Final resume
Student Name: Muhammad Suliman **Supervisor:** Prof. Hirofumi

Deformation Characteristics in K_0 Consolidated Soils Considering Ground Rebound Behavior

（地盤のリバウンドを考慮した K0 圧密された土の変形特性）

Abstract

Deep excavations for underground infrastructure relieve substantial stress at the pit base, inducing upward ground movement known as rebound or heave. Reliable evaluation of this deformation remains a persistent challenge in geotechnical practice, because it depends on representative soil parameters obtained under unloading stress path. Rebound has conventionally been estimated using empirical methods or oedometer tests and cyclic loading tests to derive deformation coefficients. However, these approaches capture stress relief in limited state: e.g. under one-dimensional condition or under the compressional loading conditions.

This study establishes a more effective experimental framework for estimating rebound deformation by investigating the secant shear modulus (G_{sec}) of K_0 consolidated soils under compressional and extensional loading paths. Triaxial tests incorporating bender element (BE) and local small strain (LSS) tests were conducted on undisturbed and reconstituted specimens from a metro construction site. Two silty clay layers at (8.5–9.5) m and (21.5–22.5) m formed the main basis for discussion, with two additional layers, a silty sand at 13.5–16.5 m and 30.5–33.5 m, briefly summarized for comparison. The undisturbed specimens exhibited high stiffness despite large void ratio, reflecting strong interparticle cementation and intact natural soil fabric. The G_{sec} was normalized by the initial shear modulus (G_0) to compare degradation behavior across soil types and consolidation conditions.

The normalized results revealed a pronounced directional anisotropy in stiffness degradation for the silty clay layers. Under K_0 consolidated undisturbed conditions, extensional loading retained higher normalized stiffness to larger shear strains than compressional loading, and reconstituted K_0 consolidated specimens closely reproduced the undisturbed degradation. Therefore, the use of reconstituted specimen can be confirmed as a practical alternative to undisturbed samples for extensional loading. In contrast, isotropically consolidated reconstituted specimens failed to reproduce the extensional degradation of K_0 consolidated undisturbed soils, while agreeing well under compressional loading. For the sandy layers, consolidation condition had far less influence: isotropically and K_0 consolidated specimens followed similar degradation trends for both undisturbed and reconstituted states, although the undisturbed silty sand showed some discrepancy.

Keywords: K_0-consolidation; Bender element; Local small strain; Secant shear modulus; Triaxial

Nagaoka University of Technology, Department of Civil and Environmental Engineering,
Geotechnical Laboratory

test; Rebound.

Introduction

Rapid urbanization has pushed construction into the underground space because of dense metropolitan areas. In cities such as Tokyo and Osaka, subway tunnels, metro stations, and deep basements are built because surface land is scarce and costly (Moormann, 2004; Tan & Wei, 2012). These structures require deep excavation, which disturbs the initial stress equilibrium of the ground (Fig. 1). When overburden pressure is removed, the soil at the excavation base is unloaded and moves upward, a response known as ground rebound or basal heave (Lambe & Whitman, 1991). In congested urban settings where adjacent structures allow only limited deformation tolerance, even small movements can cause cracking or serviceability failure, and recent metro projects have shown that misjudging excavation-induced rebound can carry severe consequences (Tan et al., 2019; Li et al., 2023).

