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Study of the Deformation Behavior of Cohesive Soil under Different Loading Conditions

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ABSTRACT

Deep excavations have become a growing part of urban infrastructure development projects, especially in areas of basements, transportation buildings, and utility corridors, and underground stations. Under these conditions, stress is generated and thus alters the stresses in surrounding soil. This is the case in cohesive deposits; rebound or "excavation induced up thrust" can be produced during the unloading stage. Traditional methods adopted for estimating the rebound include compression based. Study deformation parameters, or empirical relationships; however such methods cannot be used to compensate for all deformations completely. Represent the extension dominant path of stress which occurs during unloading during excavation. The present behaviour of cohesive soil during compression and extension is examined in this study. Small-Strain (LSS) measurements and bender element measurements have been and will be used for the quantification of local stress and strain in the future using K0-consolidated triaxial specimens. (BE) testing. The program of the experiment is undisturbed and reconstituted Tokyo. 84-9 (24-36 m depth) at 24–36 m depth. In the town of Metropolitan, cohesive soils have been collected from two representative depths: 3De-8 (at 8.50–9.50 m depth), and 84-9 (at 24–36 m depth). 3De-21 at 21.50–22.50 m depth. The experimental results reveal that there is significant non-linear stiffness. Degradation is accompanied by large differences in the initial shear modulus G0 as the shear strain increases, geological layers. The shallower 3De-8 clay has a reported G0 of ~103 MPa at The clay at the intermediate level 3De-21 has a compressive strength of around 68MPa, while the deep clay has a compressive strength of about 30MPa. These results also indicate that 3De-8 has higher peak shear resistance than 3De-21 in both states. Important, the normalized secant shear modulus Gsec/G0, The similarity of results from reconstituted material and undisturbed specimens in the same case suggests that NINST results are largely unaffected by the preparation of hydrated specimens. Response to the very low strains. The findings therefore support the use of reconstituted specimens for evaluating normalized stiffness degradation, provided that the absolute G0 is independently established from field measurements or high-quality undisturbed samples. The study further demonstrates that extensional stiffness is systematically different from compression stiffness and should be considered explicitly when estimating excavation-induced rebound. The findings are consistent with recent research emphasizing small-strain stiffness, soil structure, sampling disturbance and stress-path dependency in advanced deformation analysis. The proposed framework provides a practical basis for integrating laboratory extension testing with field shear-wave velocity measurements and advanced constitutive modelling for improved prediction of cohesive-soil deformation.

Introduction

The massive increase in demand for underground space along with deep basements, metro stations, underground roads, utility tunnels and other subsurface structures has been brought on by rapid urbanization. Excavation in these areas is often in close proximity to existing tunnels, foundation excavations and underground utilities, typically present in a metropolitan environment. The excavation

