Geotechnical centrifuge modeling of tunnel behavior in difficult soft soil conditions

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ABSTRACT: This paper presents a synthesis of an investigation into the long-term behavior of tunnels excavated in challenging soft soil conditions. A reconstituted clay, created by mixing 50% kaolin and 50% diatomaceous soil (50K–50DS), was developed to replicate the high compressibility and low permeability of natural lacustrine deposits while reducing consolidation time. One-dimensional consolidation tests demonstrate that the mixture increases the coefficient of consolidation by a factor of approximately three within the stress range relevant for urban tunnels, while maintaining strength and compressibility compatible with soft clays found in cities such as Bogotá and Mexico City. The material was subsequently utilized in centrifuge models simulating a circular tunnel embedded in a soft layer overlying a hard stratum, subjected to regional groundwater drawdown. The experimental program incorporated pore pressure transducers, surface settlement gauges, and earth pressure cells installed around the tunnel lining. Test results indicate that pore pressure dissipation leads to significant regional settlements and a progressive increase in vertical and tangential loads acting on the lining, with the largest increments concentrated at the crown. Comparisons with numerical finite element simulations reveal good agreement for both settlements and lining pressures, supporting the use of the 50K–50DS mixture and centrifuge modelling as effective tools for studying the long-term response of tunnels in soft ground under pore water pressure drawdown (Rodríguez-Rebolledo et al., 2023; Santos et al., 2024; Shahu & Reddy, 2011; Caicedo et al., 2015).

1 INTRODUCTION

Soft lacustrine and alluvial deposits are frequently encountered in large metropolitan areas and are characterized by high compressibility, low permeability and pronounced time-dependent behavior. Tunnels constructed in these deposits may experience long-term changes in loading conditions due to regional consolidation and groundwater-level variations. Field observations in Mexico City and Bogotá have shown that earth pressures acting on the lining can increase with time, often exceeding the values considered in design. Regional subsidence driven by pore-pressure drawdown may also modify the stress path imposed on the tunnel and induce additional bending and ovalisation (Onda et al., 2004; Caicedo et al., 2015).

Physical modelling in the geotechnical centrifuge provides an attractive framework to investigate these processes under stress similarity and accelerated time. However, reproducing decades of consolidation in the centrifuge requires soils with hydraulic properties that allow significant pore-pressure dissipation over manageable testing periods. A key contribution of the present research is the development and application of a reconstituted clay formed by a mixture of kaolin and diatomaceous soil (50K–50DS), which accelerates consolidation while preserving mechanical behavior representative of natural soft clays. Figure 1 summarizes the variation of consolidation coefficient and permeability with vertical effective stress for the reference kaolin (100K) and the 50K–50DS mixture (Rodríguez-Rebolledo et al., 2023).

2 MATERIALS AND METHODS

2.1 Prototype

The research concept is founded on an idealized prototype comprising a circular tunnel situated within a thick soft soil layer resting above a stiff or hard stratum. Regional groundwater extraction results in a uniform drawdown of pore pressure within the aquifer, leading to an increase in effective stresses and inducing regional settlement. To assess the influence of the hard layer on tunnel behavior, two distinct tunnel positions were modelled and analyzed: one positioned near the soft-hard interface (Model 1) and the other located higher within the soft layer (Model 2). This is illustrated in Figure 2, which presents the conceptual scheme, emphasizing the tunnel elevation, the thickness of the soft layer, and the alteration in pore-pressure profile induced by drawdown (Caicedo et al., 2015).

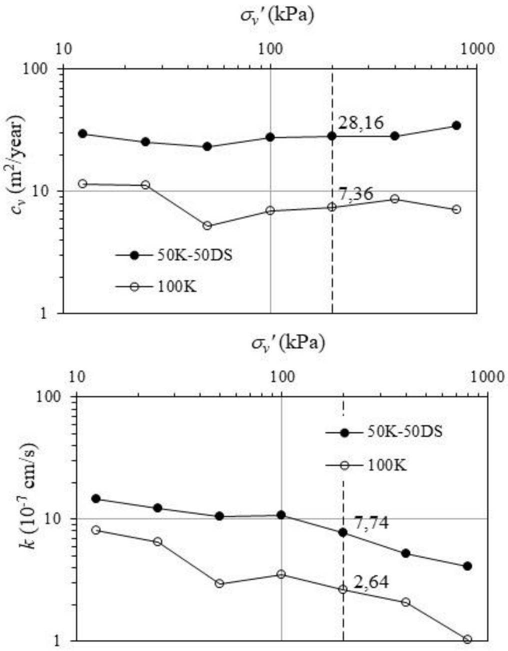

Figure 1. Variation of consolidation coefficient c_v and permeability k with vertical effective stress for 100K and 50K–50DS.

