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Title: Compressional and extensional deformation characteristics in K_0 consolidated soils

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, which is known as rebound or heaving deformation, occurs. Ground rebound occurs when overburden pressure is removed during deep excavations for high-rise buildings, tunnels, and underground structures. The rebound amount has been estimated using empirical approaches. In the laboratory, the deformation coefficient, which is used to predict rebound has been determined through monotonic compression or cyclic loading tests. However, these deformation coefficients are not appropriate for capturing the 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 real soil and artificial soil specimens of two different layers 3De-8 (depth: 8.50 to 9.50 m) and 3De-21 (depth: 21.50 to 22.50 m). The results can be used to evaluate the rebound phenomenon in the practical field. The results revealed that the strain dependent trends of the secant shear modulus are equivalent between real soil and reconstituted soils under both compressional and extensional loading. Therefore, artificial soil (reconstituted soil) can be substitute for real soil (undisturbed soil) for the small strain test. However, attention is needed in the larger strain because real 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.

2. Objectives:

- To Understand the real soil and artificial soil behavior through compressional and extensional tests.
- To propose a suitable testing procedure for studying the rebound problems in practical work.

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3. Testing Materials

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. 3.1). 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 from top and bottom by applying 70 kPa pressure for 4 days. The physical properties for layer 3De-8 are specific gravity ρ_s 2.60 (g/cm^3), liquid limit (WL) 60.18 %, Plastic limit (WP) 41.03%, and Plasticity Index (IP)27.14 %, and for layer 3De-21 are specific gravity ρ_s 2.694 (g/cm^3), liquid limit (WL) 72.163 %, Plastic limit (WP) 37.497% and Plasticity Index (IP) 34.665 %. The grain size curve is shown in Fig 3.2.

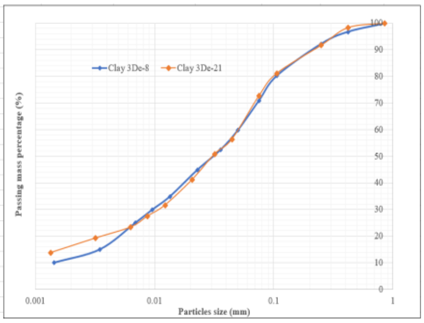


Fig.3.2. Grain size distribution curve

Real soil 3De-8 | Final shape H:12.5, D:5cm. | 2. Real soil 3De-21 | Final shape: H;12.5, D: 5cm

Fig. 3.1 Undisturbed samples

4. Experimental Methods

In this study, three distinct methods were used to measure shear strain at different levels as shown in Figure 4.1. Specimen with a dimension of 125 mm in height and 50 mm in diameter is used. Initial shear modulus G_0 was obtained from both LSS and BE tests, During K_0 consolidation, axial stress is set to σ'a = 158 and 300 kPa, and 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 loading to reproduce the rebound phenomenon as shown in Fig 4.2. We obtained 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.

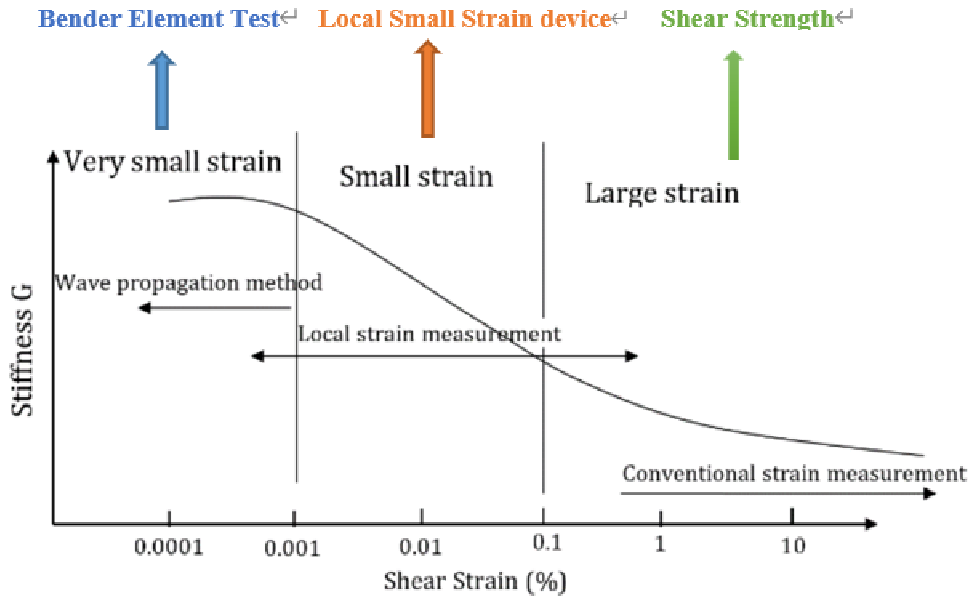


Figure 4.1 Methods for measuring shear strain at different strain levels.