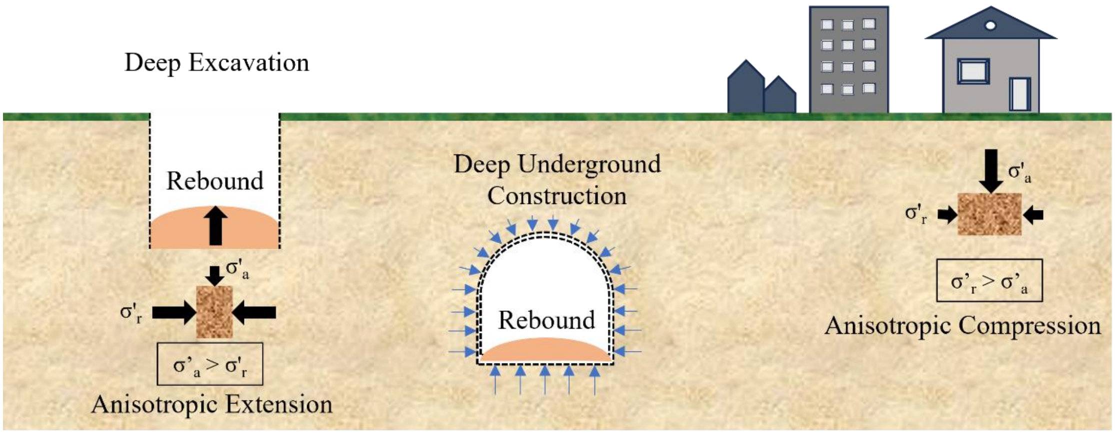

Fig. 1: Schematic of stress release and resulting rebound during deep excavation.

Reliable evaluation of this deformation remains difficult in practice. Conventional empirical methods based on one-dimensional consolidation and a single swelling index, together with numerical analyses using the linear-elastic perfectly plastic Mohr-Coulomb model, have been shown to overestimate rebound (Goh et al., 2024). These approaches cannot reproduce the non-linear small-strain stiffness of soils, the stress-path dependence of the unloading response, or the loss of natural structure during stress relief. Advanced characterization of stiffness under realistic in-situ stress paths is therefore essential for the design of deep excavations.

Shear strains beneath deep excavations rarely exceed 1% and typically lie between 10^{-5} and 10^{-2}, a range in which soil stiffness is highly non-linear (Burland, 1989; Atkinson, 2000). The response is governed by the initial shear modulus G_0 and the secant shear modulus G_{sec}, whose normalized degradation curve G_{sec}/G_0 against shear strain (Fig. 2) links laboratory measurement to field deformation behavior (Mair, 1993). Because no single technique evaluates the full strain range, bender element (BE) tests are used here to determine G_0 below 0.001% strain following JGS 0544 (Japanese Geotechnical Society, 2011), while local small strain (LSS) transducers based on the concept of Goto et al. (1991) measure the response between 0.001 and 1 %, providing continuous stiffness characterization within a single specimen.

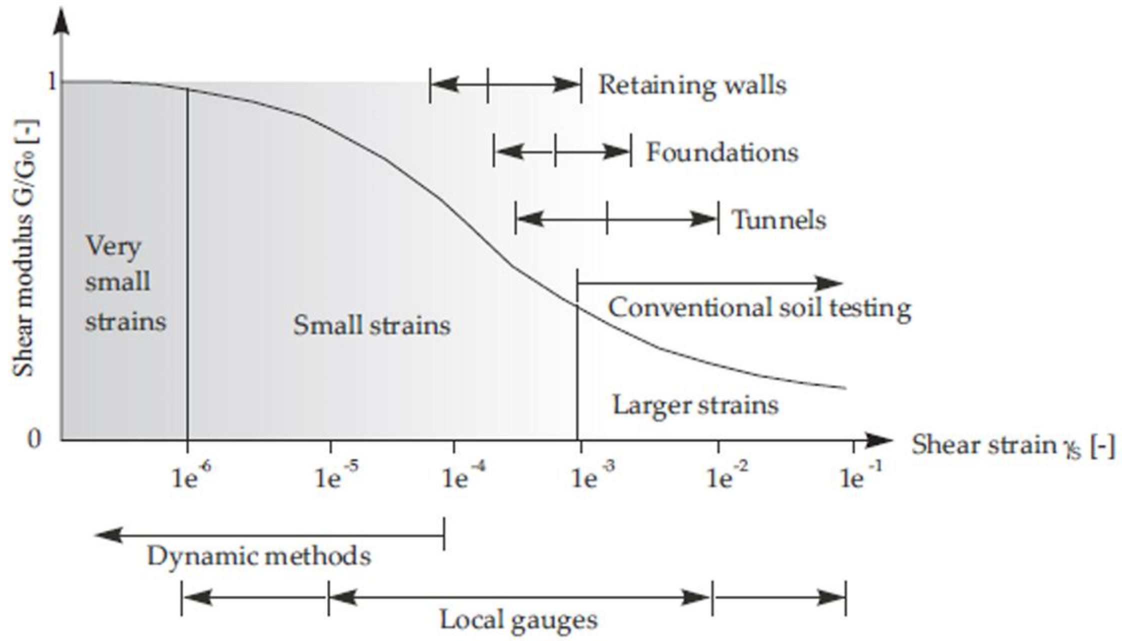

Fig. 2: Strain ranges on the normalized stiffness-degradation curve (Mair, 1993).