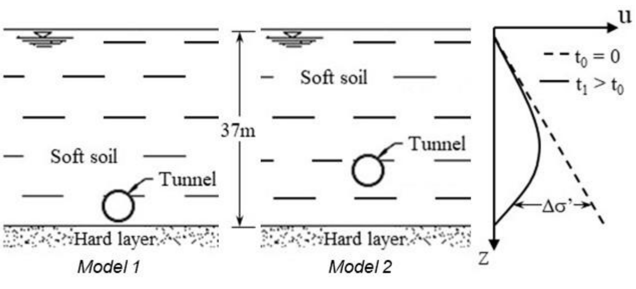

Figure 2. Conceptual prototype scheme of tunnel in soft soil layer overlying a hard layer subjected to pore pressure drawdown.

2.2 Reconstituted soil

The centrifuge models employ two reconstituted materials: a reference kaolin clay (100K) and the 50K–50DS mixture. Detailed procedures for specimen preparation and element testing are reported in Rodríguez-Rebolledo et al. (2023). The oedometer results, summarized in Figure 1, show that the mixture significantly increases c_v in comparison with 100K, particularly for effective stresses between 50 and 200 kPa, which correspond to typical overburden levels at tunnel depth. At the same time, compressibility parameters and undrained strength remain within the range of values measured for natural lacustrine clays, indicating that the mixture is suitable to represent difficult soft soil conditions (Rodríguez-Rebolledo et al., 2023).

2.3 Centrifuge facility

The tests were performed in the 40 g-ton geotechnical centrifuge at Universidad de los Andes. The equipment, its main characteristics and the model box used are presented in Figure 3. The soil profile was constructed in layers inside a strong box, with a sand drain at the base, an overlying clay layer composed either of 100K or 50K–50DS, and a sand crust at the top. The model tunnel is represented by a rigid aluminum cylinder with an external diameter scaled to prototype dimensions. Pore-pressure transducers were installed along the soil column and LVDTs were positioned at the ground surface to measure regional settlements, as indicated in Figures 3 and 4 (Rodríguez-Rebolledo et al., 2023; Caicedo et al., 2015).

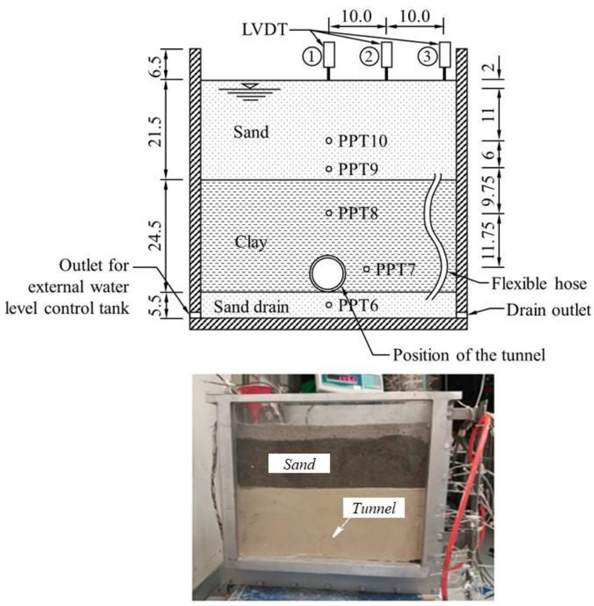

Figure 3. Cross-section of the centrifuge model box showing sand and clay layers, sand drain, tunnel position and pore pressure transducers for Model 1.

2.4 Tunnel instrumentation

A hollow aluminum cylinder measuring 12.0 cm in length, with an external diameter of 7.5 cm and a wall thickness of 5 mm, was employed to represent a prototype tunnel featuring concrete linings with an outer diameter of 6.0 m and a lining thickness of 50 cm. The wall thickness of the model cylinder was defined to preserve similarity between the model and the prototype with respect to flexural rigidity.

The aluminum tunnel lining was instrumented with strain gauges, displacement transducers and earth pressure cells, arranged in circumferential sections as shown in Figure 5. This configuration allowed the determination of vertical and horizontal loads as well as bending effects at different angular positions around the lining. Pore-pressure drawdown was imposed in stages by lowering the water level in an external control tank connected to the sand drain, which produced uniform changes of pore pressure at the base of the model. Each test comprised an initial phase under hydrostatic conditions followed by a consolidation phase during which pore pressures, settlements and lining loads were recorded (Onda et al., 2004).