process is mechanically different from conventional foundation loading because the removal of soil represents a reduction in the total overburden stress. Consequently, the soil surrounding and beneath the excavation follows an unloading and stress-redistribution path that may produce significant deformation. The uploaded experimental study was developed specifically around this engineering problem. It recognizes the released overburden pressures when excavating at deep depth as the main mechanism for up heaving of excavation base, and highlights the importance of traditional vertical lifting process. Deformation coefficients from monotonic compression or cyclic loading may not be sufficient to the improvement of capturing extension-related soil expansion (Monzur 2025). Rocket rebound, which occurs as a result of excavation, is especially of significant importance in soft cohesive deposits. As the overburden goes away the effective stress will be within the volume of soil reduces and the soil could move outwards into the excavated area. Because of this, the resulting vertical and lateral spacing. The action of movements may affect retaining structures, existing piles, tunnels etc. This will cause tunnels to open up, crack, leak and affect Tunnel operations, according to the source study notes. The mechanical behaviour of a soil during this process is inherently nonlinear. Soils typically have a high stiffness at very low strains, but at medium to high strains, the stiffness becomes relatively low. The stiffness decreases gradually as the strain increases. Burland (1989), Atkinson and Sallfors (1991), this is a strain-dependent stiffness that has been identified as important by Jardine (1992) and Atkinson (2000). In modern research, it has been shown that the strength of stiffness under small strains is very important for predicting the deformation experienced by an excavation and should not be portrayed as a simple constant Young's modulus. The present study, then, takes for granted three complementary strain measures: techniques. To induce stiffness at very small strain, local and global bending is used, which is achieved through bending elements. Small-strain measurements are used to characterize the intermediate strain range, and conventional at bigger strains the response is measured using the triaxial shear-strength testing. The source dissertation is identified by These 3 domains for measurement is mentioned specifically. A fundamental issue in excavation engineering is that the soil Many of the parameters that are used in standard rebound calculations are usually extracted from compression tests. But it is unloading and stress-path reverse that are they associated with the action of excavation. Lambe developed states of stress. It was shown by (1967) that soil behaviour is not only dependent on the initial and final states of stress but also on the stress path during the deformation of the soil. Therefore, a compression test and an extension test to similar stress fracture. Equivalent response from Magnitudes doesn't produce equivalent deformation responses. This distinction is more significant at small strains where movements in retaining walls and or foundations may be expected below 0.1% strain (Atkinson, 1993). At these strains, the initial strain/ secant strain change difference is very small AND permissive for the measurements recorded. Stiffness may be quite severe. The specific research on the source is directed towards strain in the vicinity of. 0.0001% and 1% and uses extensional shearing to explore deformation of the rebound. A second issue is the difference between undisturbed and reconstituted specimens. The treasures of the earth are natural clay with a history of geology (fabric) and bonding history and stress conditions that are subject to change during sampling. Consequently, the in-situ value of absolute stiffness may not be the same as the value from a disturbed or reconstituted sample. Zhou et al., 2024, have recently shown that both sampling and lab consolidation can cause significant disturbance in soft clay and that the stress normalized small strain stiffness can be mobilized. It has been employed to determine the severity of structural damage.

2. Research objectives

The principal aim of this research is to **analyse the deformation characteristics of cohesive soil at various stress conditions**, with particular emphasis on compression and extension loading. The specific objectives are to:

1. investigate deformation behaviour under compressional and extensional stress paths;
2. reproduce the natural anisotropic stress condition through K_0 consolidation;
3. determine initial and secant shear stiffness;
4. compare undisturbed and reconstituted cohesive soil;
5. evaluate the influence of geological depth and soil structure;
6. establish whether reconstituted soil can be used for small-strain rebound evaluation; and
7. develop a practical methodology for combining laboratory stiffness degradation with field V_s measurements.