Beneath an excavation base the vertical effective stress decreases while the horizontal stress is only partially relaxed, so the field unloading trajectory is better represented by an extensional path than by the conventional compressional (Berre, 1973). Representative parameters further require consolidation to the in-situ K_0 stress state, since isotropic consolidation erases the stress-induced anisotropy of the natural deposit and misrepresents its stiffness (Pennington et al., 1997). K_0 consolidation, standardized in JGS 0525 and JGS 0526, is therefore adopted for shearing in both directions.

Undisturbed specimens define the absolute stiffness and the contribution of natural cementation and fabric, pronounced in the tuffaceous silty clays of volcanic origin common in Japan, but high-quality sampling from deep sites is costly, and disturbance during recovery and preparation can bias results (Tanaka, 2000). Reconstituted specimens from the same parent soil isolate the intrinsic response and suit normalized degradation study (Burland, 1990). This study therefore compares G_{sec}/G_0 of undisturbed and reconstituted K_0 consolidated specimens under compressional and extensional loading, to establish a reliable and cost-effective experimental basis for evaluating deformation under excavation-induced stress relief.

Tested Materials

Undisturbed specimens were collected from a borehole at a deep excavation construction site in Tokyo, where stress relief in the underlying deposits has induced ground rebound. The two primary layers are 3De-8 (8.50 to 9.50 m), a tuffaceous silty clay of the Pleistocene Lc unit formed from weathered volcanic ash, and 3De-21 (21.50 to 22.50 m), a shell-bearing marine clay of the Toc unit within the Tokyo Formation. Clay sampling employed a rotary double-tube sampler conforming to JGS 1222 to preserve the natural structure and fabric. The comparison layers 3Tr-13 (13.50 to 14.50 m) and 3De-30 (30.50 to 31.50 m) are silty sands. The 3Tr-13 specimens were stored frozen while 3De-30 was stored sealed at room temperature. Index properties and particle size distributions of all layers are given as Fig.3.

