Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1131

Physical modeling in geotechnical centrifuge: analysis shallow tunnel experiment in non-cohesive soils

Cleiton Cabral, André Marques, Aldo Durand, **Fernando Saboya**
Department of Civil Engineering at UENF, Campos dos Goytacazes-RJ, Brazil, cleitoncabraleng@gmail.com

Aldo Durand
Associate professor at UENF, Brazil

ABSTRACT: With the increase in urban expansion, areas suitable for construction have suffered significant impacts, leading to the depletion of such territories. Consequently, transportation and utility networks need to be integrated into the underground. To facilitate access, in many cases, tunnels are constructed at shallower depths, avoiding interference with existing infrastructure, such as foundations. In this study, physical modeling in a geotechnical centrifuge was carried out at a reduced scale, with acceleration of up to 50g, simulating the Tunnel Boring Machine (TBM) excavation method for shallow tunnels in non-cohesive soils. The simulation focused on assessing the excavation face of a shallow tunnel with a cover-to-diameter ratio (C/D) of D/2. The soil used was standardized industrial sand, supplied by the Technological Research Institute (IPT). All tests were conducted in accordance with the study's methodology, using both loose and dense sand. For model preparation, a rectangular container was employed, and the execution process was primarily carried out in two stages: rainfall simulation and excavation simulation (relief and pressure). The acceleration level was 50g, simulating a shallow tunnel with a diameter of 5 meters, aiming to measure the potential influences of this method on this type of soil.

KEYWORDS: Tunnel Boring Machine, Geotechinical centrifuge, non-cohesive soils.

1 INTRODUCTION

With the increase in urbanization, the construction of shallow tunnels for underground service and transportation networks has become essential, including road, rail, sewage, water, gas, and pedestrian tunnels, meeting the growing population demand.

Thus, in urban areas, tunnels are commonly built in soft soils and located close to the surface. Given the high volume of tunnel construction, it is crucial to understand the tunneling process, considering aspects such as ground displacements, induced stresses, and their effects on adjacent structures.

Despite advances in computational techniques, which have enabled extensive numerical and analytical research on tunneling, geotechnical engineers still rely heavily on physical modeling to understand related phenomena, such as deformation patterns and failure mechanisms. According to Ng (2014), in the last fifty years, centrifuge modeling has emerged as one of the most significant advances in geotechnics, ranking fifth among the most relevant developments. Extensive research has been conducted using geotechnical centrifuges in countries such as China, Japan, Colombia, and Brazil.

It is common to operate Tunnel Boring Machines (TBMs) in urban areas under inadequate and low-strength soil conditions. The use of TBMs enables accelerated, efficient, and safe construction, taking into account the stability of the tunnel excavation face (Schwandl, 2020).

In a TBM-assisted excavation, the tunnel face is supported by the cutting mechanism of the TBM and by the pressure applied within the excavation chamber. Proper determination of this pressure at the design stage, as well as the operator's experience, is essential (Kim & Tonon, 2010).

This study describes a reduced-scale experimental simulation carried out in a geotechnical centrifuge. The simulation focuses on assessing the excavation face of a shallow tunnel in non-cohesive soils, with a cover-to-diameter ratio (C/D) of D/2, aiming to compare the results with the findings of Idinger et al. (2011).

2 MATERIAL AND METHOD

2.1 *Geotechinical centrifuge*

The physical modeling was carried out using the Geotechnical Centrifuge at the Civil Engineering Laboratory of the State University of Northern Rio de Janeiro Darcy Ribeiro (UENF). The centrifuge has a maximum speed of 227 revolutions per minute, allowing the creation of a gravitational field up to 100 times the value of Earth's gravity. Figure 1 shows a photograph of the centrifuge prepared for the test.

Figure 1. Geotechinical centrifuge at UENF.

2.2 *Test box*

Figures 2 and 3 show the test box used to contain the tunnel model. The test box is made of steel (A36), with a thickness of 19.05 mm, and has internal dimensions of 581 mm in length, 700 mm in width, and 300 mm in depth. A 30 mm thick acrylic plate was fixed to the front wall of the box.

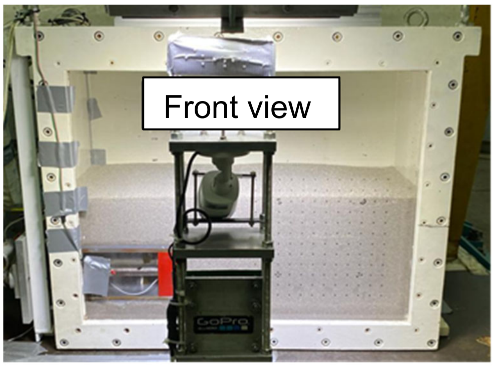

Figure 2. Front view of the test box.

