EUROPEAN JOURNAL OF MATERIALS SCIENCE AND ENGINEERING
Volume 10, Issue 2, 2025: 95-108 | www.ejmse.ro | ISSN: 2537-4338

DOI: 10.36868/ejmse.2025.10.02.95

INNOVATIONS IN ONE-DIMENSIONAL CONSOLIDATION TESTING: A REVIEW OF THE DOUBLE-ACTION OEDOMETER

Zakaria OWUSU-YEBOAH[1][0009-0003-0433-6839], Mircea ANICULAESI[1][0000-0002-1900-5819], Iancu-Bogdan TEODORU[1][0000-0001-8298-9374], Irina LUNGU[1,*][0000-0003-0963-7027]

[1]Faculty of Civil Engineering and Building Services, Gheorghe Asachi Technical University of Iasi, 67 Prof. D. Mangeron Blvd, RO-700050 Iasi, Romania

Abstract

This study presents an in-depth evaluation of the double-action oedometer (DAO) as an advanced testing apparatus for simulating soil compressibility under near-field conditions. Unlike the classic oedometer, which enforces full lateral confinement and single-direction loading, the DAO introduces a dual-loading mechanism. A large platen simulates preconsolidation pressure σ'_p, while a concentric piston does the incremental vertical loads, which in effect allows partial lateral deformation. The objective is to reflect the in-situ anisotropic stress paths so that post-test theoretical corrections could be minimised. Silty clay samples were tested using both the DAO and the classic oedometer. Compressibility parameters E_{oed}, C_c, m_v and a_v were compared. The DAO results recorded higher stiffness E_{oed} = 10,867 kPa, reduced strain, and more realistic e_i trends. The DAO E_{oed} in comparison with the classic gives M_0 = 1.04, which is lower than the theoretical M_0 from the correction coefficient in the NP 112/2014. These outcomes could indicate the overestimation of the M_0 in theoretical standards. Additionally, the lower strain and settlement yields from the DAO testing under identical stress levels indicate reduced influence of sample disturbance. The apparatus effectively simulates the natural soil stress history and void ratio evolution. This leads to improved prediction of settlement and more accurate derivation of mechanical parameters used in design. The DAO demonstrates clear benefits for geotechnical modelling, offering a cost-effective alternative to classic and modified oedometers. Its potential for standardization and integration into geotechnical codes is significant.

Keywords: *double-action oedometer, soil compressibility, preconsolidation pressure, lateral deformation, oedometer modulus.*

Introduction

Brief Evolution of Oedometer Testing

Soils exhibit compressibility through time-dependent volumetric changes governed by primary consolidation, which is driven by pore water dissipation, and secondary compression attributable to delayed particle reorientation and structural readjustment under sustained load. Recent literature on soil compressibility has stressed that while one-dimensional (1D) consolidation testing is fundamental in time-dependent deformation, it does not replicate fully the field stress paths [1]. Consolidation in fine-grained soils occurs not only through vertical stress application but also under anisotropic boundary conditions [2]. Lateral stress histories influence pore structure, compressibility and rate of deformation. The Casagrande-type fixed-ring oedometer (Fig. 1a) testing does not capture undrained anisotropy, fabric changes and suction-dependent particle rearrangement for fine-grained soils [3, 4]. It rather produces artificial deformation modulus values (E) and underestimates field settlements. As a result, empirical correction

*Corresponding author: irina.lungu@academic.tuiasi.ro

coefficients (M_0) which is standardized in codes such as NP 112/2014 (Annex J) to scale oedometer-derived moduli (E_{oed}) to field conditions [5]. These corrections were based on field-related tests and assumptions which make them unreliable for unstable fine-grained soils [6, 7].

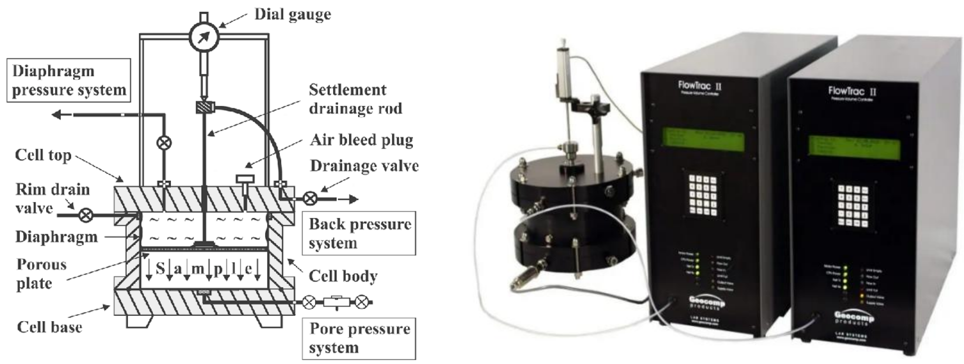
Aside the E_{oed} other mechanical parameters ($C_c; m_v; a_v; C_r; \sigma'_p$) that characterize the soil behaviour as foundation soil can be obtained from the classic oedometer tests [8, 9]. The oedometer testing methods are standardized under EN ISO 17892-5:2017 and ASTM D2435 to ensure consistency and traceability globally. It continues to be of relevance today due to its simplicity, reproducibility, minimal spatial requirement and the comparability of results across projects and jurisdictions [8, 10]. However, the classic oedometer presents several limitations that affect the reliability of the obtained parameters for design and analysis purposes. As mentioned earlier, it applies vertical load only in the vertical direction while assuming zero lateral strain. This contradicts the in-situ soil conditions where the soils experience both vertical and lateral stresses. The soil sample being tested is also restricted in a ring which prevents lateral deformation completely. This gives a false stiffness of the soil and suppresses volumetric strain thereby underestimating the settlement potential of the soil. Aside from these mechanical limitations, the classic oedometer testing encounters sample disturbance during extraction and trimming, which can affect the results. Therefore, while the oedometer remains a valuable soil testing apparatus, its configuration needs to evolve to eliminate its limitations. Specific devices have been developed like the consolidometer [11] and the double-action oedometer [12] for the study of soil compressibility which caters for some of the limitations [13]. Over the decades, improvements like the Rowe cell [14], hydraulic oedometers (ASTM D2435) and automatic consolidation, Fig. 1b (for automatic incremental loading and data acquisition) have been developed to mitigate some of the limitations of the traditional oedometers.