3. Literature Review

The stress- strain relationship of cohesive soil is controlled by effective stress and stress history, fabric and structure, drainage conditions and amplitude and direction of strain. In deep excavation, the removal of soils results in stress relief, and the content and displacement of soils below the excavation will move upwards. There may be lateral soil movement and the change of pore-water pressure may occur during this rebound. A number of studies have occurred before that has suggested different methods for estimating rebound caused by excavation. The study that is uploaded examines the various empirical approaches, as well as the foundation-code methods and residual-stress or bounce/re-capture methods. These methods typically involve a measure of rebound index or other measures of deformations such as resilient modulus. The rebound–recompression method has been of special interest since the in-situ properties can be different from the conventional laboratory parameters. For instance, Li et al. (2021) have studied field curves of rebound and recompression of soft clay, and later studies have elaborated on the procedure of testing to modify parameters from laboratory to best mimic field conditions. Recent research shows that in-situ void ratio and rebound parameters can have a significant effect on heave calculations. The stress-path theory that has been developed by Lambe is still the basis for the analysis of the excavation. Soil structure, soil fabric and soil plastic strains (Lambe, 1967) change along the path along which the effective stress tensor moves. Unloading at the shale/fine grained sand interface during excavation can then result in another shear/yield response compared to traditional compression. Unloading at the shale/fine grained sand interface during excavation can thus give rise to another shear/yield response compared to “conventional” compression. The source study uses extension loading as these results in the release of stress and expansion during excavation. The horizontal effective stress will increase relative to the vertical effective stress with extension: $\sigma v' < \sigma h'$. Compression on the other hand is shown by: $\sigma v' > \sigma h'$. The methodology employed for this experiment incorporates the contrasting conditions in an explicit manner, and thus fosters a manifestation of rebounding potential. Field studies in recent years demonstrate the significance of this distinction. Zhao et al. (2024) observed measurable vertical and horizontal movements occurring in a case study in Shanghai where deep excavation in soft clay was accompanied by upward and divergent movement of the adjacent metro tunnel. The small-strain shear modulus, G_0, is easily determined from shear-wave velocity, as $G_0=\rho Vs2$, and is a measure of soil stiffness.$G_0=\rho V_s^2$. The shear-wave velocity is: $Vs=L\Delta t$, or $Vs=\frac{L}{\Delta t}$ where LL is the distance that the shear wave travelled and Δt\Delta t is the measured time of travel. This study uses bender elements operating at 10, 15, 20 and 30 kHz, and repeats the measurements at each frequency. The bender-element testing technique to measure very small strain stiffness is now a reliable procedure. It is the result of the efforts of Viggiani and Atkinson (1995b), Kuwano et al. (1998), Yamashita et al (2009) and ASTM D8295. This is supported by recent research

work indicating that the stiffness of the boulders, under small strains, is still very sensitive to the stress state and the soil structure. The results presented by Zhou et al. (2024) showed that the stress normalized small strain stiffness may be helpful in predicting the degree of disturbance between an undisturbed and a disturbed state of clay for a specific at-rest stress condition. External axial displacement measurements can be affected by apparatus compliance, bedding effects and non-uniform deformation. Local displacement transducers eliminate some of these drawbacks by measuring the deformation at an incremental section of the specimen. Proximity sensors based on the eddy-current principle are used for the source apparatus. The specimen is equipped with two axial and one radial measuring instrument. This method is especially useful as a tool to capture the mechanical behaviour of samples that are subject to large or small deformations, especially when the range of external displacements is not within a resolution of conventional measurement techniques. Local strain measurements are therefore a link between both types of measurement, wave-based G_0 and the conventional large-strain strength measurements. Structured material of natural cohesive soils is considered natural cohesive soils. The engineering behaviour of their deposits is correlated to a bond formation, an ageing process, a compaction process and formation of fabric. Leroueil and Vaughan (1990) have shown that structure can have a strong effect on strength and compressibility of the natural soils. This can be partially destroyed by the sampling process. The last study, done by Zhou et al., 2024, has been experimental and found that the introduction of conventional sampling involves a measurable disturbance, with an additional disturbance when stresses are imposed in the lab during consolidation that exceed the structural yield. The undisturbed and reconstituted samples of the source being considered are relevant to the current study. To compare the strain-degradation behaviour without assuming that the two materials have identical absolute stiffness, the secant stiffness was normalized by that of G_0.

4. Materials and Experimental Programme

4.1 Geological materials

Four Tokyo Metropolitan soil layers were originally investigated, including two cohesive and two sandy layers. The present paper concentrates on the two cohesive materials:

- **3De-8:** 8.50–9.50 m depth;
- **3De-21:** 21.50–22.50 m depth.

The 3De-8 material is described as tuffaceous clay containing clay minerals and volcanic ash, whereas 3De-21 contains clay particles with fragments of seashells. The reported index properties are summarized in Table 1.

Table 1. Physical properties of cohesive soils

Property	3De-8	3De-21
Specific gravity, Gs	2.60	2.694
Liquid limit, wL (%)	68.18	72.163
Plastic limit, wP (%)	41.03	37.497
Plasticity index, PI (%)	27.14	34.665

The higher plasticity index of 3De-21 indicates a more plastic cohesive material, although the mechanical response cannot be attributed to plasticity alone because mineralogy, fabric, stress history and structure also differ.