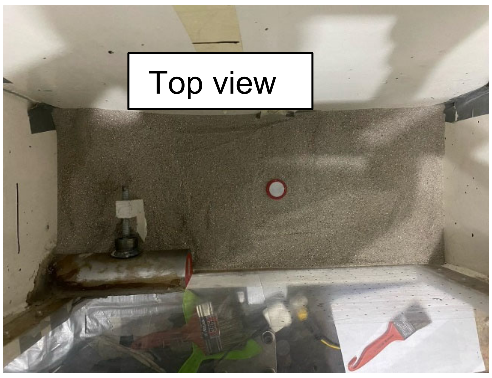

Figure 3. Top view of the test box.

2.3 *Soil used*

The physical models were developed using industrial sand standardized by NBR 7214 (N50 and N30), marketed by the Technological Research Institute (IPT) as a representative material for the soil. This sand was chosen because it can highlight the most critical conditions, which favors our analysis in comparison to a real situation. A combination of the sands was made, with 60% (N50) and 40% (N30). The sands were then dyed to improve grain visibility.

The test box was filled with the standardized sand, which had an average particle diameter of approximately d50 = 0.52 mm. The density of the sand was controlled by means of a specific fall height. The maximum and minimum void ratios of the sand used were 92% and 67%, respectively. For the interaction between the soil and the structure at the tunnel face, the TC2 commission of the ISSMGE recommends that the dimensional ratio (D/d50) be greater than 175 (Indiger et al., 2011). In this context, the model achieved a dimensional ratio (D/d50) of approximately 211.

Table 1 and 2 shows the physical properties of the sand, while Figure 4 shows the granulometric distribution, determined through characterization tests. The tests were carried out according to the current standards.

Table 1. Properties soil.

Properties	Symbol	Value	Unit
Averague diameter	*D50*	0,52	mm
True grains density	*g*	2,66	g/cm³
Min. Void ratio	*emin*	0,67	*
Max. Void ratio	*emáx*	0,92	*

5Properties soil.

Properties	Loose sand	Dense sand
Specific weight (kN/m³)	*14,38*	15,54
Void ratio	*0,821*	0,683
Relative density	*39%*	94%

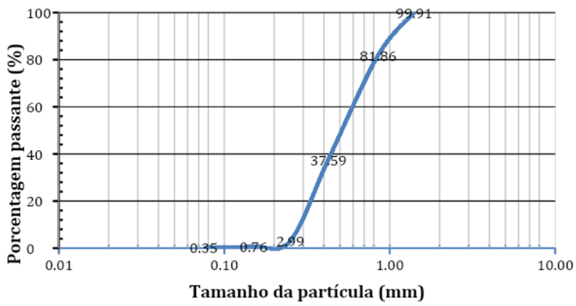

Figure 4. Granulometric curve of the sand.

2.4 *Dispenser*

The test box was filled through a sand rainfall, using a distributor developed at the Centrifuge Laboratory/UENF, which regulates the direction and deposition speed of the material. The soil density varies according to the drop height and deposition speed; higher drops result in more intense deposition energies, leading to denser soils. According to Ratton (1993), rainfall in the air allows for an adequate reconstruction of natural deposits formed by wind, which are typically composed of sands or silts.

The distributor (Figure 5) consists of an aluminum funnel that holds a specific volume of material. A flexible hose is connected to this funnel, allowing the material to flow by gravity to a passage valve. Along with the hose, there is a rigid PVC tube (D = 60 mm). The flexible hose allows the movement of the rigid tube during the sample preparation.

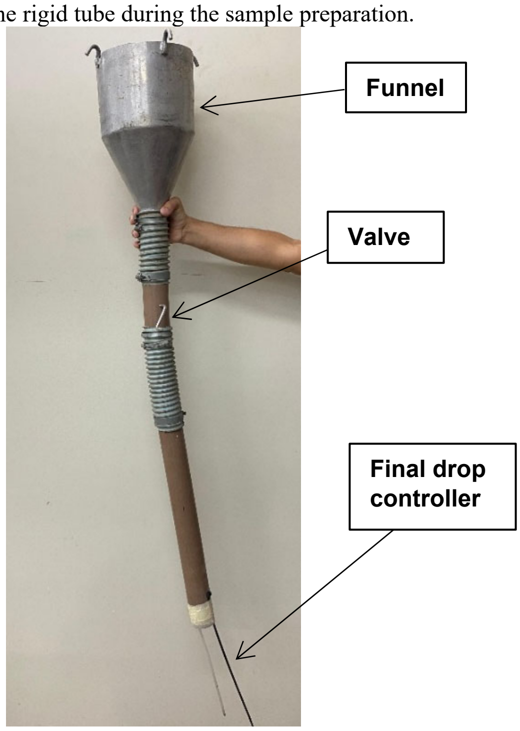

Figure 5. Dispenser.

