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Correction of the compressibility curve and the oedometric modulus based on the effects of lateral ring-soil friction in the oedometric test

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ABSTRACT: Lateral friction at the soil-ring interface constitutes a critical factor in oedometric test interpretation, recognized by multiple researchers as the test's primary limitation. This study analyzes a comprehensive dataset of published oedometer tests complemented by nine controlled tests (three soils × three ring materials) where friction effects were directly measured or indirectly inferred, revealing three key findings: (1) initial applied stresses are severely attenuated by friction, with up to 90% dissipation at low load levels; (2) compressibility curves with higher soil-ring friction plot systematically above those with lower friction and friction's influence becomes nearly constant at higher stresses, resulting in corrected semi-log compressibility curves that maintain parallelism to but systematically offset from uncorrected results; and (3) the characteristic parabolic initial stiffness observed in conventional interpretations - an artifact of friction - vanishes when proper boundary corrections are applied. These findings confirm that the true oedometric modulus follows a linear stress-dependent relationship from an initial value E_0, establishing the theoretical basis for the proposed oedometric-continuous law. The research methodology leverages systematic reinterpretation of existing test results across diverse soil types and loading conditions, providing robust empirical validation of friction's distorting effects on one-dimensional compressibility assessment.

KEYWORDS: Oedometric test, compressibility, ring-soil friction, oedometric modulus, oedometric-continuous law.

1 INTRODUCTION

Lateral friction at the soil-oedometer ring interface is a critical factor that must be accounted for in the interpretation of oedometric test results. This phenomenon has been studied since the oedometer's inception, and some researchers consider it the test's primary limitation (Mendes, 2016). Its effects have been extensively investigated. Key contributions include Berre & Iversen (1972); Burland & Roscoe (1969); Chang (1981); De Lima & Keller (2019); El-Sohby (2005); Hansbo (1960); Julie & Nagaratnam (2015); Larissa (2015); Leonards & Girault (1961); Lodahl et al. (2016); Marcial et al. (2006); Monden (1969); Muhs & Kany (1954); Nakase (1963); Sivrikaya (2001); Tan (1967); Taylor (1942); Tsubakihara et al. (1993); Watabe et al. (2008).

Early studies quantified lateral friction through direct measurements of stress attenuation between the top and base of oedometer samples. Taylor (1942) reported frictional forces accounting for 12–22% of the applied load in reconstituted clays and 10–15% in intact specimens. Nakase (1963) expanded this analysis using clay samples of varying heights (1–4 cm), demonstrating that the friction coefficient (μ) exceeded 0.9 at very low stresses, gradually decreasing to 0.3 before preconsolidation and stabilizing at 0.15–0.3 in the normally consolidated range. Notably, the dispersion of μ values diminished with increasing load, and corrected compressibility curves (using mid-height stresses) diverged markedly at low pressures but became parallel—or even converged—at higher stresses, a pattern later replicated by other researchers (Muhs & Kany, 1954; Hansbo, 1960; Burland & Roscoe, 1969).

Collectively, these studies reveal that friction effects are most pronounced at stresses below preconsolidation pressure, diminish significantly upon exceeding σ'_p, and asymptotically approach a residual (but non-negligible) value at high pressures. The magnitude of friction depends on ring material, sample preparation (reconstituted vs. intact), and interface lubrication—factors analyzed in detail in subsequent sections.

The cited authors' results, systematically reanalyzed here, compare three scenarios: (1) conventional compressibility curves (uncorrected for friction), (2) friction-corrected data (where friction was directly/indirectly measured), and (3) tests with reduced friction (achieved via lubricated rings or smooth materials). This work proves that the apparent high initial stiffness - graphically represented by a parabolic segment in traditional oedometric curves - is a friction-induced artifact. Based on these findings, we establish the methodological requirements for systematic correction of both: (a) the compressibility curve and (b) the oedometric modulus, which are distorted by lateral friction effects at the ring-soil interface during testing. Thus, the hypothesis the true oedometric modulus (Es) varies linearly with axial stress from an initial value (E_0) is confirmed, providing the theoretical basis for the oedometric-continuous law proposed by Naime (2019).

2 RING-SOIL FRICTION EFFECTS IN OEDOMETER TESTING: SYSTEMATIC LITERATURE EVALUATION

This study analyzes a comprehensive dataset of published oedometer tests on natural clays (Little Belt, Väsby, Drammen) and reconstituted soils (kaolinite-montmorillonite mixtures), where friction effects were directly measured (via top/base load comparisons) or indirectly inferred through comparative analysis of: (i) lubricated versus unlubricated interfaces, (ii) alternative ring materials (steel, Teflon), (iii) variable diameter-to-height ratios, and (iv) zero-friction membrane tests. Systematic interpretation of compressibility curves, corrected/uncorrected oedometric modulus-stress relationships, and F/σ evolution demonstrated how ring-soil friction systematically distorts conventional interpretations of one-dimensional compressibility and the oedometric modulus.