a) b)

Fig. 1. Oedometer - (a) Front Loading Oedometers (b) Automatic consolidation apparatus **[15, 16]**

State-of-the-art in Oedometer Testing

The Rowe Cell in Fig. 2, developed by Rowe and Barden (1966), is an advanced classical oedometer design that incorporates radial drainage and hydraulic pressure application. Unlike the classic oedometer setup, which allows drainage only through top and bottom porous stones, the Rowe Cell integrates a latex membrane and lateral drainage boundaries. This configuration enables both vertical and radial flow, which accelerates pore pressure dissipation in low-permeability clays. Testing time is often reduced by up to 50% in over-consolidated or stiff plastic soils. Hydraulic actuators replace mechanical levers and allow stress-controlled loading up to 3 MPa with minimal load application error. This enhances control over vertical stress increments and enables uniform loading under predefined paths. It also facilitates back pressure saturation and suction control which are important in the analysis of unsaturated soils. However, the Rowe Cell still constrains lateral deformation due to its rigid confining boundaries. Therefore, lateral strain effects remain absent while vertical and radial flow are captured. Consequently, E_{oed} values obtained still require empirical correction coefficients when applied to field-scale foundation design. ISO 17892-5:2017 and BS 1377 Part 5 recognize the Rowe Cell as an advanced and valid alternative to the classic fixed-ring oedometer for offshore, soft clay and embankment projects [17, 18]. However, it cannot replicate partial lateral strain or simulate layered anisotropic stress histories.



a) b)

Fig. 2. Rowe Cell (a) Schematic diagram **[19]**(b) Rowe (Hydraulic) Consolidation Test System.

Recent advances in oedometer testing have been focused on integrating specialized apparatuses to expand their functions beyond normal consolidation. One such innovation is the temperature-controlled oedometer in Fig. 3, which uses Peltier elements or embedded heating coils. These devices enable precise control of thermal gradients within the sample during loading. These systems are important in studying thermo-hydro-mechanical (THM) interactions in clays for applications in geothermal energy piles, deep geological repositories, and permafrost degradation. They allow for the analysis of temperature-induced pore pressure changes and thermally driven swelling or shrinkage. This is essential for infrastructure exposed to climatic variations or subsurface thermal loading. Cekerevac et al. (2018) demonstrated the accuracy of temperature-controlled oedometers in simulating field conditions in energy geo-structures. Global engineering practices have recognized these risks [20]. Arup (2023) emphasizes temperature-dependent soil responses as a key concern in resilient geotechnical design. These enhanced systems provide actionable data for climate-adaptive foundation engineering and long-term underground containment strategies [21].

Suction-controlled oedometers, Fig. 4 have been developed to address the needs of unsaturated soil mechanics in the face of the challenges of expansive clays with their seasonal wetting-drying cycles. These systems control matric suction in a very precise way using high-air-entry ceramic disks or humidity chambers, and can be applied to slope stability in arid regions and infrastructure strength in water-prone regions [22]. The common suction-controlled oedometer test is axis translation, where air pressure is applied while maintaining pore pressure to obtain a specific matric suction (other techniques also used include vapor equilibrium and osmotic control). Much like classic oedometer tests wherein vertical stress is applied step-wise, suction is maintained constantly or adjusted systematically with this device. This enables both compressibility and collapse potential assessments to provide important insights into the relationships between void ratio, suction and applied stress to facilitate field behavior predictions. Recent progress with polymer-based suction control represents a cheaper solution for laboratories in developing economies [23].

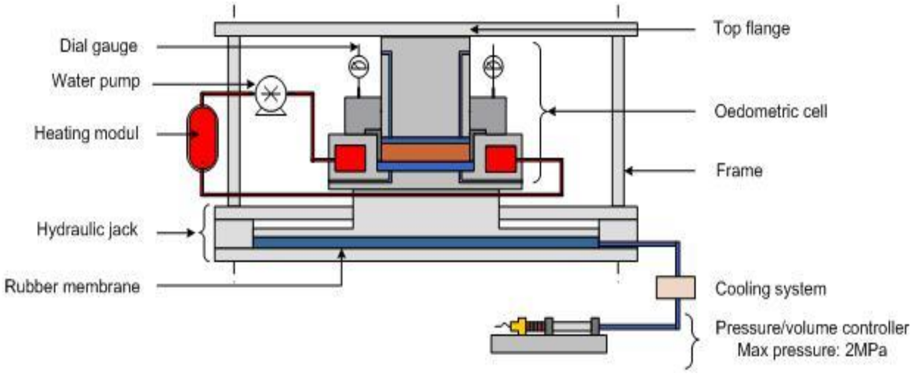


Fig. 3. Oedometer with vapour equilibrium technique: vertical load and temperature application system (École Polytechnique Fédérale de Lausanne Library).

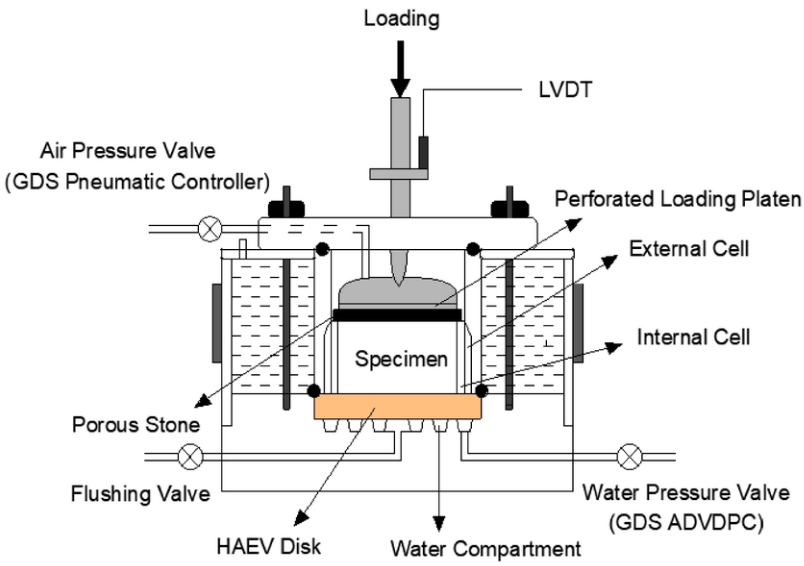


Fig. 4. Schematic diagram of modified suction-controlled oedometer testing equipment **[24]**