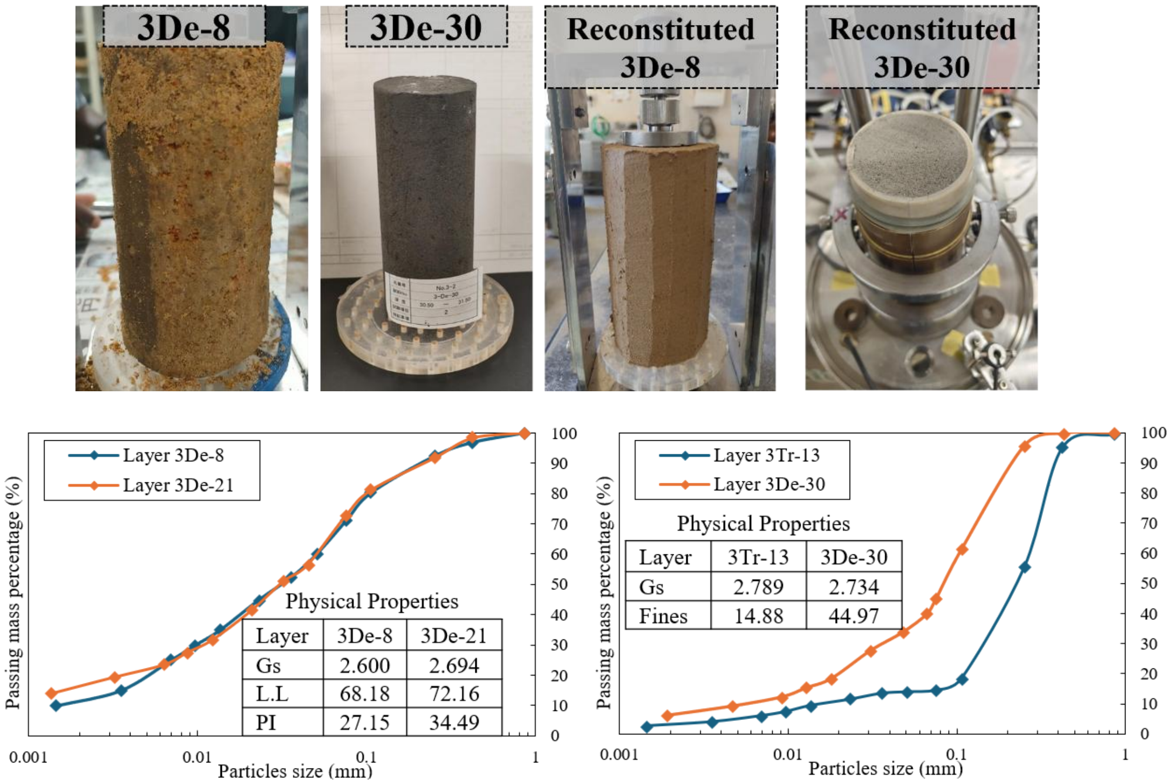

Fig. 3: Physical properties and particle size distributions of the tested layers.

Reconstituted clay specimens were prepared from the same material after undisturbed testing, following the slurry consolidation method of Le et al. (2024). Sieved soil was mixed with de-aired water to approximately 80% water content, above the liquid limit to ensure complete de-structuring, then one-dimensionally consolidated under 70kPa with double drainage before trimming. For the sandy layers, limited undisturbed material present, so reconstituted specimens were prepared by split-mold air pluviation, depositing oven-dried soil through a funnel at a controlled drop height to achieve the target density.

Testing Methodology

Specimens were K_0 consolidated under in situ overburden stress with zero radial strain. Bender element tests measured G_0 at very small strains, followed by drained monotonic shearing with LSS measurement to obtain G_{sec} up to 1% strain. Procedures are detailed below (Fig. 4).