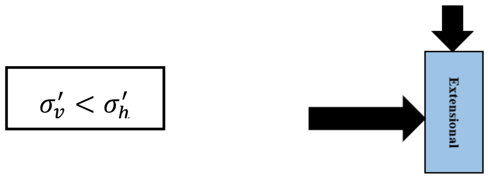


Fig.4.1 (a) Extensional loading condition (reducing σ_v' under constant σ_h')

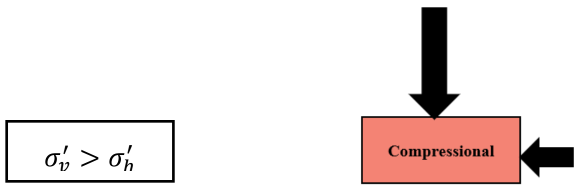
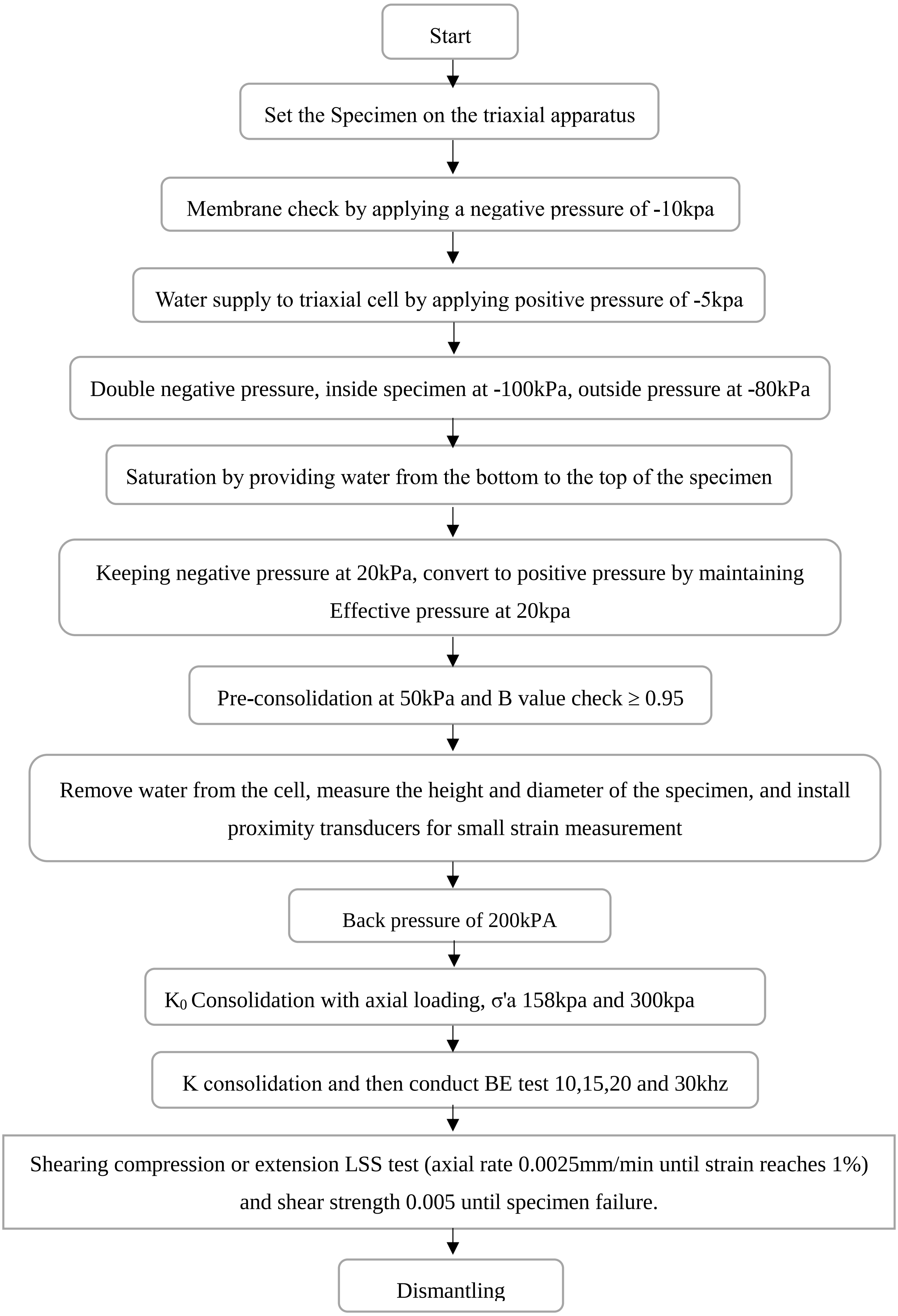


