Research Article/Civil and Sanitary Engineering https://doi.org/10.15446/ing.investig.99197

Soil Conditions and Shield Tunneling Viability for Bogotá Metro Line 1

Análisis de las Condiciones del Suelo y Viabilidad para la Línea 1 del Metro de Bogotá con Tuneladora

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ABSTRACT

Bogotá, the capital city of Colombia, has experienced a critical situation regarding its public transport and road network condition. Unfortunately, the city has lacked an analytical long-term evaluation with regard to transport planning and infrastructure that is able to meet the growing demand. The metro system has been planned for more than half a century, and the existing soil investigations have not been fully used to evaluate the feasibility of building a metro in Bogotá's subsoil. In order to estimate the construction viability of an underground system in the city, the authors studied the ground conditions along the alignment of Metro Line 1, as proposed in 2014. This research brought forward the stratigraphic profile of the first 6,6 km of the alignment. The ground displacements induced by tunneling were estimated by means of a finite element analysis, and the results are presented in this paper along with their significance. The results forecast surface settlements lower than 10 mm, showing that the condition and strength of the soil are suitable for underground metro construction. However, soil consolidation and appropriate monitoring during and after tunneling should be taken under consideration for the sake of the project's success.

Keywords: congestion cost, lacustrine deposits, Bogotá subsoil, tunneling

RESUMEN

Bogotá, la capital de Colombia, se ha caracterizado por su situación crítica en temas de transporte público y condiciones de conexión vial. Desafortunadamente, la ciudad ha carecido de una evaluación analítica a largo plazo con respecto a la planeación del transporte, así como de una infraestructura que sea capaz de satisfacer la creciente demanda. El sistema metro ha sido planeado por más de medio siglo, y los estudios de suelos existentes no han sido aprovechados en su totalidad para evaluar la viabilidad de construir un metro en el subsuelo de Bogotá. Para estimar la viabilidad de construir un sistema subterráneo en la ciudad, los autores estudiaron las condiciones del suelo a lo largo del trazado de la Línea de Metro 1, tal y como se propuso en 2014. Esta investigación puso de manifiesto la columna estratigráfica de los primeros 6,6 km del trazado. Los desplazamientos del suelo inducidos por la construcción de túneles se estimaron mediante un análisis de elementos finitos, y los resultados se presentan en este artículo en conjunto con su significancia. Los resultados pronostican asentamientos menores a 10 mm, indicando que las condiciones y la resistencia del terreno son aptas para la construcción de un metro subterráneo. Sin embargo, la consolidación del suelo y un monitoreo adecuado durante y después de la construcción de los túneles deben ser consideradas en pro del éxito del proyecto.

Palabras clave: costo del congestionamiento vial, depósitos lacustres, subsuelo de Bogotá, construcción de túneles

Received: October 25th, 2021
Accepted: August 25th, 2022

Introduction

Bogotá is the fourth most populated and largest capital city in South America, with an urban population of 7,8 million (as of 2021) (DANE, 2020) and a great infrastructure demand. In the last five years, the city administration prioritized two projects to improve mobility and provide a solid transport system: i) the integration of the bus rapid transit (BRT) system with public buses, and ii) the construction of the first metro line (hereinafter referred to as BML1). Despite the economic and social costs of traffic congestion and more than US$45 million spent in the last eight contracts on the analysis of an urban mass transit system, Bogotá still lacks a reliable transit service. According to a study on the future impacts of traffic jams due to time lost, Bogotá ranked first in the Top 5 of global congestion impact ranking in 2018 (Read and Kidd, 2019), which is shown in Table 1.

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How to cite: Matta-Diaz, D. M., Rivera-Pardo, S., Liu, X., and Bai, Y. (2023). Soil Conditions and Shield Tunneling Viability for Bogotá Metro Line 1. *Ingeniería e Investigación, 43*(2), e99197. https://doi.org/10.15446/ing.investig.99197

Table 1. Top 5 most congested cities in the global congestion impact ranking

Impact Rank	City	Hour Lost	Last Mile Speed (MPH)
1	Bogotá	133	11
2	New York City	100	12
3	Moscow	100	15
4	Philadelphia	94	12
5	Paris	88	13

Source: Read and Kidd (2019)