2.1 *Burland & Roscoe (1969)*

Burland and Roscoe (1969), performed paired oedometer tests on identical Spestone kaolin specimens: one with unlubricated ring-soil contact and another with internal grease lubrication. The unlubricated test exhibited higher friction forces. Semilog compressibility curves (Figure 1), initiated at 30.68 kPa (with limited sub-30kPa data), revealed pronounced divergence at low stresses - the unlubricated curve plotted systematically above the lubricated one. This separation decayed progressively with increasing stress until curves became parallel at high pressures, demonstrating constant residual friction. Results confirm friction's dominant role diminishes from maximum impact at low stresses to a stabilized residual effect. Figure 2 presents oedometric modulus vs. stress plots. Both tests show clear linear trends, revealing friction's significant impact on initial modulus (E_0). The unlubricated case erroneously suggests negative E_0 values - an artifact eliminated with lubrication. While friction strongly affects E_0 (increasing by 616 kPa when reduced), slope (λ) shows lesser sensitivity (decreasing from 14.4 to 12.8).

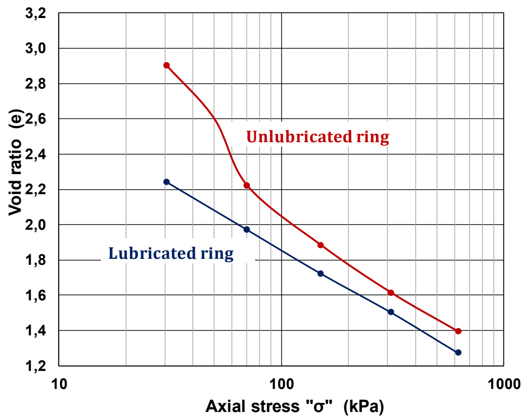

Figure 1. Spestone kaolin compressibility: lubricated vs. unlubricated ring tests. Data after Burland & Roscoe (1969).

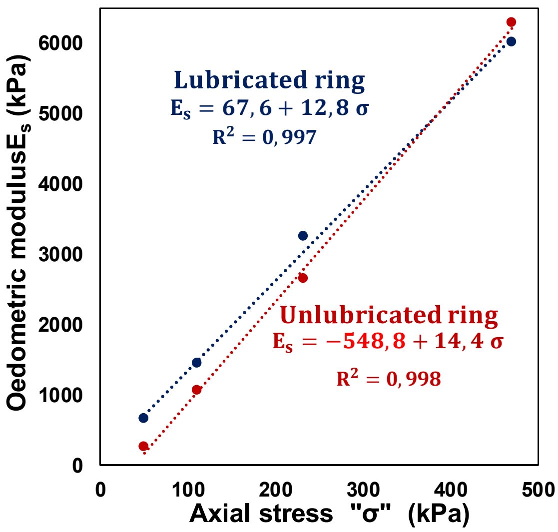

Figure 2. Spestone kaolin oedometric modulus vs. axial stress: lubricated vs. unlubricated ring tests. Data after Burland & Roscoe (1969).

2.2 *Chang (1981)*

Oedometer tests on Väsby clay (Sweden) quantified ring-soil friction through dissipated load measurements. Three tests included: (1) friction vs. applied load curves, and (2) compressibility curves comparing top-stress vs. mid-height stress (friction-corrected) analyses. Figure 3 plots friction ratio (F/σ) versus applied stress (σ), revealing extreme initial friction (70-90% of load) decaying to 20–30% at high stresses consistent with Taylor (1942), Hansbo (1960), and others.

Figures 4–5 illustrate the divergence between top-stress and mid-height stress interpretations for Väsby clay. While the compressibility curves (Figure 4) show progressive convergence toward parallelism in the normally consolidated range, the modulus-stress relationship (Figure 5) reveals how friction correction eliminates the apparent parabolic pattern, yielding a linear stress-dependency. Figure 4 demonstrates the distinct divergence between friction-affected and corrected compressibility curves, with both trends converging toward parallelism in the normally consolidated branch. Figure 5 reveals that the uncorrected oedometric modulus plot follows the apparent parabolic pattern typical of Janbu (1963) and (Stamatopoulos and Kotzias, 1978), whereas the corrected data eliminates this artifact, exhibiting a linear stress-dependent relationship.

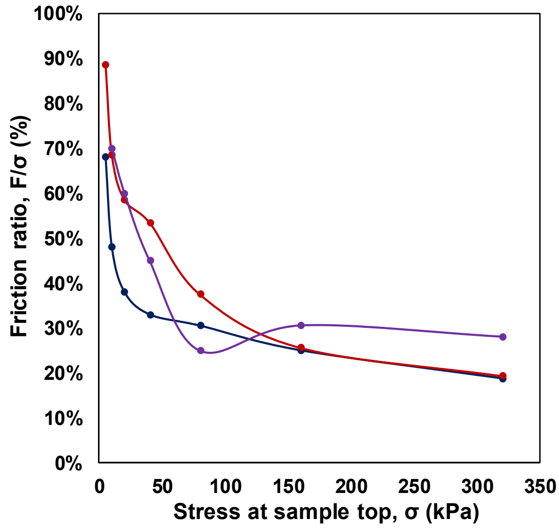

Figure 3. Friction ratio (F/σ) vs. top stress in Väsby clay tests. Data: Chang (1981).