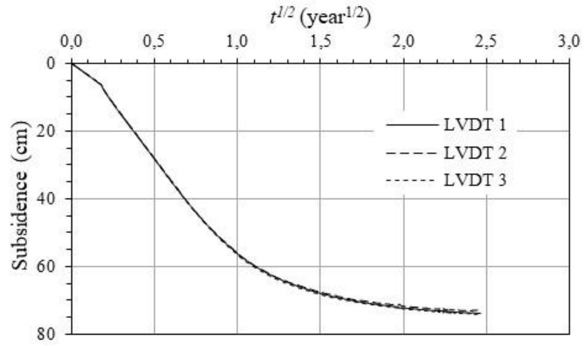

Figure 4. Regional surface settlements recorded by LVDTs during drawdown in prototype scale.

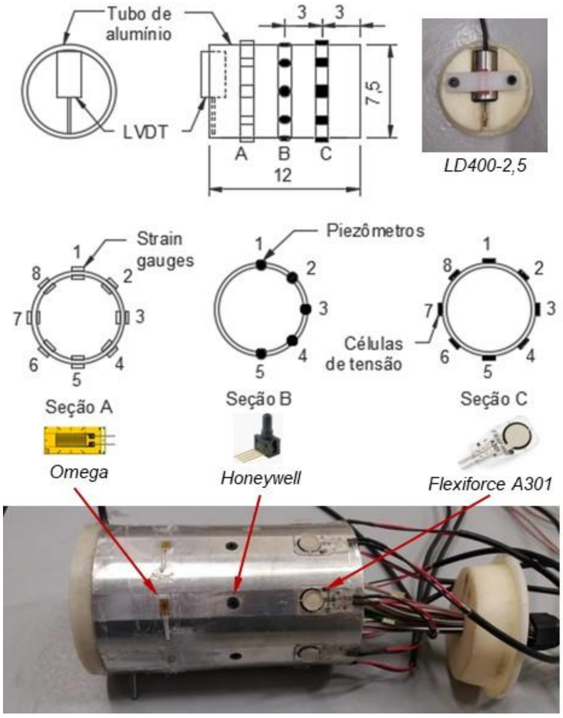

Figure 5. Tunnel lining instrumentation layout with LVDT for convergence, strain gauges, piezometers and earth pressure cells.

3 RESULTS

3.1 Effect of soil mixture on consolidation parameters

Figure 1 compares the variation of c_v and permeability k with vertical effective stress for the 100K and 50K–50DS materials. In the stress range of 50–200 kPa, c_v for the mixture is roughly three times larger than for 100K, while k is also moderately higher. Therefore, the time required to reach a given degree of consolidation is reduced by about 70%, which is essential to simulate multi-year prototype processes within a single centrifuge flight. These differences justify the choice of 50K–50DS as the base material for the tunnel tests presented in this paper (Rodríguez-Rebolledo et al., 2023).

3.2 Pore-pressure evolution during drawdown

Figure 6 displays piezometric profiles obtained at different degrees of consolidation U for the two centrifuge models. Immediately, after the drawdown is applied, the pore-pressure distribution departs significantly from hydrostatic conditions, particularly near the sand drain. With time, excess pore pressures dissipate and the profiles tend towards the final drawdown line. The measurements reveal reasonable agreement with the numerical predictions, although the numerical model tends to slightly overestimate the residual pore pressures near the interface between the soft layer and sand crust.

3.3 Subsidence

The settlement history at the ground surface is presented in Figure 4, using $t^{1/2}$ as the time variable. The curves are approximately linear over a wide range, which is consistent with one-dimensional consolidation theory. Maximum prototype settlements of the order of 0.7 m are obtained at the end of the drawdown process, in good agreement with regional subsidence rates reported. The use of the 50K–50DS mixture allowed these long-term settlements to be reproduced within a few hours of centrifuge operation (Rodríguez-Rebolledo et al., 2023).

3.4 Lining load

Figures 7 and 8 illustrate the measured and computed evolution of earth pressure around the tunnel lining as a function of U, for two different tunnel positions relative to the hard layer. In the model where the tunnel is situated near the soft-hard interface (Model 1), the drawdown leads to a significant increase in vertical pressure at the invert (cell C5), with increments exceeding 1 MPa on a prototype scale. Conversely, the pressures at the springlines (cell C3) and crown (cell C1) show smaller variations.