4.2 Specimen preparation

This was done using undisturbed samples and expecting the samples to retain the natural moisture, and density. The factors are: content, fabric and stress condition. The original plants collected in the field were about 200 mm tall they were 75 mm in diameter, and then was trimmed to about 75 mm x 50 mm x 125 mm. diameter. In the slurry method, the reconstituted specimens were prepared by using a soil sample from the same ground. For the slurry method, the reconstituted specimens were prepared from the same ground using a soil sample. A sample of 700 g of water and 1000 g of dry soil, another sample (3De-21) contained 800 g of water and 1000 g of dry soil. g water and 1100 g clay. The slurry was left to stand and then was vacuum desired and consolidated at the pressure applied to the material before it is extruded is 70 kPa. These are all the principles behind the contrast that is the basis of the study: undisturbed – keeps some aspects of natural geological structure; reconstitution – is the same, but involves the addition of elements." Produces a significantly altered fabric.

5. Experimental Methodology

5.1 Triaxial apparatus

In the experimental program a system of triaxial testing with a high accuracy series was used with a pressure controlled system, the small-strain sensors and bender elements, local, axial loading, and drainage measurement. The system Enabled testing over a wide range of strains. The LSS system was based on proximity sensors with an approximate the measurement gap was 80mm. At each step of the sensor calibration procedure, the relationship between was determined. Before testing, note down the output voltage and displacement.

5.2 Saturation and back pressure

Negative pressure was first applied to the specimens to release entrapped air, and then they were saturated with water containing no dissolved air. A criterion of Saturation (Skempton BB-Value) of 0.95 was chosen. The saturation was then increased by applying a back pressure of 200 kPa. This process cannot be ignored since it can be important in affecting the pore-pressure response, effective stress, and measured stiffness.

5.3 K_0Consolidation

The natural stress state was replicated via the application of K0 consolidation, in which the lateral deformations were prevented but axial effective stress was increased.

The relationship is:

$$K_0=\sigma_h'\sigma_v'.K_0=\frac{\sigma'_h}{\sigma'_v}.$$

The aims of the axial effective stresses were:

$$\sigma_v'=300\ \text{kPa}\sigma'_v=300\;{\rm kPa}$$

for 3De-8 and

$$\sigma_v'=158\ \text{kPa}\sigma'_v=158\;{\rm kPa}$$

for 3De-21.

The use of K_0 consolidation is significant as it would not create the anisotropic stress condition of the natural deposit if isotropic consolidation was used.

5.4 Bender element testing

Top cap and pedestal have been equipped with bender elements. In calculating the travel time and tip to tip travel distance, the source research used the start to start approach.

The basic calculation is:

$$V_s=d\Delta tV_s=\frac{d}{\Delta t}$$

Followed by:

$$G_0=\rho V_s2.G_0=\rho V_s^2.$$

The obtained G0 is the stiffness under very small strains and it will be used as the normalization parameter for a further G_{sec} G_{sec}-strain analysis.

5.5 Compression and extension

Following the K_0 consolidation the specimens were compressed and extended.

For compression:

$\sigma_v' > \sigma_h'$.\sigma'_v>\sigma'_h.

For extension:

$\sigma_v' < \sigma_h'$.\sigma'_v<\sigma'_h.

The extension test is particularly significant as this represents the stress relief of excavation. According to the source study, extension was used to assess the expansive potential of soils as a result of the reduced overburden stresses, and to assess the rebound potential. The rates of axial displacement used for LSS tests were 0.0025 mm/min; the larger-strain shear-strength tests were done at 0.005 mm/min.

6. Results

6.1 K_0 consolidation response

It is apparent that there are stress path differences between undisturbed and reconstituted material from the K0 paths. The undisturbed specimen measured about: for 3De-8:

K=0.47

The reconstituted sample was about:

K=0.67.