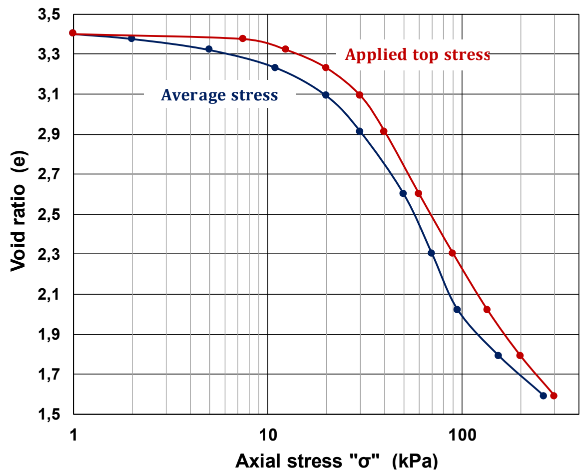

Figure 4. Väsby clay compressibility: applied top stress vs average top-bottom stress. Data after Chang (1981).

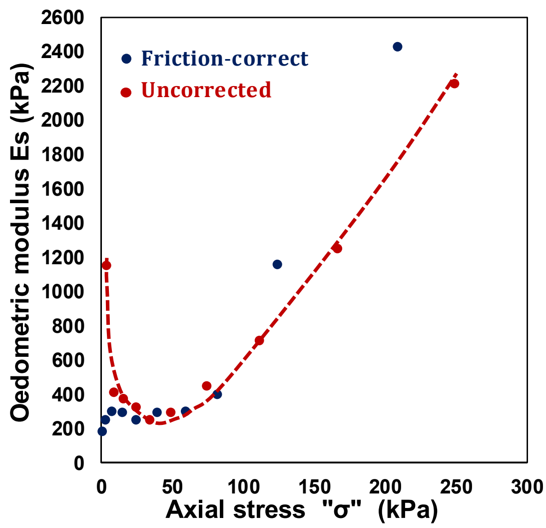

Figure 5. Väsby clay oedometric modulus vs. axial stress: applied top stress vs average top-bottom stress. Data after Chang (1981).

2.3 *Kolay & Bhattacharya (2008)*

Kolay & Bhattacharya (2008) performed oedometer tests on lightly preconsolidated, reconstituted medium-plasticity clay using: (1) a Teflon-coated ring (D=12cm, H=2cm, D/H=6) as the reference "correct" curve, and (2) conventional steel rings (D=6cm, H=2cm, D/H=3) with/without lubrication. Figure 6 compares results, quantifying conventional test errors against the lubricated large-diameter baseline.

The unlubricated steel ring curve (highest friction) plots uppermost, followed by lubricated steel, with the Teflon-lubricated curve (lowest friction) at the bottom. Only the unlubricated test shows exaggerated initial stiffness, confirming this artifact as purely friction-induced.

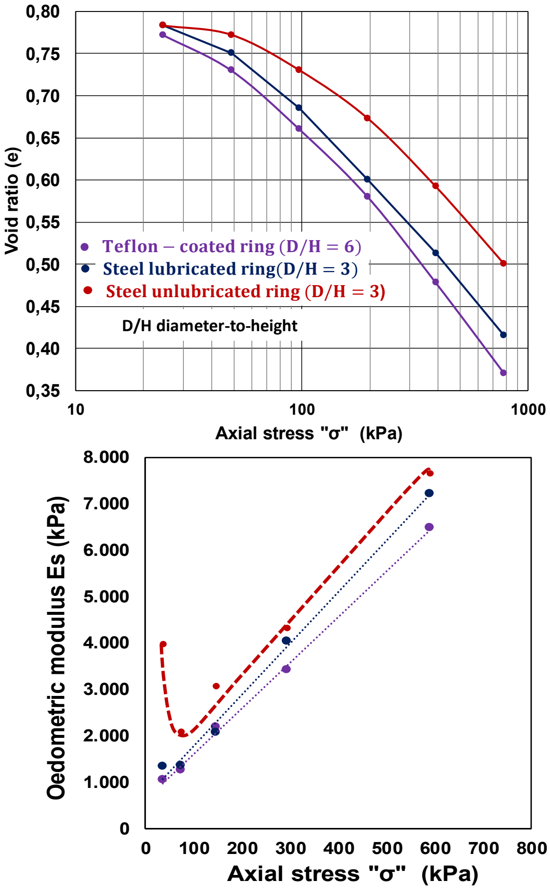

Figure 6. Compressibility (top) and oedometric modulus vs. axial stress (bottom) for lightly preconsolidated reconstituted clay: Teflon-coated ring vs. conventional steel rings (lubricated/unlubricated). Data from Kolay & Bhattacharya (2008).