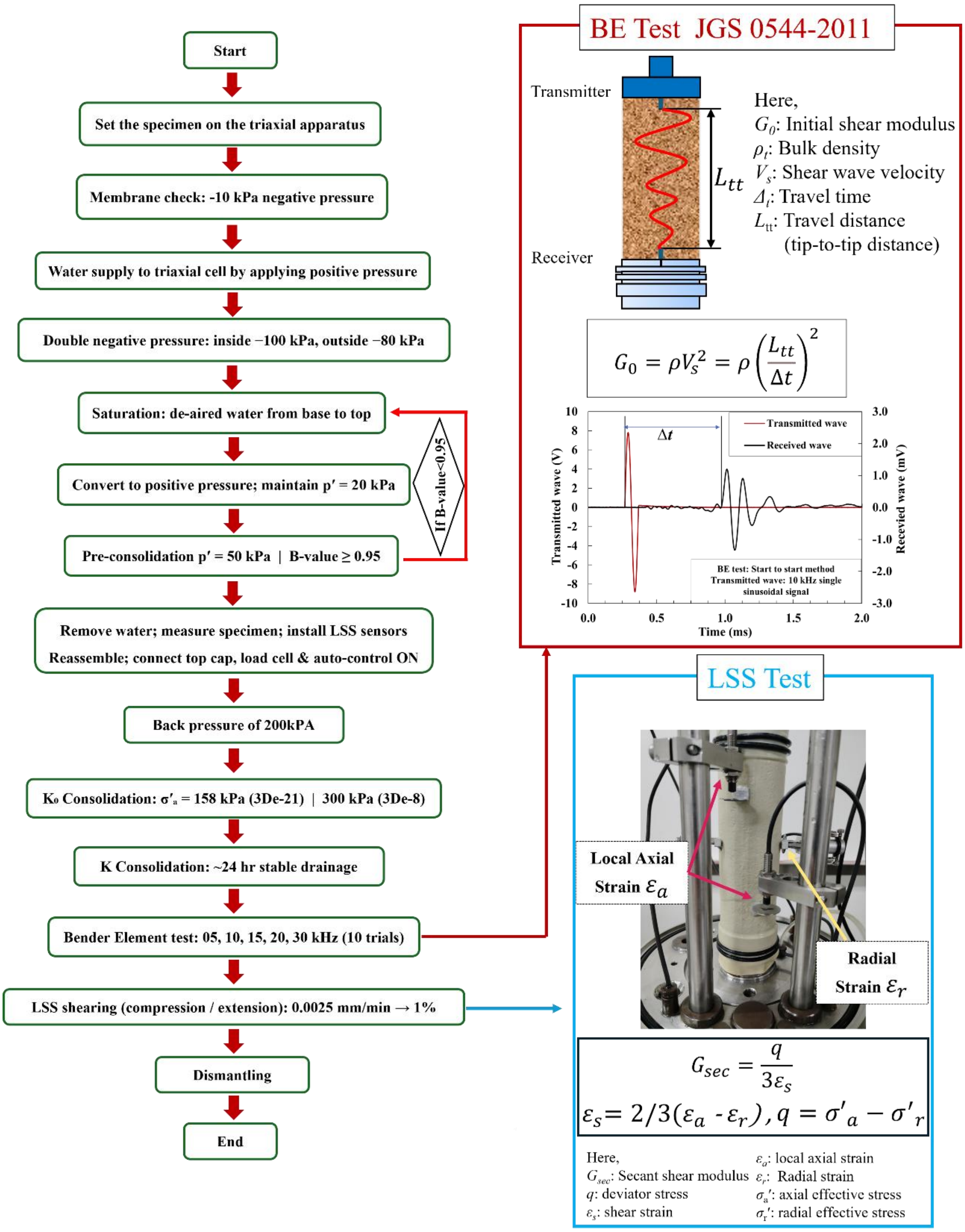

Fig. 4: Testing methodology flowchart with BE and LSS measurement setups.

Results and Discussion

K_0 consolidation and soil structure

The undisturbed specimens consolidated to a consistently lower K_0 than the reconstituted ones (0.473 versus 0.660 in 3De-8; 0.434 versus 0.505 in 3De-21). The preserved bonded fabric carries part of the vertical stress through axial force chains, reducing the mobilized lateral stress, whereas the reconstituted soil behaves frictionally, approaching Jaky's (1944) value and $K_0 \approx 0.5$ for Japanese marine clays (Watabe et al., 2003). Stress paths and summary are presented in Fig. 5, and Table 1.

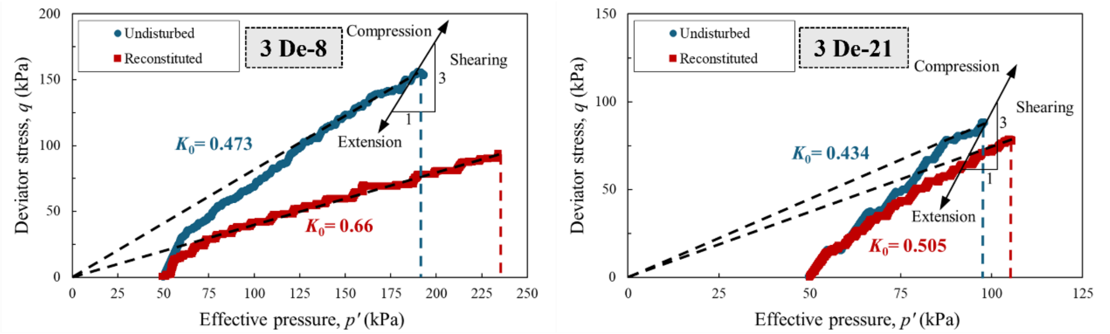

Fig. 5: K_0 consolidation stress paths: (left) layer 3De-21; (right) layer 3De-8.

Table 1: Stress ratio K_0 and mean effective stress p' at the end of K_0 consolidation.