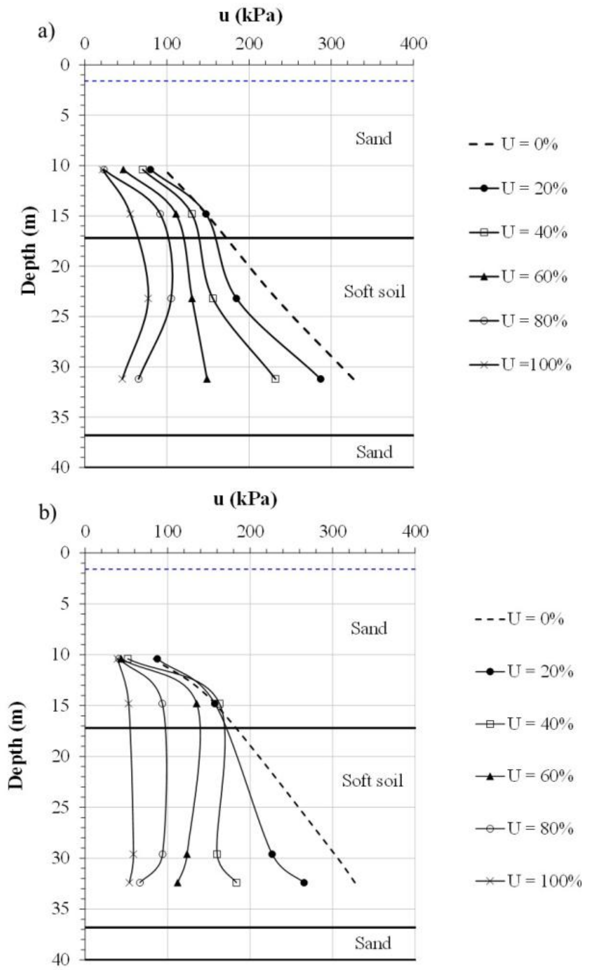

Figure 6. Piezometric profiles along the soil column for different degrees of consolidation U, measured for: a) Model 1, and b) Model 2.

When the tunnel is positioned higher within the soft layer (Model 2), the distribution of pressure increments becomes more uniform; however, significant differences emerge between the physical and numerical models. In physical modelling, the maximum load occurs at the crown (cells C1 and C2) of the model, whereas in the numerical modelling, the maximum load is observed at the invert (cell C5). This discrepancy may have arisen during the experiment, as the relatively high displacements recorded during the consolidation of the medium caused the tunnel (the aluminum tube) to become partially stuck against the walls of the model box while attempting to accommodate the subsidence.

On the other hand, Figure 9 indicates that the initial stress state, whether established through a K_0 procedure or gravity loading, also influences the magnitude of the final pressures, particularly at the crown cell, although the overall trends with *U* remain consistent (Santos et al, 2024).

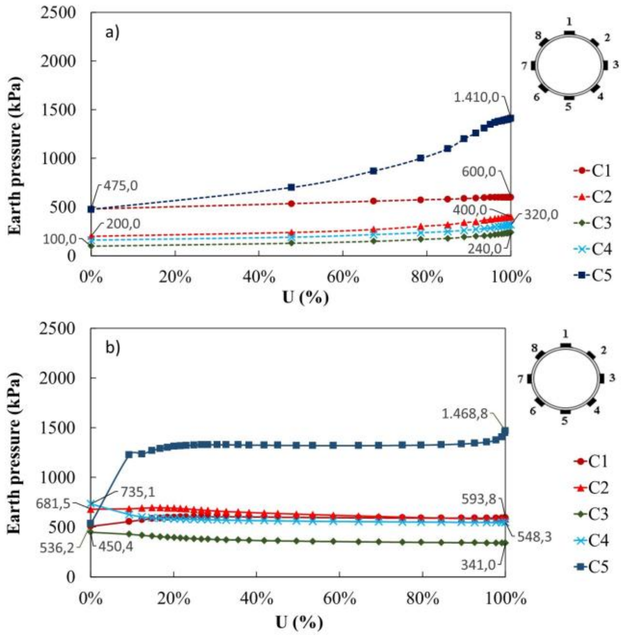

Figure 7. Earth pressures around the tunnel lining versus degree of consolidation U for: a) physical and b) numerical Model 1.