Challenges of Traditional and Some Recent Oedometers

Conventional oedometer tests, such as the Casagrande-type fixed-ring apparatus, have their own weaknesses due to their single-action loading procedure. These systems transmit vertical stress using only one lever and piston. Also, the disturbances during the extraction and sampling process, and the reconsolidation process during testing, make it difficult to simulate the stress paths that occur [6]. Again, lateral deformations are fully constrained ($\varepsilon_x = \varepsilon_y = 0$) and thus simulates a more simplified compression curve that does not fully represent in-situ behavior. Furthermore, manual load adjustments and discontinuous data acquisition lead to human error, especially when determining fundamental parameters such as C_c and m_v [25]. Even with advanced systems, such as the Rowe cell which integrates radial drainage, struggle to simulate stress paths with loading reversal [14]. This is caused by vertical pressure increments that limit their reliance on hydraulic loading. Although the Rowe cell is able to increase drainage efficiency, it maintains rigid boundary conditions of lateral stress measurement methods that distort conditions on structured soils like sensitive clays.

The classic oedometer is not equipped to handle unsaturated soils because it cannot monitor or control matric suction, which is equally important in compressibility analysis. Recent instruments like the suction-controlled and temperature-controlled oedometers tackle particular suction control and temperature dynamics, respectively, but also add layers of complexity. Suction-controlled systems require complex calibration and specialized porous stones and thus are not always accessible for routine testing [22]. Temperature-controlled oedometers [20] do not possess the modularity to accommodate combined mechanical and thermal stress paths. Both systems still have high costs and excessive specialization without fundamental solutions for problems such as boundary friction error or partial lateral deformation constraints. In addition, they possess a single-action loading framework, which inhibits the concurrent application of geologic and incremental loadings; a necessary feature for the proper simulation of in-situ stress histories. This is where the novel double-action oedometer (DAO) comes into play as a near-comprehensive solution to the above-mentioned challenges associated with the classic and modified oedometers.

Significance of the Study

The classic oedometer tests fail to replicate the full range of stress conditions experienced by soils in situ. They include preloading due to overburden soils or other loads, partial lateral deformation and the influence of disturbance from sampling as described above. Modified oedometer apparatuses such as the Rowe cell, suction, and temperature-controlled still enforce rigid lateral boundaries and rely on stepwise vertical loading alone. These constraints introduce inconsistencies in parameters such as E_{oed}, σ'_p, and e_i behavior. Correction factors are usually applied to reconcile laboratory data with field responses, but these are empirical and soil-dependent. The DAO addresses this gap. It integrates two independent loading mechanisms: a wide platen replicating in situ σ'_p and a central piston for structural loads. This configuration simulates real stress histories better for compressibility analysis. The DAO enables accurate derivation of compressibility parameters under controlled stress-path conditions. It minimizes reliance on post-test correction coefficients and hence offers a substantial improvement in E_{oed} estimation. The DAO provides a practical solution for improving the accuracy of geotechnical modeling in infrastructure design.

Mechanical Design and Operation of Double-Action Oedometer (RO 133362)

Building on the limitations of traditional systems, this study presents a DAO capable of achieving complex loading/unloading stress paths while allowing for potential remediation through the dissipation of pore air at constant applied stresses. The innovation was designed, made as a prototype, patented, and presented at the Danube-European Conference on Geotechnical Engineering (17DECGE) as part of the new laboratory devices developed for testing soil samples [13, 12]. At the core of this design is a system of two independent levers: one lever exerts σ'_p on the entire surface of the specimen using a larger-diameter (11.2 or 7.14 cm) platen (restoring porosity to in-situ levels), while a second lever incrementally loads a concentric piston (5 or 4 cm) to represent active vertical stresses. This split design allows consolidation under two different modes, first, under σ'_p, to simulate natural in-situ conditions; second, under incremental pressures to determine compressibility. The workflow works as follows: after preconsolidation stabilizes the specimen, the piston imposes incremental vertical loads while permitting partial deformation ($\varepsilon_x = \varepsilon_y \neq 0$) in the lateral direction, a deviation from full axial symmetry constraint as established in the classic oedometer configurations. This ultimately generates compression-settlement curves that simulate boundary conditions similar to field conditions. This system is embedded with two transducers to record settlements (Δh) at each stage. The apparatus decouples geologic and active pressures, resolving porosity disparities while optimizing parameter accuracy ($E_{oed}; C_c; C_r; m_v; a_v; \sigma_p'$) to enhance foundation settlement predictions with very little error.

Description of Double-Action Oedometer

The device in the Fig. 5 shows the schematic diagrams of the double-action oedometer in side and front views. It consists of a robust metal frame (2) supporting the oedometer cell (1) that houses a cylindrical soil specimen (13-Fig. 7a). A primary force-multiplying lever (3), equipped with a weight (4), fixed counterweight (5), and sliding counterweight (6), transfers preconsolidation pressure to the specimen via two guide-reinforced rods (8) and a loading yoke (7). The yoke (7) rests on a loading tripod (11-Fig. 6) anchored to a support plate (12) with three grove supports (32-Fig. 7b), which applies geologic pressure to the specimen (13). Settlement during preconsolidation is measured by a high-precision transducer (14). A secondary lever (15), with a sliding balancing weight (16) and incremental weights (17), connects to a front-loading device (20) via rods (19) and a yoke (18). This system drives a concentric piston (21) to apply stepwise active pressures, with settlements (Δh) recorded by a second transducer (22).