The effective pressures in the source were about 194.19 and 231.95 kPa respectively. The remaining undisturbed specimen exhibits a lower KK response, a suspension of stress development which could be reasonably linked with the natural fabric and stress history of the undisturbed specimen. The rebuilt one has, on the other hand, been extensively rearranged. This result supports the notion that K0 is not just a function of the friction angle. Stress history, structure and anisotropy are also important.

6.2 Initial shear stiffness

The LSS and bender-element results demonstrate a strong depth dependency.

For 3De-8, the reported initial shear modulus under extension is approximately:

$G_0 \approx 103$ MPa.G_0\approx103\;{\rm MPa}.

For the deeper 3De-21 material, the reported value under compression is approximately:

$G_0 \approx 68$ MPa.G_0\approx68\;{\rm MPa}.

The source results further indicate that stiffness decreases progressively with increasing shear strain. This result has two important implications. First, G_0 should be considered a site- and layer-specific parameter rather than a universal clay property. Second, depth alone cannot explain the difference; mineralogical composition, structure, plasticity, effective stress and geological history must also be considered.

6.3 Stress–strain and shear-strength response

The other materials show both an initial rise and a peak before a decrease in deviator stress. This represents a strain softening response beyond the maximum strength. Maximal shear stress of 3De-8 is found greater than 3De-21 in compression as well as in extension. The strength of the reconstituted 3De-21 specimen is lowest while the reduction of strength after peak is relatively high. As the strain level penetrates further into the mid-range (the domain where the mechanical effects of reconstitution is increasingly apparent), the Ludwig model suggests a change in the God-det model from Hookean to non-Hookean behaviour's the strain departs from the very shallow-strain domain, the Ludwig model indicates a transition from Hookean to non-Hookean behaviour in the God-det model.

6.4 Normalized secant stiffness

The most significant finding emerges from the normalized stiffness curves. The secant shear modulus can be defined as:

$$G_{sec}=\tau\gamma.G_\{sec\}=\frac\{\tau\}\{\gamma\}.$$

Normalizing by initial stiffness gives:

$$G^{*}=G_{sec}G_{0}.G\^*=\frac\{G_\{sec\}\}\{G_0\}.$$

At shear strains below approximately 0.001%, the undisturbed and reconstituted specimens show relatively similar normalized stiffness. With increasing strain, however, G∗G^* decreases nonlinearly. This result indicates that the absolute value of stiffness is strongly influenced by natural structure, whereas the shape of the normalized degradation curve may be less sensitive to specimen disturbance in the very-small-strain range.

7. Discussion

7.1 Nonlinear stiffness degradation

The observed stiffness degradation agrees well with the known nonlinear behaviour of soils. For very small strains, reversible deformation predominates at the level of the contacts of the particles and the skeleton of the soil. As the strain increases, the particles become further rearranged, there is development of contact slippage, alteration of the fabric and irreversible deformation occurs progressively. Therefore:

$$G_{0}>G_{sec,1}>G_{sec,2}$$

When

$$\gamma1<\gamma2.$$

This behaviour is confirmed by experimental curves of the present study. These findings have implications for numerical modelling and are relevant directly. Whereas an assumed constant elastic modulus might be appropriate for preliminary analysis, it is probably better to assume more complicated elastic modulus behaviour to represent the actual deformation characteristics of cohesive soil. An example of the latter is the Hardening Soil model with small-strain stiffness, which explicitly contains the nonlinear stiffness degradation. Recent researches prove the usefulness of such models in the analysis of excavations and emphasize the significance of a reliable setting of their parameters.

7.2 Why extension is critical for rebound

The most important finding of the study is that extensional and compressional stiffness trends are different.