Soil layers	3De-8		3De-21	
	σ'_a = 300 kPa		σ'_a = 158 kPa	
	K_0	p' (kPa)	K_0	p' (kPa)
Undisturbed-Compression	0.473	193.0	0.467	101.0
Undisturbed-Extension	0.408	161.9	0.434	97.8
Reconstituted-Compression	0.660	228.4	0.499	104.4
Reconstituted-Extension	0.642	228.3	0.505	105.3

Initial shear modulus from BE and LSS

Undisturbed G_0 exceeded reconstituted one despite higher void ratios, confirming bonding dominates over density. The BE vs LSS gap in 3De-8 marks non-uniform cementation, the wave favoring stiff paths, while agreement in 3De-21 indicates uniform bonding as shown in Fig. 6.

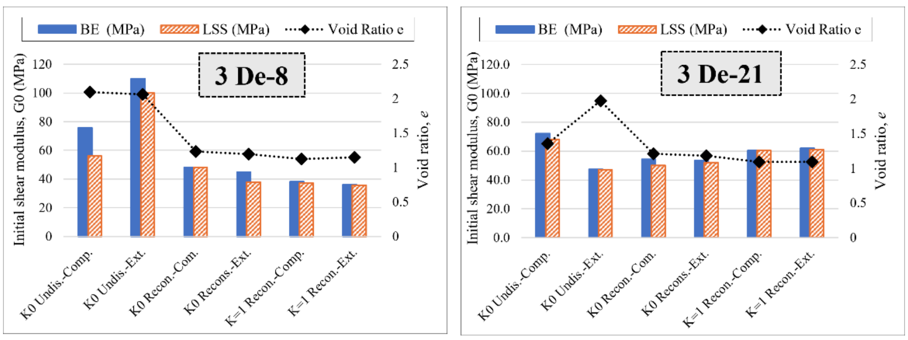

Fig. 6: G_0 from BE and LSS at 0.001% shear strain with the respective void ratios.

Compression versus extension for K_0 consolidated undisturbed specimens

At both depths the extension curves retained higher G_{sec} than compressions' across the full strain range, and the asymmetry persisted after normalization (Fig. 7). This reflects kinematic hardening on stress-path reversal, reinforced by K_0 fabric anisotropy (Atkinson et al., 1990).

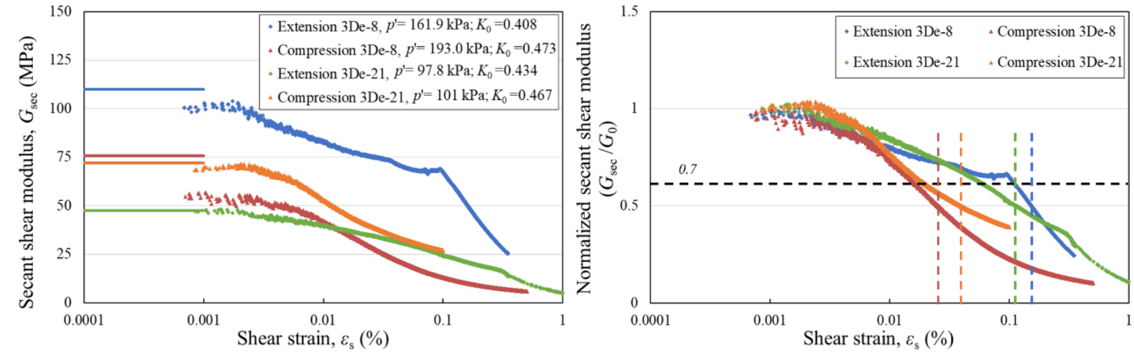

Fig. 7: In-situ response and normalized G_{sec}/G_0 of both clay layers.

Undisturbed versus reconstituted specimens

In extension, all K_0 consolidated curves normalized onto a common plasticity-governed trend (Vucetic & Dobry, 1991), so reconstituted K_0 specimens reproduced undisturbed behavior while isotropic ones degraded faster. In compression, undisturbed specimens sustained an elastic plateau to 0.003%, but reconstituted specimens easily degrade. That is lack of bonded structure (Cotecchia & Chandler, 2000). However, K_0 and isotropic reconstituted trends nearly identical (Fig. 8).