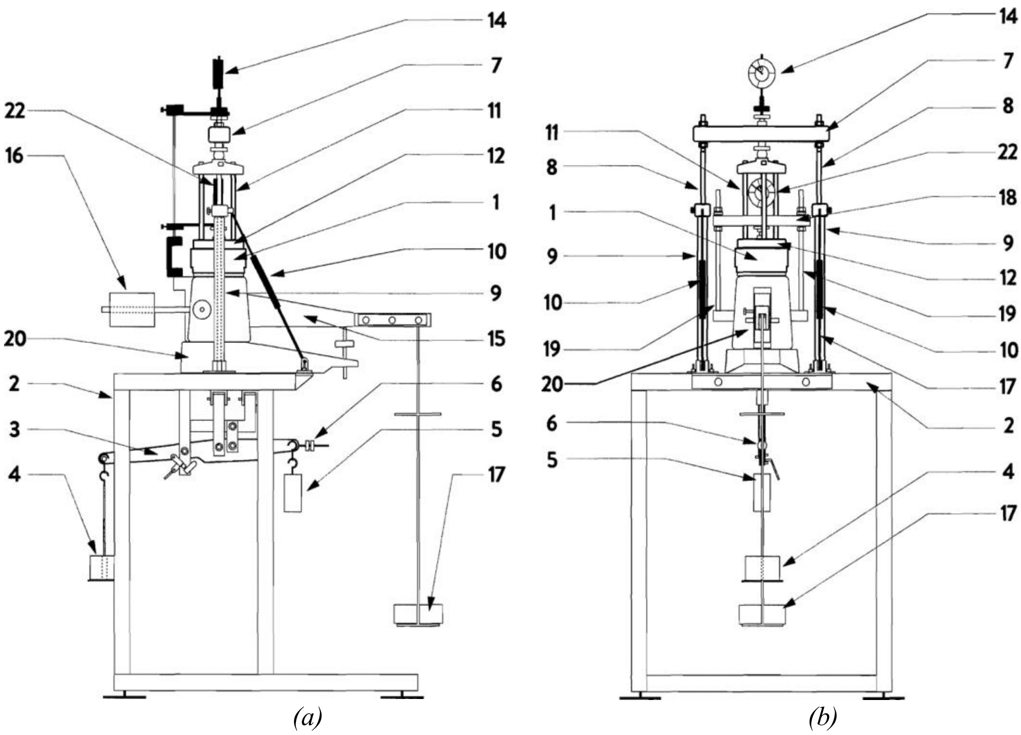
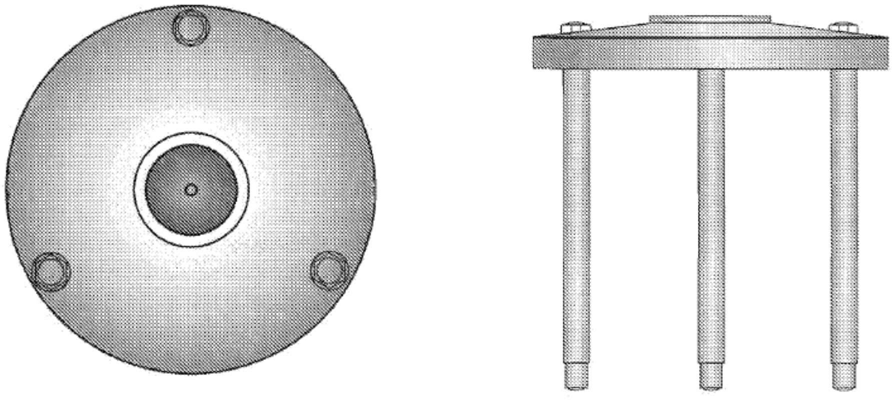


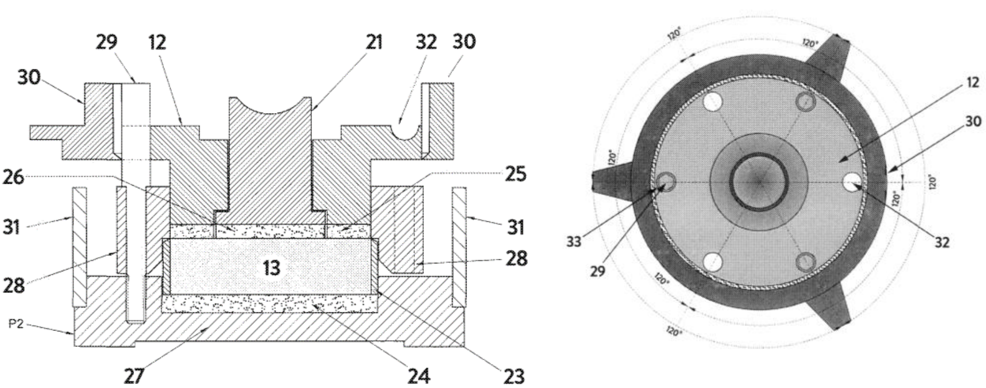
Fig. 5. Double-action oedometer Setup (a) Side view of front-loading device (b) front view of the front-loading device [13].



a) b)

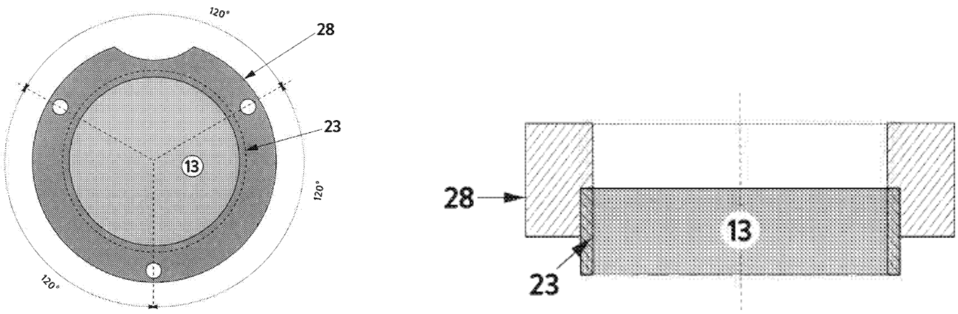
Fig. 6. Step loading tripod (a) plan view (b) side view [12].