The source research reports:

$$G_{sec,extension}>G_{sec,compression}.G_\{sec,extension\}>G_\{sec,compression\}.$$

For the materials investigated such a relationship exists and is recognized as being one of the reasons that extensional testing should be performed for the purposes of rebound analysis. When calculation of excavation rebound is based on the stiffness of compression, the soil can be assumed to be more deformable than it truly is along the appropriate extension path. This rebound estimate could be on the conservative or even the high end. This find is important not just for the Laboratory. It can be seen in recent numerical and field investigations that some factors, such as construction sequence of soil, unloading, and small-strain stiffness, have an impact on the deformation caused by excavation. For example, Wu et al. adopted numbers in the figure to represent the various properties of clay, and demonstrated the relation between these properties and the deformation of deep excavations in clay in the city of Shanghai (Wu et al., 2024).

7.3 Influence of geological depth

The two coherent layers exhibit very different stiffness and strength responses. The shallower 3De-8 is tuffaceous clay, whereas 3De-21 is more friable and has shell fragments in it, and thus a higher PI. It is clearly seen that 3De-8 has higher shear strength and small-strain stiffness than 3De-21, from the source data. This shows that the term "clay" should not be used as an engineering material. Clay properties can vary greatly between two clay layers of a single metropolitan deposit. With this in mind, geotechnical investigation should be conducted separately to discover the constituent geologic units of the site instead of being limited to a single mean stiffness for the site.

7.4 Undisturbed versus reconstituted specimens

The comparison between specimen types produces an especially useful engineering conclusion. The undisturbed specimen provides a better representation of the natural soil structure and absolute G_0. However, undisturbed sampling is expensive, technically difficult and susceptible to unavoidable disturbance. Reconstituted specimens are easier and cheaper to produce. The present results indicate that, after normalization by G_0, the extensional stiffness degradation of reconstituted specimens is approximately consistent with the undisturbed response.

Consequently, a practical approach is:

$$G_{sec}=G_0(GsecG0)\boxed{ G_{sec}=G_0\left(\frac{G_{sec}}{G_0}\right) }$$

Where the normalized degradation function is determined from economical reconstituted specimens, while G_0 is obtained independently from in-situ V_s. This concept is strongly supported by recent work on stress-normalized small-strain stiffness and soil disturbance. Zhou et al. (2024) demonstrated that normalized small-strain stiffness can be used to evaluate structural disturbance across intact, sampled and remoulded conditions.

7.5 Implications for field V_s measurement

Because the absolute G_0 varies strongly between layers, the source study recommends determining field shear-wave velocity and using:

$$G_0=\rho Vs2.G_0=\rho V_s^2.$$

Field V_s may be obtained through PS logging, downhole or crosshole testing, or other appropriate seismic methods. The recommended methodology is therefore:

1. collect disturbed soil from the field;
2. prepare reconstituted specimens;
3. apply K_0 consolidation;
4. perform extensional LSS testing;
5. establish G_{sec}/G_0
6. determine field V_s;
7. calculate field G_0; and
8. combine the field G_0 with the laboratory normalized degradation relationship.

7. Engineering Applications

7.1 Deep excavation

The results have direct application to excavation projects in soft cohesive deposits. A conventional rebound calculation may be represented conceptually as:

$$\Delta H=f(\Delta\sigma,Er,Cs,e0,\ldots)\Delta H=f(\Delta\sigma,E_r,C_s,e_0,\ldots)$$

Where $\Delta H\Delta H$ is rebound, $\Delta\sigma\Delta\sigma$ is unloading stress and E_r or C_s represents a rebound-related deformation parameter. The present study suggests that the deformation parameter should not be regarded as independent of stress path. Instead:

$$G_{sec}=f(\gamma,\sigma',K_0,\text{stress history},\text{loading direction}).G_{sec}=f(\gamma,\sigma',K_0,\text{stress history},\text{loading direction}).$$

This is a more physically realistic representation of excavation behaviour.

7.2 Numerical analysis

The findings are particularly relevant to finite-element analysis using advanced constitutive models.