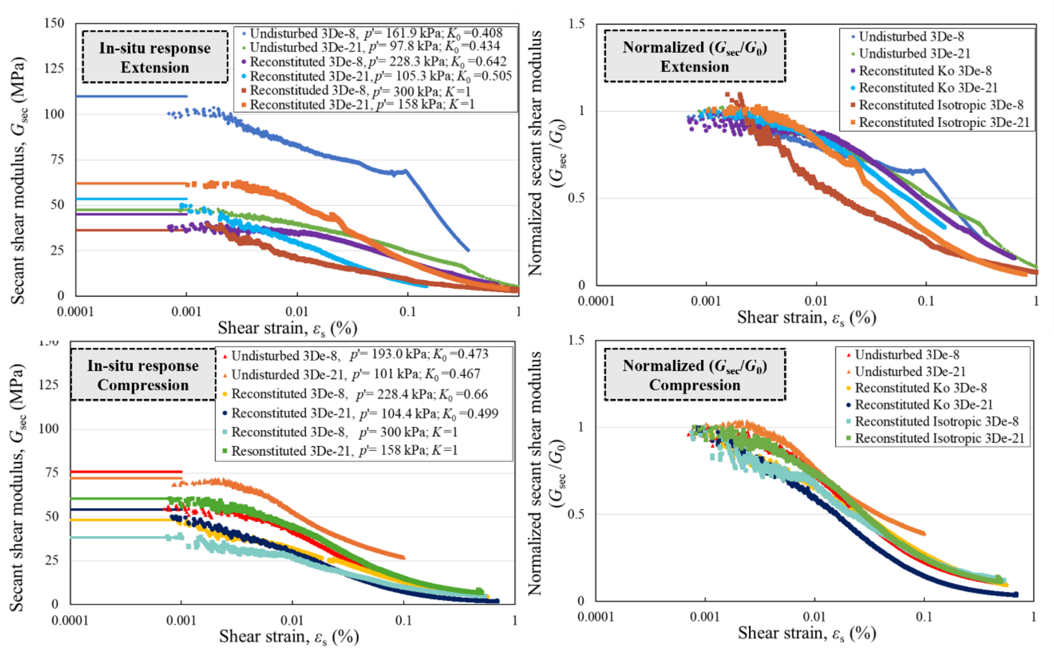

Fig. 8: In-situ response and normalized G_{sec}/G_0 under extension and compression paths.

Effect of isotropic consolidation and consolidation stress level

Under isotropic consolidation, compression and extension became almost similar in trend, confirming the path asymmetry originates from K_0 stress-induced anisotropy (Wood, 1990). Normalized curves at $K_0(\sigma'_a)$ and $K_0(2\sigma'_a)$ coincided, so the degradation shape is insensitive to consolidation stress magnitude (Fig. 9).