Fenalco (2014) studied the cumulative cost of traffic congestion for Colombia in the 2013-2030 period, for which they estimate gridlock costs of US$3,9 billion. They classified congestion costs into direct costs, such as the value of fuel and the time spent in traffic and not at work; and indirect costs, where higher freighting and business fees from company vehicles idling in traffic are passed on as additional costs to household bills (Cebr, 2014). In addition to these already occurring congestion costs, future congestion costs resulting from the current BRT system must be considered. The capacity of the BRT system used in Bogotá is 45 000 passengers per hour per direction (pphpd), whereas the capacity of a metro system falls in the range of 60 000-80 000. In order for the BRT system to match the efficiency of a metro system, the city would need to invest in additional BRT lanes. The problem with adding more BRT lanes is that there is not enough space in the city to accommodate them without affecting the traffic of privately-owned cars, which results in an increase in the cumulative cost of traffic congestion.

This research aims to develop a model that is able to predict ground settlements caused by shield tunneling in Bogotá for future metro lines. Major advances have been made in shield tunneling, particularly with the introduction of the pressurized face type, which allows tunnels to be built in all types of soils. This includes recent advances on EPB (earth pressure balance) and BSS (bentonite slurry shield) operation and control, particularly under difficult ground conditions. Developments related to shield tunneling technology have been reviewed by Clough (1993), Fujita (1989), and Béjui and Guilloux (1989).

The model was built based on information and data from the BML1, including a precise analysis of ground conditions (soil parameters and water presence), location, and other aspects of construction (tunnel diameter and depth). Unlike a regular analysis, where a deterministic simulation based on known inputs is first used and a probabilistic study is then applied to provide realistic estimates and confirm the validity of the outputs, this study proposes building a statistical model that aims to provide the best inferences needed as inputs for the deterministic analysis.

Overview of metro plans

Cities like London, Madrid, Shanghai, México DF, and Bogotá share a common feature: a soft soil medium beneath their ground (Sainea-Vargas *et al.*, 2020; Melis-Maynar, 1998; Ding and Xu, 2017). Bogotá's metro has been planned for over 70 years, but political issues and funding are the main reasons why citizens are still waiting to ride the first metro line (Figure 1). Table 2 lists some features of the four main studies that have been conducted for the BML1. Although these four proposals had different alignments, the proposed average length is 23,44 km. The estimated costs differ on the length and construction method; the lowest cost was US$1,96 billion of at-grade and cut-cover stations, and the highest cost was the earliest, proposed in 1981 with a combination of elevated, at-grade, and underground stations.

Table 2. Main BML1 construction proposal

Year	Alignment	Length [km]/ stations	Design capacity per hour	Construction method	Cost (billion USD)
1987	Ciudad Bolívar –C. Histórico & admo.	23/10	Unknown	TBM, at grade rail, bridge structure	7,97
2008-2010	San Victorino – Calle 170	19,7/19	29 300	Cut-cover, at-grade rail	1,96
2013-2015	Ptal. Américas, Av. Villao – Calle 127	27/27	48 000	TBM	7,55
2016	Ptl Americas-Calle 72	24/16	60 000	Bridge structure	3,48

Source: Contraloría de Bogotá (2019)

The feasibility study conducted between 2013 and 2015 for an underground metro line was significantly more detailed than the former. The detail-design phase reached 80% completion, whereas the others only reached the conceptual design phase. The estimated cost was 9,42% higher than the budget approved by both local and national governments, and therefore the project was never executed.

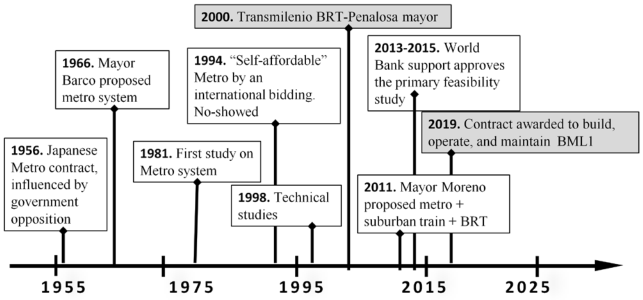


Figure 1. Timeline of Bogotá Metro Line 1
Source : Authors

In 2016, the city administration carried out a comparative study between the different construction alternatives in order to quantify and assess costs (Contraloría de Bogotá, 2019). The results suggested building an elevated metro line due to the decrement of initial costs compared to the underground option proposed in 2014. Although this cost estimation was based only on conceptual designs, the international bidding to design, build, operate, and maintain the future metro line 1 was awarded for a US$5,16 billion contract.