In Fig. 7 is a cross-section of the DAO highlighting the component parts and a plan view with the positioning of the settlement locking. The specimen (13), which is confined in the oedometer ring (23-Fig. 8b and Fig. 9e), is supported on the base porous stone filter (24) and capped with ring-type filter (25) with a center opening which is matched to the piston (21-Fig. 9a and b). A smaller porous stone (diameter of the concentric piston 5 or 4 cm, depending on the larger diameter) (26-Fig. 9c) is present to provide uniform drainage. The oedometer ring (23) is held by a step holder (28) with punch support (33-Fig. 7b), fastened by screws (29) to the support plate (12). Once preconsolidation is completed, the specimen is stabilized via a threaded locking mechanism (30) that interfaces with a cylinder (31) attached to the base plate (27). The dual-loading design of the system allows the application of geologic and incremental pressures at the same time, such that replica in-situ stress paths are simulated, which, combined with controlled lateral deformations, enables compressibility determinations in terms of true triaxial analysis.

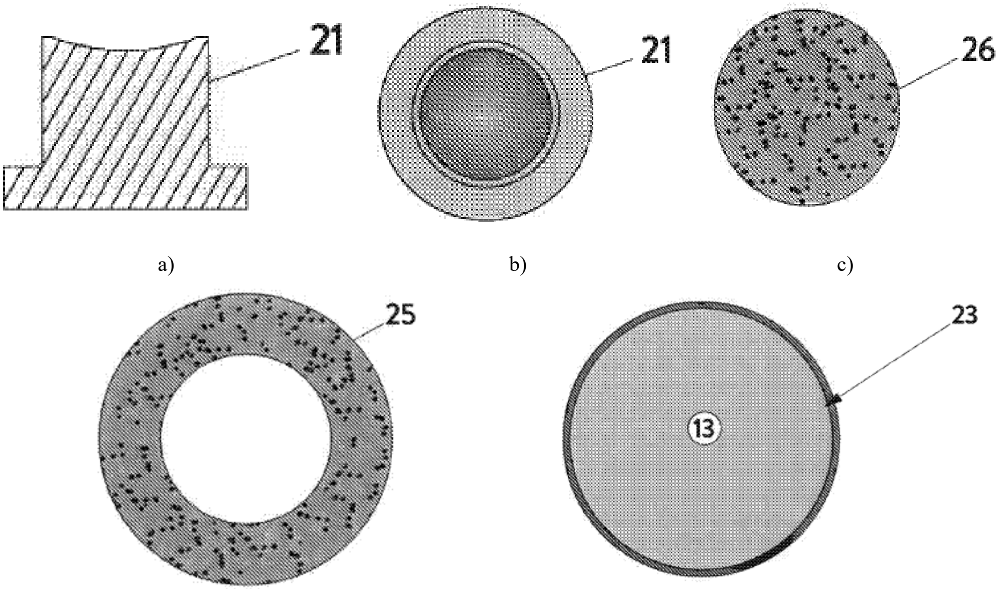


a) b)

Fig. 7. (a) A cross-section through the double-action oedometer highlighting the component parts (b) A plan view of the double-action oedometer with the positioning of the settlement locking [13].



a) b)
Fig. 8. (a) plan view of the step holder (b) a cross-section through the step holder **[12]**.



a) b) c)

d) e)
Fig. 9. (a) cross-section of loading piston (b) plan view of loading piston (c) plan view of concentric circular porous stone filter (d) plan view of porous stone filter (e) plan view of oedometer ring [13].

Operation of the Double-Action Oedometer

The DAO, as per the invention, incorporates two pressure transmission components on the specimen (13): a larger-diameter platen (12) and a concentric piston (21) with a smaller diameter. The larger diameter is currently in two sizes: 11.2 cm (which uses a concentric piston with a diameter of 5 cm) and 7.14 cm (which uses the concentric piston with a diameter of 4cm). These components allow for the independent application of forces via the two levers (3, 15) mounted on a metal frame (2). Initially, the loading platen (12), activated by the first lever (3), uniformly compresses the specimen (13) across its entire surface to achieve a consolidation/porosity state similar to the corresponding in-situ soil, reaching consolidation under the geological load or σ_p' corresponding to the sample depth. Subsequently, the second lever (15) applies an active pressure in incremental loading steps, as in traditional oedometer testing, onto the smaller-diameter piston (21) already engaged with the consolidated specimen (13). Settlements (Δh) are then measured (with transducers 14, 22) for the loading increments under conditions of partially constrained lateral deformation, as the top of the soil specimen (13) subjected to the smaller diameter piston (21) is not laterally confined directly. Utilizing the resulting data, on the specimen (13) with porosity or consolidation like that of the corresponding in-situ sample and with partially impeded deformations, the compression-settlement or compression-porosity curve is plotted, and the parameters defining the compressibility of the soils are calculated according to standardized methodologies.

Advantages in the Use of Double-Action Oedometer over Classic Oedometer

The DAO offers several technical advantages over the standard oedometer. It contrasts with standard oedometers that can apply vertical loads incrementally via a single lever, which does not simulate the in-situ reconsolidation stress history for soils [26]. In soft clay testing, Leroueil & Hight (2003) observed such differences in results between field and laboratory specimens in terms of porosity and σ_p'. The double-action oedometer resolves this issue by applying two separate loading steps, a σ_p' that realigns in-situ density and pore water pressures, followed by active/ incremental loads to simulate relevant post-sampling stress paths. Such a dual-pressure system does away with porosity disparities, leading to near-field compression curves and also eliminates the need for correction factors. Sampling disturbance, effectively reported in structured soils including sensitive clays by many researchers and industry practitioners, skews the e_i and C_c values with classic systems. Although the Rowe cell resolves drainage challenges in tested specimens, the method is still prone to manual handling of specimens, leading to increased reorientation of soil particles. The preconsolidation phase under σ_p' of this device stabilizes the specimen before being subjected to incremental loading under in-situ conditions, thereby addressing disturbance-induced errors common in conventional oedometers.