2.5 *Tunnel model and instrumentation*

The shallow tunnel model featured a semi-circular cross-section (Figure 6), considering only half of the tunnel's cross-section. The tunnel model had a lining made of half a steel cylinder, with a diameter of 110 mm. The tunnel face was simulated by a semi-circular support, which could be moved forward or backward by means of a controlled displacement linear actuator. These movements induce pressure and relief in the soil in front of the excavation, respectively. It is important to note that, in this study, we will evaluate only the relief movement for both loose and dense sand.

For the tests in this study, an inductive LVDT (Figure 7) was used to measure the displacement on the rigid plate at a speed of 0.008 mm/s. The displacement of the tunnel, considering that the relief (recession) of the tunnel was performed, was 5 mm.

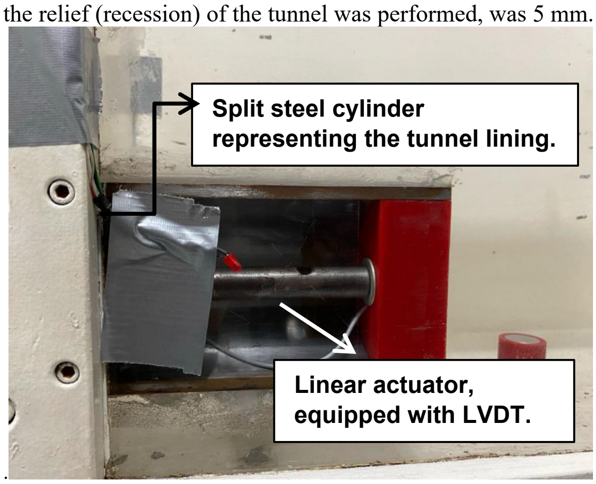

Figure 6. Tunnel model.

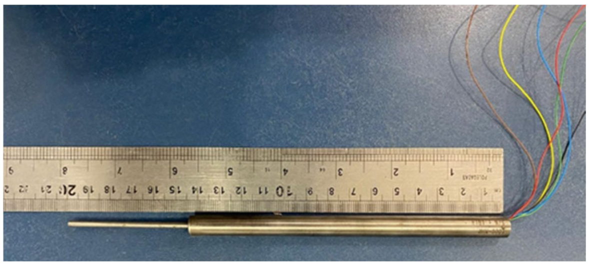

Figure 7. Instrumentation (LVDT).

3 RESULTS

Figure 8 shows, for the condition of C/D = 0.5 (D/2) in the relief mode, the correlation between the images obtained in the physical tests, the displacement analysis by PIV, and the normalized support pressure curves as a function of the normalized displacement of the face. As in the studies by Kirsch (2010) and Idinger, images of the physical model were recorded before and after the movement of the tunnel face, along with the respective PIV analysis, allowing for a visual correlation between the evolution of the deformation zone and specific points on the experimental curve.

It can be observed that, for loose sand, the curve shows higher initial values, followed by a sharp drop and stabilization at nearly constant levels, a behavior similar to that observed by Kirsch for loose samples, where collapse occurs more abruptly and the failure zone rapidly develops toward the surface. In contrast, for compacted sand, the initial support pressure is lower, with a more stable behavior throughout the displacement, resembling the pattern identified by Kirsch and Idinger in dense samples, characterized by the gradual progression of the failure zone toward the surface, without immediate collapse.

The PIV analyses reinforce this interpretation: in loose sand, the deformation distribution is broader and more diffuse, quickly reaching the surface; while in compacted sand, the failure zone is more confined and concentrated near the tunnel face, progressing gradually. These results confirm that the compaction degree significantly influences the collapse mechanism of the face, fully aligning with the patterns reported in the literature for soils with different relative densities.