Normally, the cost ratio for elevated *vs.* underground systems is approximately 1/2,5 (ITA-WG13, 2004). In the case of the BML1, the cost ratio of these two alternatives differs in the number of stations and trains, the length, BRT additions, and the design stage. However, from the overall cost of the two proposals, the cost ratio for elevated *vs.* underground systems can be calculated as 1/2,3. As shown in Figure 2, the proposal for an elevated line included 15 stations with a total length of 24 km, compared to an underground option of 27 stations within 27 km. The estimated construction cost of all 27 underground stations was US$2,14 billion, whereas the cost of the elevated stations was US$0,41 billion (Contraloría de Bogotá, 2019). Thus, the cost ratio of elevated *vs.* underground stations is approximately 1/2,8.

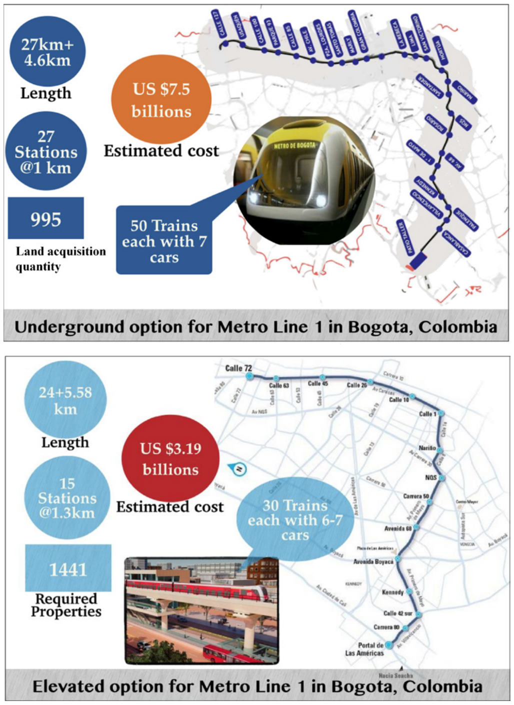


Figure 2. Key features of the BML1: a) underground metro line and b) elevated metro line
Source: Adapted from Contraloría de Bogotá (2019)

Methodology

The computational model is briefly divided into three stages: (1) the definition of stratigraphic soil profiles along the alignment of the BML1 via a statistical analysis of geotechnical data; (2) an approach to an optimal tunnel system suitable for Bogotá; (3) the collection of computational results by means of a numerical model which can approximate the real conditions to the model parameters with the aim of estimating the ground movements induced by shield tunneling. The software RStudio was used to analyze the data obtained from geotechnical investigations of each section of the alignment. The deterministic model was built using PLAXIS2D, a two-dimensional finite element code.

Statistical analysis

Geological, geotechnical, and hydrogeological investigations are the backbone of a baseline geological report. Previous experience in metro projects has shown that having a substantial amount of geotechnical investigation and using adequate methods with scientific accuracy can reduce construction costs and lower the risks. Therefore, laboratory and field testing (CPTu, SDMT, PMT, and geophysics) were performed on the BML1's alignment from 2013 to 2015 (Figure 3). The geotechnical data were collected within 0 to 50 m in depth and uploaded to an online open-access platform (IDU, 2013). Unfortunately, there were no stratigraphic profiles developed along the alignment, and the extensive laboratory data was not organized or verified. In order to get the stratigraphic profiles needed to conduct this study, a statistical analysis was carried out. This process is shown in Figure 4.

