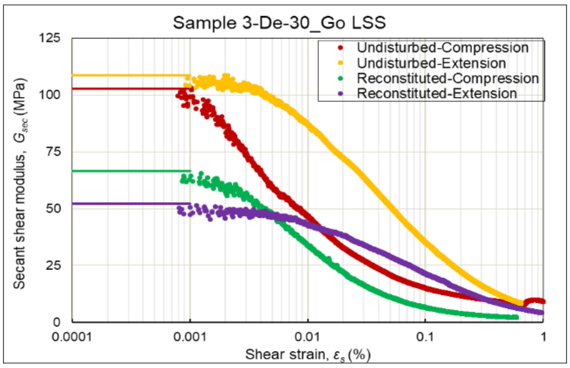


Fig. 6.3(b) 3De-30 soil LSS and BE results.

Figures 6.3(a) and 6.3(b) show the same kinds of figures with Figs. 6.2(a) and 6.2(b): Treated samples are sandy soils of 3Tr-13 and 3De-30. Good agreements in G_0 values are obtained between LSS and BE tests in Fig. 6.3(b). However, a large difference in G_0 appears between BE and LSS tests because Bender Element uses wave propagation to calculate shear wave velocity and derive G_0 and LSS devices directly measure soil deformation during triaxial loading. Due to soil fabrication, soil disturbance and pore pressure this difference occurred. To examine the strain dependent trend of G_{sec}, the same normalization manner with Figs. 6.2(c) and 6.2(d) was used.

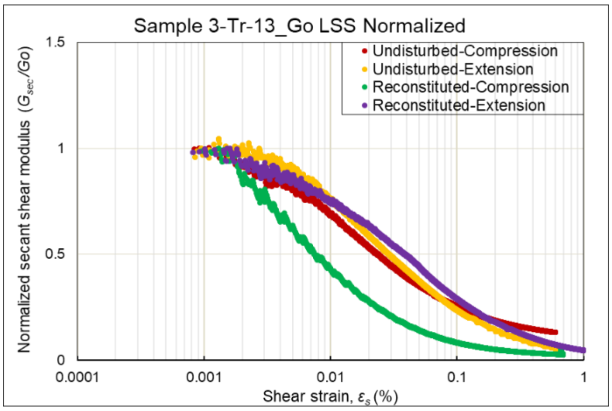


Fig. 6.3(c) Normalized LSS result for sample 3Tr-13

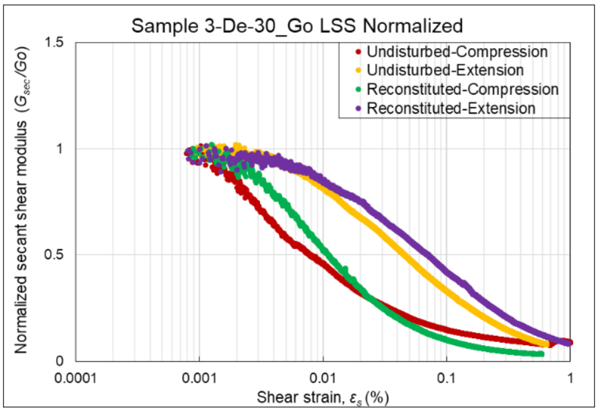


Fig. 6.3(d) Normalized LSS result for sample 3De-30

Figures 6.3(c) and Fig. 6.3(d) shows the normalized results of reconstituted and undisturbed soil samples with two different layers (3Tr-13: depth 13.50 to 14.50m) and (3De-30: depth: 30.50 to 31.50m) in compressional and extensional loading tests to remove the difference of G_0. Degradation of G is smaller in extensional loading than in compressional loading. Therefore, extensional loading tests are necessary to evaluate the rebounding behavior. In Fig. 6.3(d), similar trend appears in compressional loading between undisturbed and reconstituted samples. However, different trend is exhibited in Fig. 6.3(c) because of strong soil structure (cementation) developed in undisturbed sample. Concerning extensional loading, similar degradation trends between undisturbed and reconstituted samples are obtained in both types of sands (Figs. 6.2(c) and 6.2(d)).

7. Conclusion:

The findings obtained in this study for four different layers (two cohesive layers and two sandy layers) of undisturbed and reconstituted specimens 3De-8 (depth: 8.50 to 9.50m, 3De-21 (depth: 21.50 to 22.50m), 3Tr-13 (depth: 13.50 to 14.50m), and 3De-30 (depth: 30.50 to 31.50m) are as follows.

i) For both cohesive and sandy soils, large difference appears in G_{sec} trend between compressional and extensional loadings: degradation degree of extensional loading is smaller than compressional loading. Therefore, **extensional loading tests are necessary** to evaluate the rebounding behavior.

ii) Extensional G_{sec} trend is similar between the undisturbed and the reconstituted samples. Therefore, **the use of reconstituted sample is acceptable** as a cost-effective testing procedure.

iii) The values of G_0 are largely dependent on ground layers. Therefore, $\boldsymbol{G_0}$ has to be evaluated from **in-situ investigation** or undisturbed sample.

8. Recommendations:

The following procedures are recommended:

1. Collect **disturbed sample** from the real ground
2. Make triaxial **reconstituted** specimens from the soils
3. Conduct $\boldsymbol{K_0}$ **consolidation** and **extensional LSS** tests for $\boldsymbol{G_{sec}}$ **trend**

4. Obtain $\boldsymbol{V_s}$ **from the real ground** (e.g. PS logging tests)
5. Create $\boldsymbol{G_{sec}}$ **trend** of the undisturbed samples using $G_0 = \rho \cdot V_s^2$
6. Estimate the rebounding amount in a suitable strain range