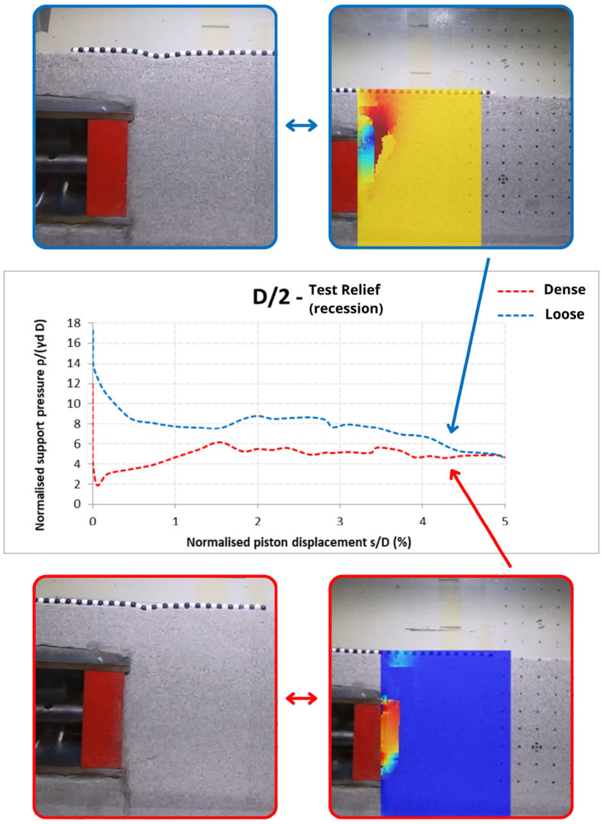

Figure 8. Normalization of the support e pressure and piston displacement.

4 CONCLUSION

Considering the scenario of non-cohesive soil in this article, and in parallel with the studies by Idinger and Kirsch, it was observed that the curve for compacted sand presents a lower normalized pressure than the curve for loose sand, as also discussed by Idinger and Kirsch. It is worth noting that Idinger's curves (2011) are less pronounced due to the reasons explained earlier. The analytical interpretations in the literature were compared to the experimental results, and the experiments conducted by Kirsch and other authors showed good agreement with the data obtained in this study.

5 ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the funding agency FAPERJ for their invaluable support through the APQ1-2021 Project. This financial assistance was crucial in enabling the development of this research, and we deeply appreciate FAPERJ's commitment to advancing scientific knowledge and fostering innovation. We also acknowledge the instrumental role that this partnership has played in supporting the progress and success of our work.

6 REFERENCES

Assis, A. P. (2002a). MECÂNICA DAS ROCHAS: OBRAS SUBTERRÂNEAS. Brasília, DF: Departamento de Engenharia Civil, UnB.

Bucky BP (1931) The use of models for the study of mining problems, Technical publication No.425, American institute of mining and metallurgical engineers, pp 3–28.

ECO Túneis. (2020). TUNNEL LINER. Retrieved December 26, 2020, from http://ecotuneis.com.br/tunnel-liner/.

Garrides M., Souza P., Campos Neto L. Transporte público em Belo Horizonte: um estudo comparativo entre metrô e monotrilho. Petra, 2016.

IDINGER, Gregor; AKLIK, Pelin; WU, Wei; BORJA, Ronaldo I.. Centrifuge model test on the face stability of shallow tunnel. Acta Geotechnica, [S.L.], v. 6, n. 2, p. 105-117, jun. 2011. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s11440-011-0139-2.

Kim, S., Tonon, F. (2010). Face stability and required support pressure for TBM driven 96 tunnels with ideal face membrane – Drained case. Tunnelling and Underground Space Technology, 25(5), 526–542. https://doi.org/10.1016/j.tust.2010.03.002.

KIRSCH, Ansgar. Experimental investigation of the face stability of shallow tunnels in sand. Acta Geotechnica, [S.L.], v. 5, n. 1, p. 43-62, 6 mar. 2010. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s11440-010-0110-7.

Ng, C.W.W., Van Laak, P., Tang, W.H., et al., 2001a. The Hong Kong geotechnical centrifuge. Proceedings of 3rd International Conference on Soft Soil Engineering, Hong Kong, p.225-230.

NG, Charles W. W.. The state-of-the-art centrifuge modelling of geotechnical problems at HKUST. Journal Of Zhejiang University Science A, [S.L.], v. 15, n. 1, p. 1-21, jan. 2014. Zhejiang University Press. http://dx.doi.org/10.1631/jzus.a1300217.

Pietro, L. (2008). Design and construction of tunnels: Analysis of Controlled Deformations in Rock and Soils (ADECO-RS). Milano: Springer Science & Business Media. https://doi.org/10.1007/978-3-540-73875-6.

Schwandl, R. (2020). UrbanRail.Net. Retrieved October 1, 2020, from http://www.urbanrail.net/

Seidenfuss, T. (2006). Collapses in tunnelling. École Polytechnique Federale de Lausanne-EPFL.

Schwandl, R. (2020). UrbanRail.Net. Retrieved October 1, 2020, from http://www.urbanrail.net/.

Zare Naghadehi, M., Thewes, M., Alimardani Lavasan, A. (2019). Face stability analysis of mechanized shield tunneling: An objective systems approach to the problem. Engineering Geology, 262, 105307. https://doi.org/https://doi.org/10.1016/j.enggeo.2019.105307.

Zizka, Z., Thewes, M. (2016). Recommendations for face support pressure calculations for shield tunnelling in soft ground. German Tunnelling Committee (ITA-AITES), Cologne, Germany.