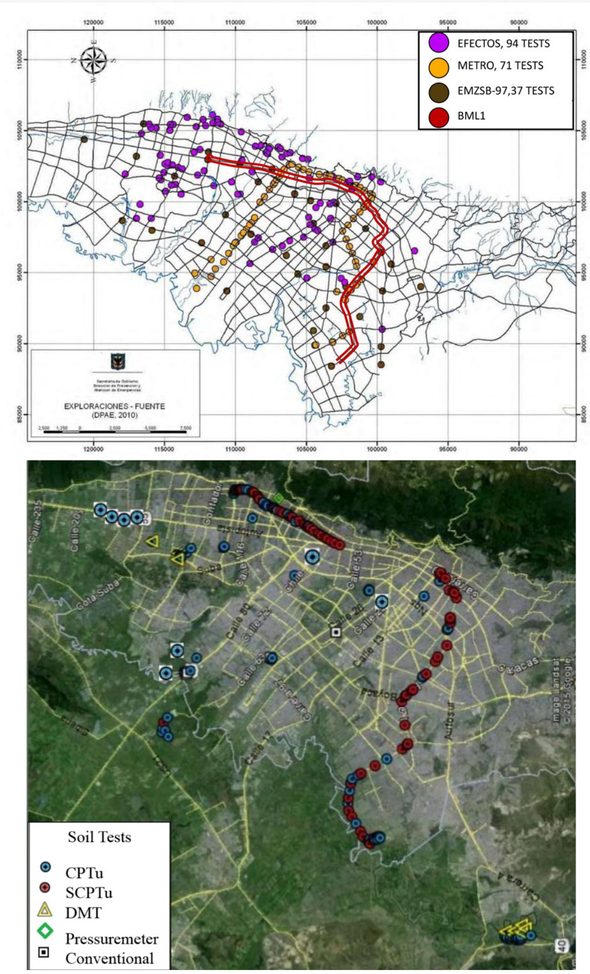


Figure 3. Field geotechnical tests along the BML1's alignment
Source: Adapted from Consorcio L1 (2015) and Alcaldía Mayor de Bogotá (2010)

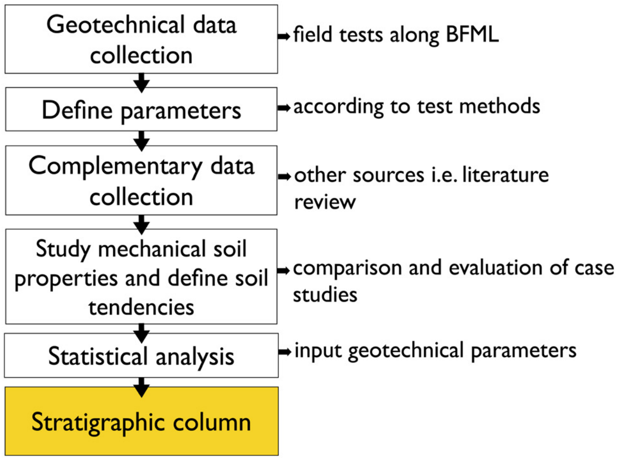


Figure 4. Statistical analysis process
Source: Authors

A statistical hypothesis is an assumption about a population parameter, which may or may not be true. Hypothesis testing is used to accept or reject a sample based on its consistency. There are two types of statistical hypotheses (null hypothesis H_o and alternative hypothesis H_1), as well as a region of acceptance α. For example, the hypothesis formulation used to analyze the values of the friction angle is described using the expression in Equation (1). Where μ can be equal to 35°, 32,5°, 30°, 25,5°, 24,5°, 23,5°, 22,5°, 17°, 16°, 15°, or 10° depending on the soil type to be tested, within a region of acceptance of 0,5°. The statistic used is described using Equation (2).

$$H\_o : \mu\_part = \mu \qquad H\_1 : \mu\_part \neq \mu \tag{1}$$

$$\frac{\bar{X} - \mu}{s / \sqrt{\eta}} \sim N(0,1) \tag{2}$$

To analyze the laboratory data obtained from each section of the alignment, a statistical model was built by means of confidence intervals and t-test hypotheses via the RStudio software. The essential soil parameters that describe the deformation characteristics, strength, initial state, plastic, and elastic behavior of soils were studied, *i.e.*, friction angle, Poisson ratio, cohesion, modulus of deformation, and unit weight of the soil. The total length of the first metro line was divided into four sections (Table 3). This study presents the results obtained for Section I after analyzing the data obtained from 81 boring tests and 67 piezocone penetrations.

Proposed tunnel design

An optimal design for a subway tunnel satisfies the construction safety, operation, and maintenance requirements with a cost-benefit analysis. A diameter of 6,5 m was used in this study, referencing Shanghai's subway tunnels. However, the final values shall be decided by the owner of the project. The authors proposed two single parallel tubes for the Bogotá subway system. The clearance distance between them is discussed below.