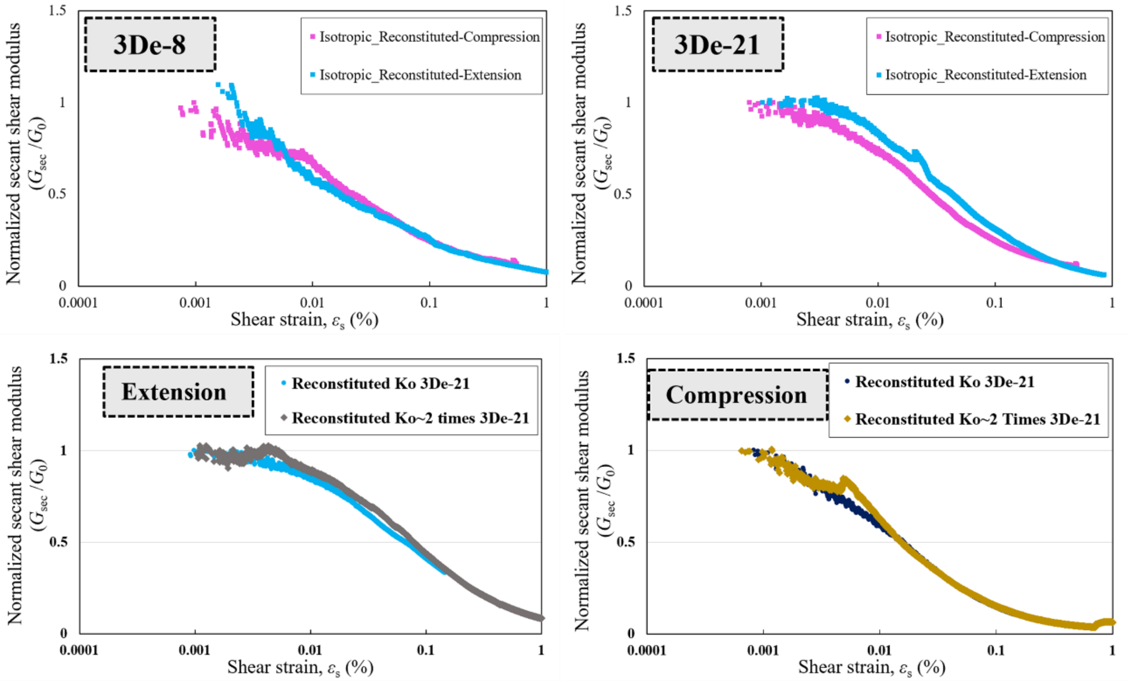

Fig. 9: Effect of isotropic consolidation and K_0 consolidation stress level.

Comparison with the sandy layers

Unlike the clay's layers, 3Tr-13 and 3De-30 retained a compression - extension asymmetry even under isotropic consolidation (Fig. 10). In granular soils this persists because the contact network, particle rearrangement, and dilatancy remain direction-dependent regardless of the initial stress state (Iwasaki et al., 1978). Some discrepancy appears in the undisturbed 3Tr-13 compression.

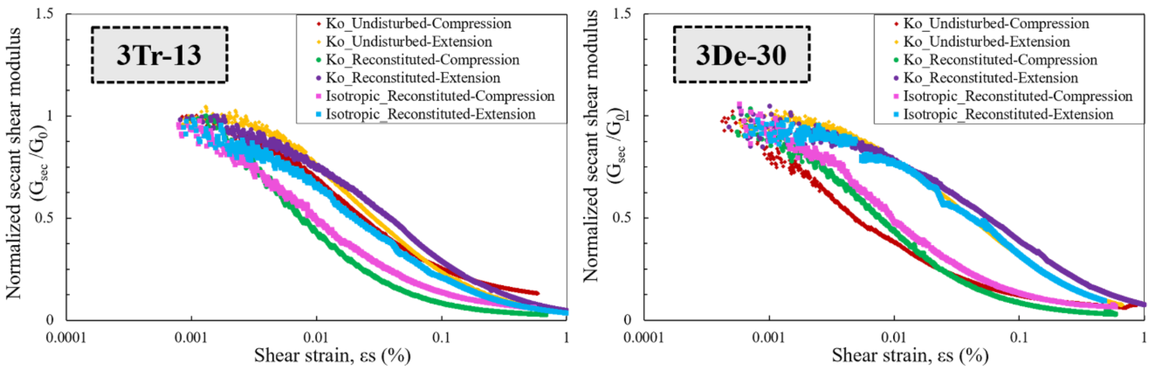

Fig. 10: Normalized G_{sec}/G_0 for the sandy layers 3Tr-13 and 3De-30.

Conclusions

- Undisturbed specimens showed greater deformation resistance than reconstituted ones, with lower K_0 and higher G_0 and G_{sec}, reflecting natural cementation and fabric that govern stiffness.
- For the K_0 consolidated clays, G_{sec} degraded less under extension than compression, so compression-derived stiffness would overestimate rebound.
- After normalization, K_0 consolidated undisturbed and reconstituted extension curves merged, allowing reconstituted specimens as a low-cost substitute once in-situ G_0 is measured. The substitution fails in compression, where the bonded elastic plateau cannot be reproduced.
- The coarser deposits 3Tr-13 and 3De-30 retained path asymmetry even under isotropic consolidation. Therefore, simplified testing method is difficult to propose, comparing to cohesive soils.

Proposed method and future research recommendations

- Two approaches follow from this work. Where accuracy is critical, K_0 consolidated extension tests on high-quality undisturbed samples give the stiffness parameters directly. Secondly, a cost-effective alternative measures in-situ G_0 from shear-wave velocity (PS logging) and applies the normalized extensional degradation trend from reconstituted specimens.

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