The tests revealed greater differences between steel ring trials than between lubricated cases, confirming the critical role of proper ring-soil lubrication. The disparity between lubricated tests stems not only from ring material (Teflon vs. steel) but also from aspect ratio (D/H). Larissa (2015) demonstrated that eliminating ring friction renders D/H irrelevant to compressibility results. Berre & Iversen (1972), testing Drammen marine clay with sample heights from 2–40 cm, observed increased stiffness with greater height—consistent with friction effects. While 2 cm samples yielded markedly lower compressibility curves, tests with heights ≥10 cm converged or even crossed, indicating an upper friction-effect limit for such specimens.

2.4 *Lodahl et al. (2016)*

Lodahl et al. (2016) conducted comparative oedometric tests on Little Belt clay (a highly preconsolidated marine clay, overconsolidation ratio OCR=10) and reconstituted kaolinite-montmorillonite mixtures, analyzing both: (1) frictionless tests using a steel-reinforced rubber membrane to restrict radial deformation while allowing axial movement, and (2) conventional tests with measured friction (calculated as the load difference between top and base platens). Their results for 100% kaolinite (Figure 7) distinctly show the zero-friction compressibility curve versus conventional (uncorrected) and mid-height stress (friction-corrected) interpretations.

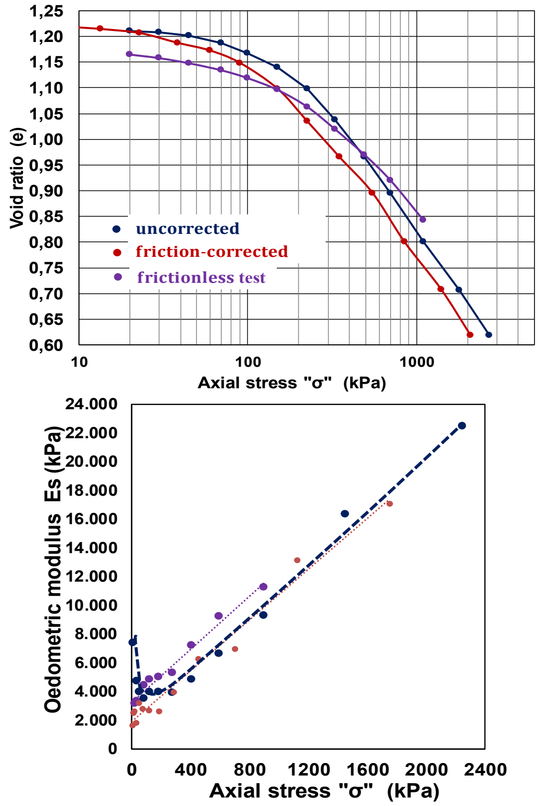

Figure 7. (Top) Compressibility and (bottom) oedometric modulus vs. axial stress for Little Belt clay reconstituted kaolinite clay: frictionless tests vs. conventional tests with measured friction (uncorrected / friction-corrected). Data from Lodahl et al. (2016).

The frictionless test's distinct initial void ratio explains its behavioral deviation from conventional tests. While both uncorrected and friction-corrected conventional curves show characteristic initial divergence and subsequent parallel compression, only the uncorrected curve exhibits the telltale initial irregularity - conclusively proving this artifact stems solely from boundary friction, as evidenced by its absence in both corrected and frictionless results.

Figure 8 presents Lodahl et al.'s (2016) frictionless ring test results, demonstrating: (1) consistent linear correlations in all cases, (2) definitive proof that initial curve irregularities and artificially high stiffnesses are friction-induced artifacts, and (3) reliably positive initial modulus values (E_0) with linear stress-dependent behavior. These findings confirm friction's disproportionate impact on low-stress conditions while validating the fundamental linearity of true oedometric response.

Figure 9 shows the F/σ ratio versus applied stress for reconstituted medium-plasticity Little Belt clay, including hysteresis cycle data. Friction stresses become negative during unloading - consistent with Väsby clay observations (Chang, 1981) where residual negative friction was detected during full unloading - then increase through reloading until recovering positive values, replicating the initial loading trend. The positive-friction behavior matches Figure 3's pattern.