Conventionally, oedometers apply fully constrained lateral deformations, a condition that seldom occurs in situ where soils are subject to partial confinement. The ability of the DAO to enable controlled lateral deformations while applying incremental loads allows for the simulation of semi-confined field scenarios (e.g., the soils under foundations), potentially improving alignment with in-situ pressuremeter or finite element modelling results. Classic oedometers require several tests to determine compressibility parameters which can lead to variations because of sample handling [8]. Due to the preconsolidation of specimens in the to in situ σ_p' prior to incremental loading, these parameters can be obtained on a single test, which helps decrease errors. Conventional workflows require sequential tests (e.g., Rowe cell for C_v, hydraulic oedometer for C_c,), resulting in increasing expenses and timeline [27]. This device could bring all these stages inside one appliance with modular parts (e.g., interchangeable porous stones), reducing lab costs and making it easier. This matches the industry's need for accuracy and cost efficiency for sustainable infrastructural development.

Testing Procedure and Case Study

Sample Preparation

Soil specimens were collected at depths of 1 – 2 m from Copou, Iași County, Romania. Undisturbed samples were collected in monolithic blocks (50 × 50 × 100 cm) with careful excavation to conserve in situ structure and moisture. To avoid disruption, samples were tightly sealed in stretch film wrappings just after extraction and maintained at 23°C until tested. Disturbed samples were also collected in bags and properly sealed off to conserve the soil moisture. A comprehensive set of laboratory tests was carried out to determine the physical properties of the soil in Table 1. From the monolith, the specimens were carefully trimmed to fit the cylindrical oedometer rings with sizes: a larger ring (2.5 cm height × 11.2 cm diameter) and a standard ring (2.0 cm height × 7.14 cm diameter) for testing. The larger ring design is to give a bigger surface area for the preconsolidation of the soil and also a large concentric area (5 cm diameter) for incremental loading. The standard size was used for the classic oedometer testing to enable comparison of the results. The design is to help in comparing the behaviour of the soil with the standard oedometer testing. It has an area for incremental loading with a 4cm diameter.

Table 1. Physical Properties of the Soil

Test Parameter	Soil Classification	Atterberg Limits	OMC	Dry Unit Weight	Bulk Unit weight
Results	***Silty Clay (si.Cl)*** Silt content = 63.53% Clay content = 26.94% Sand Content = 9.53%	LL = 36.5% PL = 24.1% PI = 12.4% I_c = 1.0	14.9%	15.37 kN/m^3	16.84 kN/m^3

Testing Procedure

The testing procedure begins with specimen installation and the initial setup. The cylindrical soil specimen is cut using the oedometer ring (23) from the monolith and trimmed. It is then placed onto the base porous stone filter (25). A concentric assembly of dual-layer porous stone; a ring-shaped filter and the central porous stone (26), is placed in alignment with the loading piston (21) to provide uniform drainage and load distribution. The specimen is held in place with a step holder (28) and punch support (33), fastened by three screws (29) to stabilize the sample. The preconsolidation phase is initiated by activating the first force-multiplying lever (3), which applies geologic pressure to the sample through the tripod (11) onto the support plate (12). Adjustments to the fixed and sliding counterweights (15 and 16) stabilize the system. The lever is then loaded incrementally on (4) to the preconsolidation pressure, in this case 50 kPa, with the settlements monitored in real time via the transducer (14) and recorded on the PC via the data logger. With this sample, the preconsolidation loading follows a period of 72 hours. Once equilibrium is achieved, the specimen is locked into place using a threaded locking mechanism (30) to preserve in-situ porosity.

After preconsolidation, the incremental active loading phase begins. This is done through the front-loading device (15) which is activated through the secondary loading lever set up (9) using a slidable balancing weight (16). Vertical pressures loaded (17) are transmitted through rods to the concentric piston (21), which applies stepwise loads to the specimen (from 12.5–500 kPa). A second transducer (22) records settlements (Δh) at each load increment until the end of primary consolidation, thus 95% excess pore pressure dissipation, assumably after 7 days of loading. Step-by-step unloading of incremental weights is done if needed until completion of a dual-lever-disengagement system. The specimen is then extracted for final moisture content, void ratio and porosity measurement, cross-validated against initial in-situ conditions to quantify sampling disturbance.

Results and Discussions

Results Analysis

The tests performed were aimed at quantifying the compressibility parameters under controlled laboratory conditions. The derived parameters include $E_{oed}, C_c, m_v\ and\ a_v$. These parameters are essential to evaluate settlement behaviour and to design foundations on fine silty clay soil deposits. The averages of these parameters obtained are presented here. The standard oedometer test yielded a $C_{c,(200-300)} = 0.104$ and $E_{oed,200-300} = 10{,}471.20\,kPa$. The $a_{v,200-300} = 0.00018\,1/kPa$, $m_{v,200-300} = 0.0000955\,1/kPa$ and the specific settlement under 200 kPa, $\varepsilon_{p,(200)} = 3.1\%$ classify the soil as having medium compressibility. The initial void ratio was ($e_0 = 0.91$) which reduced significantly after testing to ($e_f = 0.80$). The DAO recorded a higher $C_{c,(200-300)} = 0.116$ and a slightly higher $E_{oed,200-300} = 10{,}866.96\,kPa$ reflecting higher stiffness of the soil. The coefficients $a_{v,200-300} = 0.00017\,1/kPa$, and $m_{v,200-300} = 0.000092\ 1/kPa$ and $\varepsilon_{p,(200)} = 2.77\ \%$ classify the soil same as having medium compressibility. The partial lateral deformation resulted in reduced void ratio/porosity of ($e_0 = 0.84, e_f = 0.73$). This is summarized in Table 2.