Fig.4.1 (b) Compressional loading condition (increasing σ_v' under constant σ_h')

4.1. Experimental procedure flowchart.



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5. Experimental results and discussions.

5.1. Representative stress path.

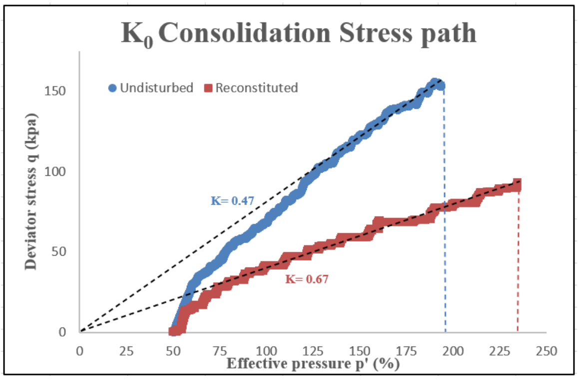

Fig. 5.1(a) K_0 consolidation stress path.

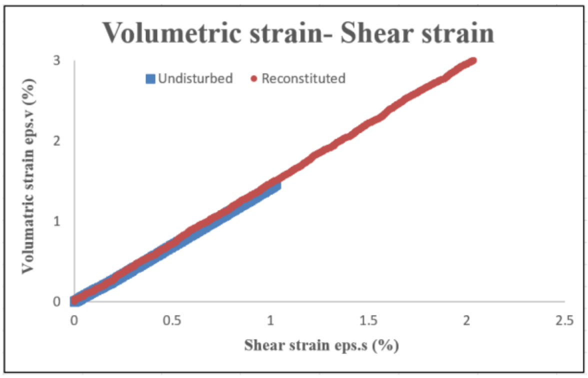

Fig. 5.1.(b)volumetric strain and shear strain.

K_0 consolidation can be considered as the same stress conditions with the original ground. Figure 5.1(a) graph shows the K_0 consolidation stress path for undisturbed and reconstituted specimens of layer 3De-8: (depth:8.50 to 9.50m) where σ'a is set at 300 kPa. The undisturbed sample (blue line) has a lower stress ratio (K=0.47) effective pressure p' is 194.19 kPa. On the other hand, the reconstituted sample has a stress ratio (K=0.67) and effective pressure is 231.95kpa. Figure 5.1(b) graph shows the relationship between volumetric strain and shear strain of undisturbed and reconstituted specimens. Reconstituted soil has a higher volumetric strain than undisturbed soil at the end of consolidation because of soft and weak structure.

5.2. Real soil behavior (Comparison between compression and extension loadings)

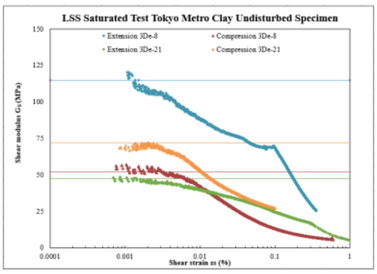

Fig. 5.2(a) Real soil LSS and BE

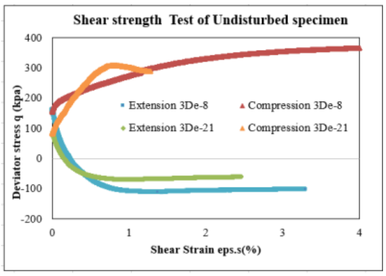

Fig. 5.2(b) Real soil Shear strength.