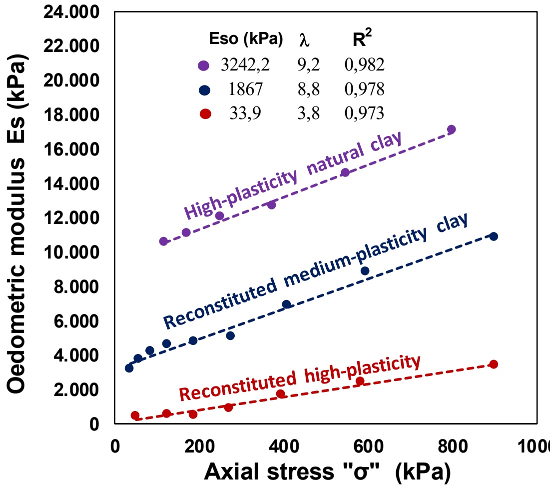

Figure 8. Oedometer test results for Little Belt clays using zero-friction membrane. Data from Lodahl et al. (2016).

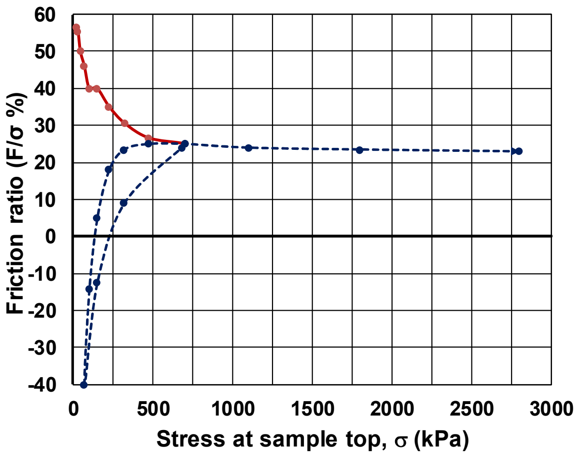

Figure 9. Friction ratio (F/σ) vs. top stress in reconstituted medium-plasticity Little Belt clay tests. Data from Lodahl et al. (2016).

The authors' analysis of reconstituted high-plasticity clay revealed persistent anomalous behavior during the first reloading cycle (post-unloading). While friction correction significantly reduced the initial modulus irregularity - unlike its complete removal in other cases - the corrected curve retained one elevated modulus point. This stems from residual negative friction developed during unloading, contrasting with initial reloading's zero-friction condition. Although both phases follow the oedometric stress path (lateral strain-free condition, K_0 line), post-unloading reloading only partially counteracts negative friction, maintaining it through the first load increment. Consequently, stress corrections couldn't fully eliminate the initial irregularity, demonstrating how hysteresis-induced boundary effects distort oedometric interpretation even after standard friction compensation.

3 EXPERIMENTAL VALIDATION

This study conducted nine oedometer tests on three reconstituted soils: (i) medium-plasticity clay (USCS classification: CL, liquid limit, w_l=36.5%; plasticity index, I_p=15.3%), (ii) low-plasticity silt (ML, w_l=40.2%, I_p=11.1%), and (iii) non-plastic silty sand (SM). Tests compared three ring materials with standardized lubrication: Teflon-coated (low friction), copper (intermediate friction), and steel (conventional/high friction). Identical specimens were tested to isolate friction effects, analyzing: (1) compressibility curves, (2) oedometric modulus-stress relationships, and (3) relative strain error plots, systematically quantifying residual interface friction's distortion of compressibility behavior and modulus interpretation. The results are shown in Figures 10-12.

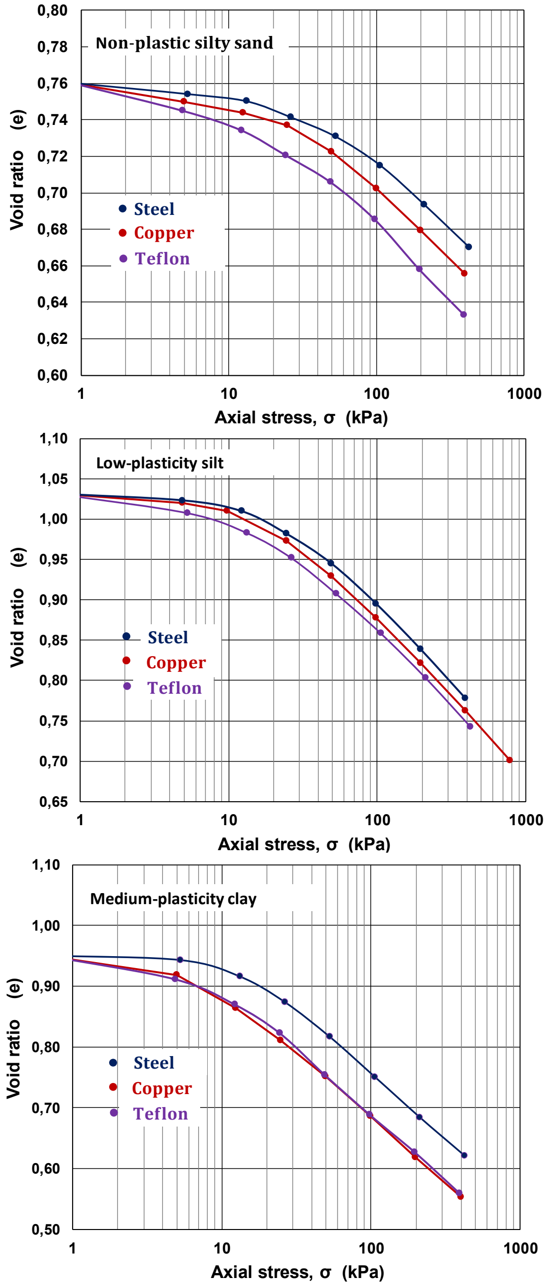

Figure 10. Compressibility curves for (top) SM, (middle) ML, and (bottom) CL soils, tested with Teflon-coated, copper, and conventional steel rings.