For example, an excavation model can incorporate:

- layer-specific G_0;
- nonlinear G/G_0 degradation;
- K_0 initial stress conditions;
- over consolidation ratio;
- stress-path dependence;
- structural effects; and
- Construction-stage unloading.

Recent 2025 work demonstrates that the Hardening Soil model with small-strain stiffness can improve excavation deformation prediction, although the accuracy remains highly dependent on parameter determination. More recent research published in 2026 further emphasizes that small-strain stiffness and its dependence on stress history remain important issues in advanced clay modelling.

7.3 Existing tunnels and foundations

In general, excavation induced rebound is more significant where excavation is conducted in close proximity to existing infrastructure. An in-depth case study on the Shanghai site in recent years reported significant lateral and vertical movement, including upwards and inwards movement of another tunnel. The design of excavations should now take into account not only the movement in the excavation retaining walls and the settlement of the surfaces above the excavation, but also heave and rebound below the base of the excavation.

8. Limitations and Future Research

The present study is valuable in the light of the experimental results provided however, a number of limitations are apparent: acknowledged. Firstly, two continuous geological layers are studied in detail. Consequently, the any correlations found for these observed relationships should be considered unrelated to other natural clays. Second, the experimental First of all, the programme acknowledges particular target stress states, mainly 300kPa for 3De-8 and 158kPa for 3De-21. A wide range of consolidation stresses would be needed to develop a general stress-dependent constitutive relationship. Third, measurements of bender elements are subject to interpretation. Wave Near field effects, boundary conditions, signal strength, and the type of adopted travel time can all affect travel time. Line-densities or first-arrival criterion (Viggiani and Atkinson, 1995b; Yamashita et al., 2009). Fourth, natural soil producing perfectly accurate structures in the lab is hard to do. For undisturbed and this is shown by the fact that the anisotropic stress response is changed by reconstitution in the responses after K0 administration. Fifthly, this study is largely mechanical description and study. Future studies could combine micro structural methods, such as scanning electron microscopy, X-ray computed tomography and particle-scale. Trying to account for the observed stiffness differences using analysis. Sixth, experimental work in the future should examine repeated unloading and cyclic extension, various over consolidation ratios. Recent studies State that small-strain stiffness is highly dependent on stress history, environmental/loading cycles. Last, however, testing in the field is essential. Laboratory extension curves should eventually be: Compared to monitored changes in heave and pore-pressure during excavation.

Conclusion

The results of this study show that the deformation properties of cohesive soil are influenced significantly by stress history, the path of stress application, soil behaviour and strain level, and that simply using compression-based stiffness parameters is not enough of a constraint to be effective when evaluating ground deformation under unloading. The experimental study performed on the cohesive soils of the area of Tokyo revealed that the shear modulus (G0) values of the soil are very sensitive to the geological horizon and thus it is potentially advisable to use in-situ measurements or carefully maintained undisturbed samples to determine the value of the shear modulus (G0). The results also show that the stiffness of soils under extension (G_{sec}) generally is greater than that of soils under compression, all being nonlinearly decreased with increasing strain. It is important to note that the normalized stiffness response $G*=G_{sec}/G_0G\hat{}*=G_\{sec\}/G_0$ from the reconstituted samples had a similar trend to that of the specimens in the undisturbed state, especially at small strains, and thus can offer insight into the stiffness degradation pattern jointly with an appropriate estimate of G0 based on field measurements. The results also validate that deformation due to unloading and from rebound created during excavation, cannot be adequately characterized by compression testing, and extensional testing is essential for this purpose. Consequently, the study suggests a practical procedure in which the normalized trends (reconstituted specimens) are compared to the in-situ shear-wave velocity measurement and/or completed using undisturbed specimens to determine the respective absolute small-strain stiffness. This method can help to better estimate excavation rebound and other stress release induced deformations in cohesive soil and serve as more rational parameters for carrying out advanced geotechnical numerical analyses and designing.

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