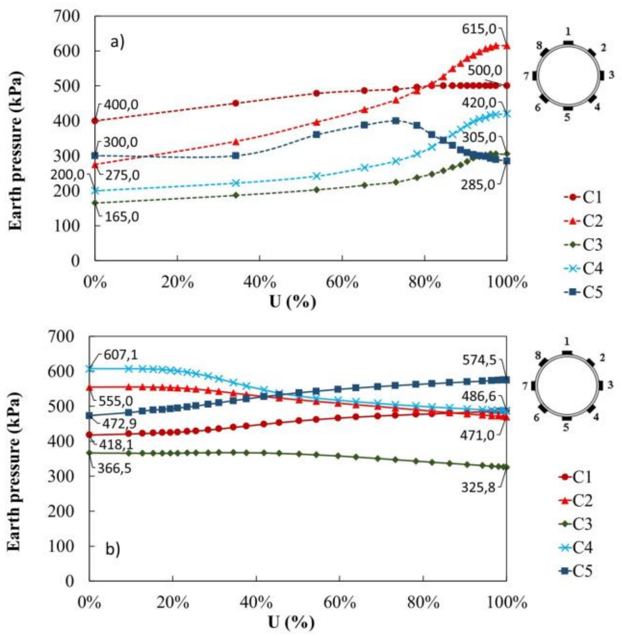

Figure 8. Earth pressures around the tunnel lining versus U for: a) physical and b) numerical Model 2.

4 DISCUSSION

The combined interpretation of pore pressure, settlement, and earth pressure measurements confirms that regional drawdown can significantly alter the loading on tunnels in soft soils. The centrifuge tests capture the coupled mechanism by which effective stresses increase in the surrounding soil, resulting in regional subsidence and a transfer of load to the tunnel lining. The concentration of pressure increments at the crown aligns with the concept of a stiff inclusion embedded in a consolidating medium, as well as with field back analyses reported in previous case histories.

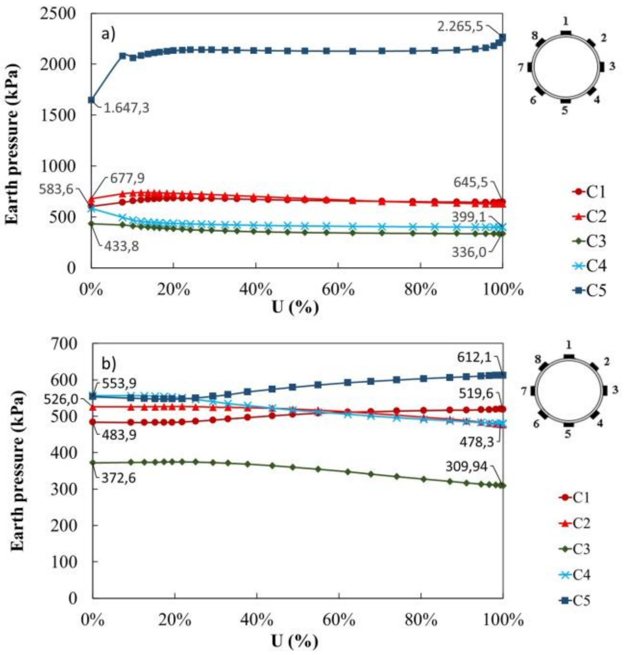

Figure 9. Effect of initial stress state imposed by gravity loading on earth pressures around the lining during drawdown for: a) Model1 and b) Model 2.

As demonstrated in Rodríguez-Rebolledo et al 2023, the use of the 50K–50DS mixture is crucial for making these experiments feasible. By increasing the coefficient of consolidation (c_v) while maintaining realistic stiffness and strength, the mixture enables the simulation of decades of prototype time within just a few hours of centrifuge operation, without introducing unrealistically permeable materials. The strong correlation between centrifuge and numerical results for both settlements and lining pressures supports the validity of the adopted modelling strategy and soil representation. Additionally, the findings underscore the sensitivity of lining loads to the tunnel's position within the soft layer and the assumed initial stress state—factors that should be carefully considered in design (Santos et al, 2024; Onda et al., 2004).

5 CONCLUSIONS

Based on the centrifuge and numerical studies presented, the following main conclusions can be drawn:

- The reconstituted 50K–50DS clay exhibits significantly higher coefficients of consolidation compared to the reference kaolin while maintaining compressibility and strength values representative of natural soft clays, making it suitable for physical modeling of regional subsidence.
- Pore pressure drawdown in the centrifuge models results in regional settlements of a similar order of magnitude to those observed in heavily urbanized basins, with the settlement-time curves following the expected $t^{1/2}$ behavior.
- Earth pressure measurements indicate that drawdown induces a substantial increase in the loads acting on the tunnel lining, with the largest increments occurring at the invert. These increments depend on the tunnel's position relative to the hard layer and the initial stress state.
- The agreement between centrifuge and finite element demonstrates that the adopted soil model and boundary conditions effectively reproduce the key aspects of soil-structure interaction under regional drawdown.
- Geotechnical centrifuge modeling using mixtures such as 50K–50DS provides a powerful framework for assessing the long-term performance of tunnels in challenging soft soil conditions and supports the development of more robust design procedures.

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