As expected, stainless steel exhibits higher friction than bronze, which in turn shows greater friction than Teflon – a trend clearly demonstrated in Figure 10's plots. These results confirm that compressibility curves with higher soil-ring friction plot systematically above those with lower friction, while maintaining apparent parallelism in the compression branch.

When analyzing friction's influence on the oedometric modulus (Figure 11), Teflon ring tests (reduced friction condition) consistently showed: (1) absence of the characteristic high initial stiffness zone, and (2) excellent linear stress-dependency of the modulus from a positive initial value (E_0) in all three test cases.

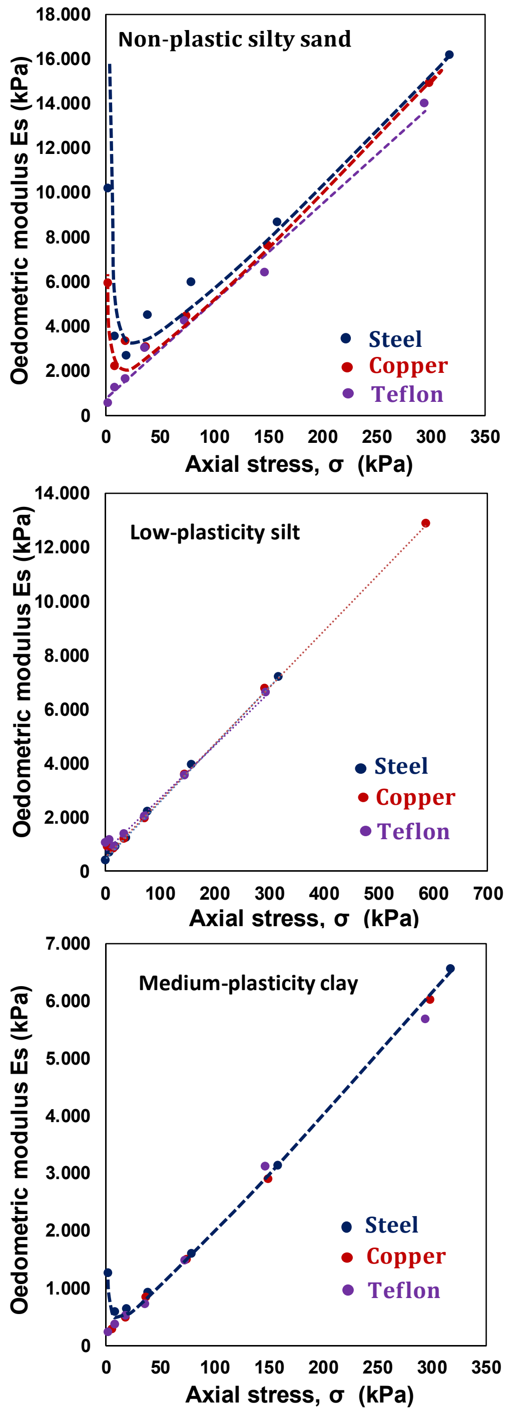

Figure 11. Oedometric modulus versus axial stress relationships for (top) SM, (middle) ML, and (bottom) CL soils, tested with Teflon-coated, copper, and conventional steel rings.

The clay exhibited artificially elevated oedometric modulus at low stress levels when tested with steel rings, but this friction-induced effect was eliminated in both Teflon and copper ring tests, confirming its origin in boundary friction rather than soil behavior. The silty sand showed marked friction-dependent behavior: steel rings produced pronounced artificial initial stiffness, bronze rings yielded moderate stiffness amplification, while Teflon rings (low-friction condition) completely eliminated this effect. This progression demonstrates how ring material selection directly controls the manifestation of boundary friction artifacts in oedometric modulus interpretation. These findings strongly support the fundamental hypothesis of the oedometric-continuous law: that the true oedometric modulus increases linearly with stress from a positive initial value (Es_0), once boundary friction artifacts are eliminated. Results show friction minimally affects λ (slope of Es-stress relationship) but significantly alters Es_0 (intercept), confirming friction primarily distorts initial modulus while preserving linear stress-dependency.