Table 2. Comparative Summary Table

Parameter	Classic Oedometer Test	Double-Action Oedometer Test	Geotechnical Implication
Compression Index ($C_{c,200\text{-}300}$)	0.104	0.116	Slightly lower compressibility compared to the DAO test.
Oedometer Modulus ($E_{oed,200\text{-}300}$) [kPa]	10,471.2	10,866.96	Slightly lower stiffness; reflects medium compressibility and moderate settlement potential.
Coefficient of Compressibility ($a_{v,200\text{-}300}$) [1/kPa]	0.00018	0.00017	Higher compressibility in the standard test, indicating more settlement for a given stress.
Coefficient of Volume Compressibility ($m_{v,200\text{-}300}$) [1/kPa]	9.55E-05	9.20E-05	A slightly higher standard test indicates more volume change under stress.
Specific Settlement under 200 kPa ($\varepsilon_{p,200}$) [%]	3.1	2.77	Higher settlement in the standard test, suggesting greater consolidation.
Initial Void Ratio (e_0)	0.91	0.84	Higher initial void ratio in the standard test, indicating a looser initial state.
Final Void Ratio (e_f)	0.8	0.73	The final void ratio is higher in the standard test, meaning more compression in the DAO test.

Fig. 10 presents the $e - \log P$ relationships derived from both the DAO and the classic oedometer test. The DAO curve shows a sharper curvature after 50 kPa. This is indicative of a more accurate simulation of field-like recompression following preconsolidation. At the initial lower stresses, both curves exhibit near-parallel compression trends, but divergence becomes evident after the preconsolidation state in the DAO. The DAO samples show a lower e_i at equivalent stress levels which could reflect better structural integrity and less sampling disturbance. The classic oedometer, by contrast, demonstrates a smoother and less steep profile which may be due to the full lateral confinement and lack of suction recovery after sampling disturbance. The partially unconfined setup of the DAO allows volumetric change, which could capture the collapse potential of silty clays more realistically. This behavior confirms that the DAO models more accurately represent the pore structure reorientation and compressibility under in-situ loading conditions. The lower e_i in the DAO as compared to that of the classic tests, also suggests that DAO results might not require correction coefficients M_0 for E estimation, improving reliability in geotechnical settlement prediction and design.

Discussions

The DAO test produced a C_c compared to the classic oedometer, indicating greater compressibility under partially confined conditions. This outcome highlights the importance of lateral strain in simulating in-situ consolidation behavior, where the soil mass experiences deformation in multiple directions. By allowing partial lateral deformation in the DAO, it enables better simulation of field anisotropic stress histories which is important for structured silty clays. The preconsolidation phase which is incorporated in the DAO is able to reflect the overburden effect to simulate the actual σ'_p. This stress history recovery produces strain responses and settlement patterns more aligned with natural field conditions. The DAO tests recorded slightly lower vertical strain rates under equivalent pressures. This confirms that the classic oedometer amplifies vertical strain due to disturbance during sampling and trimming. The E_{oed} from DAO tests was also higher, with an average ratio of 1:1.04 compared to the classic test. This could indicate improved stiffness and reduced structural degradation when partial lateral deformation is allowed.

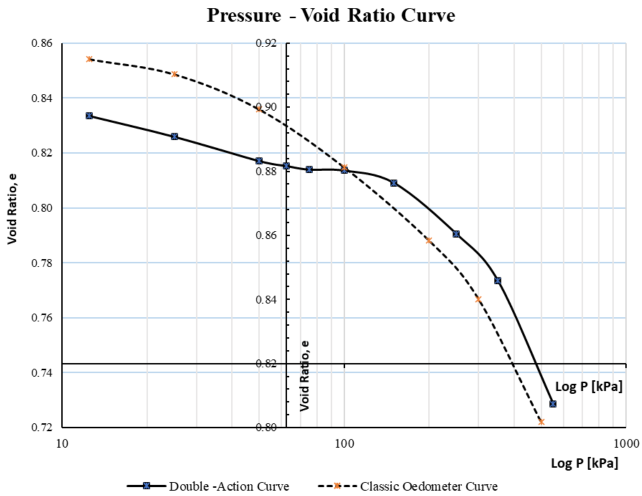


Fig. 11. Pressure – Void Ratio Curve for Classic and DAO test results

According to NP 112/2014, the correction coefficient M_0 is applied to correct E_{oed} derived from the laboratory to realistic field stiffness. For this soil used in these tests (si.Cl with $I_c = 1.0$ and $e = 0.81 - 1.0$), a theoretical correction factor of 1.3 is suggested. However, using the DAO E_{oed} in comparison with the classic give $M_0 = 1.04$ (thus $M_0 = E_{oed(DAO)}/E_{oed(classic)}$) which is lower than the theoretical M_0 from the correction coefficient in the NP 112/2014. This suggests that mechanical replication of in-situ conditions using the DAO may reduce reliance on empirical multipliers. This capability thus challenges the universality of fixed correction coefficients and opens discussion for revising calibration standards. Further studies might give a better analysis and credence to the derivation of the M_0 from the DAO.

Furthermore, the a_v and m_v were consistently lower in DAO tests. These lower values imply slower consolidation and reduced volumetric change which affirms the deduction that constrained tests tend to overpredict settlement magnitudes. Additionally, the classic oedometer exhibited higher e_i, suggesting that the porosity could be overstated porosity since there is no soil structure recovery after extraction disturbance. With these, it can be adequately stated that the DAO yields a more reliable compressibility parameter for the predictions of long-term soil deformation behavior. In practice, DAO results can guide more efficient design in fine-grained soils and thereby lead to cost-effective geotechnical solutions. It also provides evidence-based guidance for modernizing standard 1D consolidation testing procedures to match field-representative soil behavior.

Conclusion

The double-action oedometer (DAO) is a novelty in one-dimensional consolidation. It addresses the limitations of the classic oedometers by incorporating σ'_p simulation and partial lateral deformation through the integration of a dual-lever system. Results indicate that the DAO provides higher compression indices and stiffness, more realistic void ratios, and settlement behavior that better simulate field conditions. The findings also suggest that traditional correction factors like M_0 from NP 112/2014 may overestimate adjustments needed for in-situ conditions.