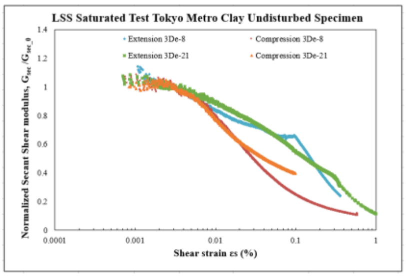

Fig. 5.3(c) Normalization of LSS

In Fig. 5.2(a), the horizontal lines show the G_0 value obtained from the bender element test. Good agreements in G_0 values are obtained between LSS and BE tests. However, there is a large difference in strain dependency of secant shear modulus between four tests. Therefore, normalization is necesssary for comparison. Fig. 5.2(b) shows shear strength test results for undisturbed samples. Fig. 5.2 (c) shows 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.

5.3. Real soil and artificial soil samples: Compression loading.

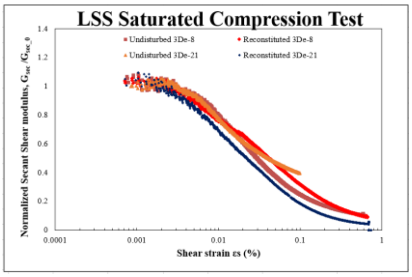

Fig. 5.3(a)LSS Real soil vs artificial soil.

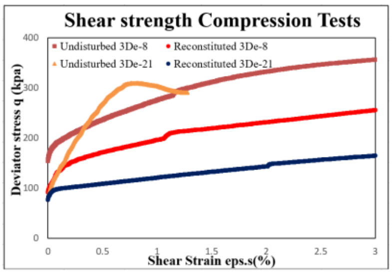

Fig. 5.3(b) Real soil vs artificial soil.

From Fig. 5.3(a), degradation curves of G have similar trend in all cases. Therefore, reconstituted samples can be substituted for undisturbed samples in compression tests. Fig. 5.3(b) indicates that the undisturbed samples have higher shear strength than reconstituted samples. Moreover, sometimes, brittle failure occurs in undisturbed samples, presenting the brittle failure in 3De-21 at shear strain of about 0.5 %. This point should be concerned in practical problems because the soil can be available before failure.

5.4. Real soil and artificial soil samples: Extension loading

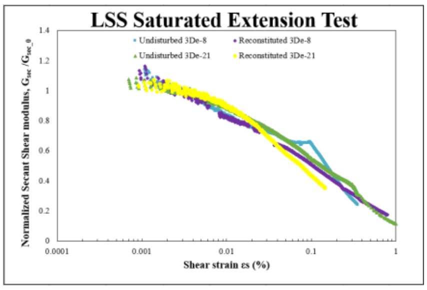

Fig. 5.4 (a)LSS Real soil vs artificial soil.

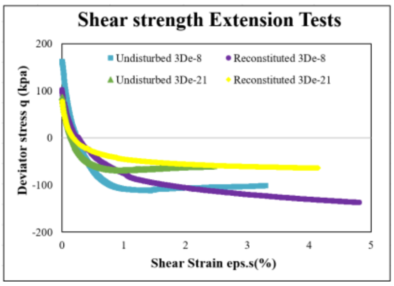

Fig. 5.4(b) Real soil vs artificial soil.

Figure 5.4(a) indicates degradation curves of G have similar trend in all cases, which is the same trend with compression tests in Fig. 5.3(a). Therefore, reconstituted samples can be substituted for undisturbed samples in extension tests. Fig. 5.4 (b) shows the shear strength of undisturbed and reconstituted samples. Results indicate that the undisturbed samples have higher shear strength than reconstituted samples. Moreover, brittle failures were observed in undisturbed samples.

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6. Conclusion:

i) **From the undisturbed soil:** The large difference in strain dependency of secant shear modulus appears between compressional loading and extensional loading. Therefore, extensional loading tests are definitely necessary to evaluate the rebounding behavior.

ii) **Undisturbed soil vs reconstituted soil:** The strain dependency of secant shear modulus (degradation of G) is very similar between the undisturbed and the reconstituted soils. Therefore, the use of reconstituted soils is recommended to assess the deformation properties of the actual ground because of easy extraction of the soil sample.

7. Recommendations:

Following procedures are recommended:

1. Obtain disturbed soil samples from natural ground

2. Conduct triaxial tests using reconstituted sample: extensional LSS tests using K_0 consolidated specimen is necessary for evaluation of ground rebound behavior.

3. Obtain the V_s from the real ground (e.g., PS logging)

4. Estimate the rebounding amount using the degradation curve of G obtained from the tests.