Friction critically influences stress-strain behavior, with higher friction yielding lower strain values at identical stress levels – directly impacting settlement predictions. Figure 12 plots the relative strain error ($\epsilon_\varepsilon = (\varepsilon_t - \varepsilon_s)/\varepsilon_t$, where ε_t and ε_s are Teflon and steel ring test strains) for medium-plasticity clay. Notably, its similarity to Figure 3's friction ratio (F/σ) curve confirms the consistent relationship between interface friction and strain underestimation across different experimental approaches.

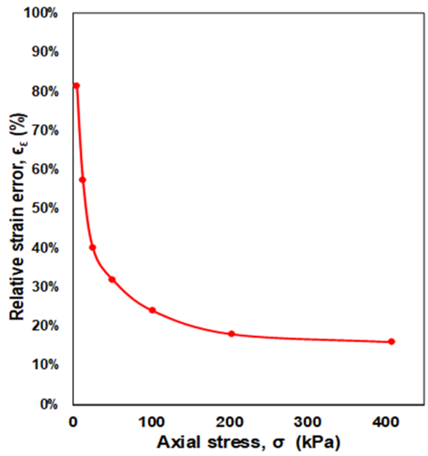

Figure 12. Relative error in strain estimation: Teflon versus steel ring tests for medium-plasticity clay.

4 CONCLUSIONS

The research methodology employs a systematic reinterpretation of existing test results combined with nine carefully controlled experiments. In these experiments, friction effects were either directly measured or indirectly inferred across various soil types and loading conditions, yielding robust empirical validation of friction's distorting influence on one-dimensional compressibility assessment. This study establishes three key advances in oedometer test interpretation:

Initial stress attenuation ranges between 60-90% at low stress levels, progressively diminishing to an asymptotic residual value of 15-30% at higher stresses. Significantly, measured strain errors exhibit an identical decay pattern - demonstrating that friction equally distorts both stress transmission and deformation measurements. This parallel behavior confirms that uncorrected data systematically underestimates soil compressibility across the entire stress spectrum. Consequently, underestimating compressibility directly compromises the accuracy of primary consolidation settlement predictions.

The compressibility curves associated with higher soil-ring friction systematically plot above those corresponding to lower friction conditions. As applied stress increases, the influence of friction reaches a nearly constant value. This behavior results in corrected semi-log compressibility curves that maintain an apparent parallelism among themselves - including both the uncorrected curves (with varying friction levels) and the corrected curve - throughout the compression branch.

Conventional oedometer tests systematically exhibit artificially heightened initial stiffness in the modulus-stress relationship, manifested through a characteristic parabolic E_s-σ' pattern at low stress levels. This behavior has been unequivocally attributed to boundary friction effects rather than representing intrinsic soil response. These findings provide conclusive validation of the oedometric-continuous law's fundamental principle: the authentic oedometric modulus increases linearly with stress from a positive initial value (E_{s0}) when boundary friction artifacts are eliminated. Crucially, the results demonstrate that friction affects λ (slope of Es-stress relationship) to a substantially lesser degree than E_{s0} (intercept), confirming that boundary friction predominantly distorts the initial modulus while preserving the inherent linear stress-dependency.

Final Note: conventional oedometer tests using lubricated steel rings with standard diameter-to-height ratios (D/H = 2-3) are methodologically assumed to minimize ring-soil friction effects. However, their results remain significantly influenced by lateral friction, as frequently evidenced by distortion of the oedometric modulus during initial load increments. More critically, the actual friction magnitude depends fundamentally on: (1) soil type and degree of sample disturbance, (2) sample preparation/placement protocols (including whether the specimen is intact or reconstituted). Reliable interpretation therefore requires explicit friction compensation through either: (i) direct measurement (dual load-cell systems), (ii) indirect validation (reference tests with minimized friction), or (iii) empirical correction (established protocols).

5 REFERENCES

Berre, T. and Iversen, K., 1972. Oedometer test with different specimen heights on a clay exhibiting large secondary compression. *Géotechnique*, [online] 22(1), pp.53–70. https://doi.org/10.1680/geot.1972.22.1.53.

Burland, J.B. and Roscoe, K.H., 1969. Local Strains and Pore Pressures in a Normally Consolidated Clay Layer During One-Dimensional Consolidation. *Géotechnique*, [online] 19(3), pp.335–356. https://doi.org/10.1680/geot.1969.19.3.335.

Chang, Y.C.E., 1981. *Long term consolidation beneath the test fills at Väsby, Sweden*. [online] Linköping, Sweden: Statens geotekniska institut. Available at: <https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1299957&dswid=-6040 >.

El-Sohby, M., 2005. Advancement in oedometer testing of unsaturated soils. In: *Proceedings of the International Symposium on Advanced Experimental Unsaturated Soil Mechanics*. [online] Trento, Italy. p.99. Available at: < https://api.semanticscholar.org/CorpusID:55350038 >.