This has significant implications for geotechnical design, foundation settlement predictions and modeling. It therefore positions this innovation as a critical tool for modern infrastructure projects where testing protocols can reflect both natural field conditions. It is also a good approach to properly ascertain the behaviour of compacted soils in the laboratory, which can be used to simulate modified field conditions of the soil. Future works would consider standardizing the testing protocols with many samples to estimate the M_0 to ascertain their reliability in practical application. Also, further research could focus on integrating AI-driven predictive models, refining the stress path simulations and enhancing automated laboratory testing methodologies. The DAO could be a cutting-edge breakthrough in 1D consolidation testing that could tackle many geotechnical problems to ensure efficiency of resource usage which is in line with sustainability and infrastructure resilience.

Acknowledgements

This research paper was supported by Boosting Ingenium for Excellence (BI4E) project, funded by the European Union's HORIZON-WIDERA-2021-ACCESS-05-01: European Excellence Initiative, under the Grant Agreement No. 101071321.

Funding

This research was funded by the Romanian National Authority for Scientific Research, UEFISCDI, through project PN-IV-P8-8.1-PRE-HE-ORG-2023-0051.

References

[1] X. Bian, J. S. Shi, S. Q. Qian & L. L. Zeng, *Influence of anisotropic consolidation stress paths on compression behaviour of reconstituted Wenzhou clay*, ***Geotechnical Engineering,*** **168 (2)**, 2015, pp. 149-159.

[2] X. Shi, X. Ling & L. Zhang, „Effect of anisotropic consolidation on the volumetric strain of Wenzhou clay," ***Geotechnical and Geoenvironmental Engineering,*** **vol. 141**, nr. 4, p. 04014122, 2015.

[3] S. Leroueil & D. W. Hight, „Behaviour and properties of natural soils and soft rocks," ***Characterisation and Engineering Properties of Natural Soils,*** **vol. 1**, pp. 29-254, 2003.

[4] A. Casagrande, „The Determination of the Pre-Consolidation Load," ***Proceedings of ICSMFE,*** **vol. 1, nr. 3**, pp. 60-64, 1936.

[5] 2. NP 112, „NORMATIV PRIVIND PROIECTAREA FUNDAȚIILOR DE SUPRAFAȚĂ, **indicativ NP 112 - 2014**," Bucharest, 2014.

[6] A. Stanciu & I. Lungu, Fundatii - Fizică și Mecanica Pământurilor [Foundations I - Soil Physics and Mechanics], Bucharest: Editura Tehnică, 2006.

[7] A. Ilaș, „Study of the Soil Compressibility as a Foundation Soil by Using an Original Apparatus," ***ISSMGE,*** 2017.

[8] K. Head & R. Epps, Manual of Soil Laboratory Testing, Volume II, 1st ed., Caithness, Scotland: Whittles Publishing, 2011.

[9] EN 1997-2, Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing, 2007.

[10] K. Terzaghi, R. B. Peck & G. Mesri, Soil Mechanics in Engineering Practice, 3rd ed., New York: John Wiley & Sons Inc, 1996.

[11] A. Stanciu, L. I., and I. A., „Device for determining mechanical characteristics of soils by axially symmetrical compression tests". **Romania Brevet RO 133293**, 2014.

[12] A. Stanciu & I.-C. Herta, „DOUBLE-ACTION OEDOMETER AND DEVICE FOR FRONT LOADING IN STEPS OF A SOIL SPECIMEN". **Romania Brevet RO 133362**, 2018.

[13] A. Stanciu, I. Lungu, M. Aniculăesi, A. Ilaș, O. E. Colț and F. Bejan, „New laboratory devices for testing soil samples," **Proceedings of the Danube European Conference on Geotechnical Engineerin**g Bucharest, Romania., 2023.

[14] P. Rowe & L. Barden, „A New Consolidation Cell," ***Géotechnique,*** **vol. 16, nr. 3**, pp. 162-170, 1966.

[15] Controls, „Oedometer, a front loading. Soil mechanics testing equipment". Italy 1968.

[16] Matest, „ Oedometer, front loading". Italy 1986.

[17] ISO 17892-5, Geotechnical investigation and testing – Laboratory testing of soil – Part 5: Incremental loading oedometer test., 2017.

[18] BS 1377-5, Methods of test for soils for civil engineering purposes – Part 5: Compressibility, permeability and durability tests., 1990.

[19] B. Olek, „Experimental insights into consolidation rates during one-dimensional loading with special reference to excess pore water pressure," ***Acta Geotechnica,*** **vol. 15**, p. 3571–3591, 2020.

[20] C. Cekerevac, L. Laloui L. Vulliet, „Thermal Effects on the Compression Behaviour of Boom Clay," ***Canadian Geotechnical Journal,*** **vol. 55, nr. 8**, pp. 1072-1085, 2018.

[21] Arup, „Geotechnical Risk in Climate-Resilient Infrastructure," Technical Report, 2023.

[22] C. Ng, B. Menzies & D. Rigby, „Suction-Controlled Oedometer Testing of Unsaturated Soils," ***ASCE Journal of Geotechnical and Geoenvironmental Engineering,*** **vol. 146, nr. 7**, 2020.

[23] W. Zhou, X. Li & Y. Xu, „Polymer-Based Suction Control in Oedometers," ***Géotechnique Letters,*** vol. 12, nr. 1, pp. 1-8, 2022.

[24] A. W. Norshakila, A. R. Ahmad Safuan, R. M. Jawed, K. Azman & R. Roslizayati, „Mechanical Behaviour of Cement and Lime-Stabilised Laterite Subgrade at Various Matric Suctions.," ***Transportation Infrastructure Geotechnology,*** **vol. 12, nr. 4**, 2024.

[25] A. Stanciu, I. Lungu, M. Aniculesei, B. Teodoru & F. Bejan, Foundations II Investigation and testing of foundation soils, Bucharest: Technical Publishing House, 2016.

[26] G. Mesri și Y. Choi, „Settlement Analysis of Embankments," ***ASCE JGGE,*** **vol. 111, nr. 4**, 1985.

[27] D. DeGroot, C. Ladd & J. Germaine, „Hydraulic Gradient Oedometer Testing," ***ASTM Geotechnical Testing Journal,*** **vol. 39, nr. 5**, 2016.

Received: May 07, 2025
Accepted: June 12, 2025