Hansbo, S., 1960. *Consolidation of clay, with special reference to influence of vertical sand drains: a study made in connection with full-scale investigations at Skå-Edeby*. [online] Available at: <https://api.semanticscholar.org/CorpusID:127712926 >.

Janbu, N., 1963. Soil compressibility as determined by oedometer and triaxial tests. In: *Proceeding of the European Conference on Soil Mechanics and Foundation Engineering*. pp.245–251.

Julie, L. and Nagaratnam, S., 2015. Tall Oedometer Testing: Method to Account for Wall Friction. *International Journal of Geomechanics*, [online] 15(2), p.4014045. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000359.

Kolay, P. and Bhattacharya, G., 2008. Remediation of the side friction in conventional oedometer tests by using large diameter consolidometer ring. *International Journal of Geotechnical Engineering*, [online] 2(2), pp.161–167. https://doi.org/10.3328/IJGE.2008.02.02.161-167.

Larissa, T., 2015. The Impact of the Diameter to Height Ratio on the Compressibility Parameters of Saturated Fine-Grained Soils. *International Journal of Engineering and Technology*, 4, pp.8–19. https://doi.org/10.15623/ijret.2015.0406002.

Leonards, G.A. and Girault, P., 1961. A study of One-Dimensional Consolidation Test. In: *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering*. [online] Paris: ISSMGE. pp.213–218. Available at: <https://www.issmge.org/uploads/publications/1/40/1961_01_0036.pdf >.

De Lima, R.P. and Keller, T., 2019. Impact of sample dimensions, soil-cylinder wall friction and elastic properties of soil on stress field and bulk density in uniaxial compression tests. *Soil and Tillage Research*, [online] 189, pp.15–24. https://doi.org/https://doi.org/10.1016/j.still.2018.12.021.

Lodahl, M.R., Sorensen, K., Mortensen, N. and Trankjær, H., 2016. Oedometer tests with measurement of internal friction between oedometer ring and clay specimen. In: *Proceeding of the 17th NGM Nordic Geotechnical Meeting*. Reykjavik, Iceland: The Icelandic Geotechnical Society. pp.289–298.

Marcial, D., Yu, J.C. and Delage, P., 2006. Effect of lateral friction on the volumetric response of highly compacted clay specimens subjected to oedometer tests [in Spanish]. *Boletin Tecnico IMME*, 44(3), pp.1–8.

Mendes, E.M.A., 2016. *O Fenómeno de consolidação na prática laboratorial (The Consolidation Phenomenon In Laboratory Practice)*. Universidade do Minho (Portugal).

Monden, H., 1969. Characteristics of Side Friction in the One-Dimensional Consolidation Test. *Soils and Foundations*, [online] 9(1),pp.11–41. https://doi.org/https://doi.org/10.3208/sandf1960.9.11.

Muhs, H. and Kany, M., 1954. Einfluss von Fehlerquellen beim Kompressionsversuch (Influence of error sources in the compression test). *Mitteilungen des Institutes der Deutschen Forschungsgesellschaft für Bodenmechanik*.

Naime, W., 2019. Oedometric-Continuous Law for soil stress-strain behavior [in Spanish]. *Revista de la Facultad de IngenieríaUCV*, [online] 34(3). Available at: < http://saber.ucv.ve/ojs/index.php/rev_fiucv/article/view/20078>.

Nakase, A., 1963. *Side friction in conventional consolidation tests*. Port and Harbour Technical Research Institute.

Sivrikaya, O., 2001. Effect of clay layer thickness on the coefficient of consolidation (Cα). In: *Proceeding of 15th International Conference on Soil Mechanics and Foundation Engineering*. Istanbul, Turkey: Publications Committee of the XV ICSMGE.

Stamatopoulos, A. and Kotzias, P.C., 1978. Soil Compressibility as Measured in the Oedometer. *Geotechnique*, 28(4), pp.363–375. https://doi.org/10.1680/geot.1978.28.4.363.

Tan, S.B., 1967. *Consolidation of soft clays with special reference to sand drains*. [online] University of London. Available at: < https://api.semanticscholar.org/CorpusID:133044575 >.

Taylor, D.W., 1942. *Research on Consolidation of Clays. Department of Civil and Sanitary Engineering, Massachusetts Institute of Technology, Serial 82*. Massachusetts Institute of Technology. Dept. of Civil and Sanitary Engineering., Publication 82.

Tsubakihara, Y., Kishida, H. and Nishiyama, T., 1993. Friction between Cohesive Soils and Steel. *Soils and Foundations*, [online] 33(2), pp.145–156. https://doi.org/https://doi.org/10.3208/sandf1972.33.2_145.

Watabe, Y., Udaka, K., Kobayashi, M., Tabata, T. and Emura, T., 2008. Effects of Friction and Thickness on Long-Term Consolidation Behavior of Osaka Bay Clays. *Soils and Foundations*, [online] 48(4),pp.547–561. https://doi.org/https://doi.org/10.3208/sandf.48.547.