Groundwater levels: The average water level value was defined from data analysis of in situ measurements, and it was also verified with values found in the literature review (Consorcio L1, 2015). The groundwater table for Section I is shown in Figure 5.

Table 3. Proposed stations and sections along BML1's alignment.

Section	Station$_{i,f}$	Crossing road	$K_{i,f}$	Length (km)
I	Portal de las Américas – Avenida 68	Av. Villavicencio, Av. 1 mayo, Av. 68	0+000~6+667	6,667
II	Avenida 68 – San Victorino	Av. 68, 1 mayo, NQS, de la Hurta, Av. Caracas, Cra. 10	6+667~13+996	7,329
III	San Victorino – Lourdes station	Cra 10, Plaza la Rebeca, Cra.13 Plaza Lourdes, Cra.11	13+996~20+162	6,166
IV	Lourdes station – Calle 127	Cra. 11, Cra 9, Calle 127	20+162~27+064	6,902

Source: Consorcio L1 (2015)

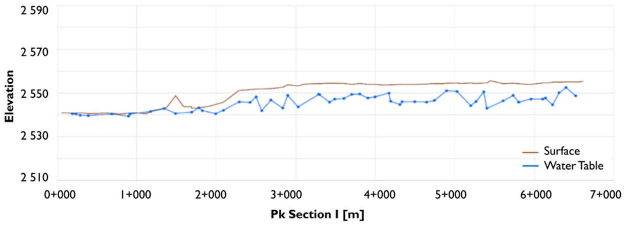


Figure 5. Water table for Section I
Source: Adapted from Consorcio L1 (2015)

Overburden: the ideal condition is to excavate throughout the most favorable strata. According to tunnel design guidelines (ITA, 1988), the overburden of shield tunnels shall be greater than 1,5-2 times the diameter of the shield machine. Two scenarios were modeled in order to compare the feasibility of subway construction based on studies about the prediction of surface settlements and parallel tunnels interaction (Hossaini *et al.*, 2012) (Table 4). This method can be used if i) the depth and tunnel diameter ratio is greater than 1,5, and ii) the distance between one tunnel center and the other is equal or greater to 1,3 D. The factors considered in each modeling scenario are the ratio of tunnel depth (z) and diameter (D), the clearance between parallel tunnels (center-center) d/D, and the water level.

Table 4. Description of scenarios used on the deterministic analysis

Section	Z_{crown} (m)	Z_{crown}/D	d (m)	d/D	Water level (m)
Scenario 1	16,25	2,5	22,80	3,5	-3
Scenario 2	13	2	16,22	2,5	-3

Source: Authors

Numerical analysis

Nowadays, almost every tunneling project requires numerical modeling in order to predict ground movement and behavior at ground surface in response to tunneling. PLAXIS 2D is one of the finite element programs that are commonly used in geotechnical applications to calculate deformations and stability. It considers both, construction and ground conditions (geometry, initial stresses, ground behavior, excavation stages, *etc.*). This software was available to compute the estimated ground response to tunnel excavation during this research. Both, settlement curves after excavation and the consolidation phenomenon were analyzed.

According to the conditions described below, the elastic-plastic MC model was used as a primary approach to calculate the settlements induced by tunneling for Section I. When soil parameters meet a sufficient condition, the results from the deterministic analysis are viable in terms of the inputs, which are good enough to make the outputs reliable. The excavation of two parallel shallow tunnels for the BML1 is expected from *Portal de las Américas* to *Primera de Mayo* (*Section 1*). It includes six stations with a total length of 6 667 m, mainly passing through stiff clay.

Lining inputs were selected according to the assumed tunnel diameter of 6,5 m. Six-plate elements of 0,35 m in thickness were connected to simulate one ring. Table 5 shows the properties of the segmental lining used for this model. The simulation in PLAXIS2D also allows for a staged construction mode by defining different calculation phases. In addition, time-dependent deformations can be calculated during consolidation. The calculation phases for this study were:

- *Phase 0*. Initial phase
- *Phase 1*. Excavation of the first tunnel (left side, referred to as LT) and lining installation.
- *Phase 2*. Excavation of the second tunnel (right side, referred to as RT) and lining installation.
- *Phase 3*. Consolidation analysis up to 365 days.

Table 5. Properties of tunnel lining

Property	Value	Unit
Thickness	0,35	m
Weight	8,40	kN/m/m
Flexural rigidity	1,43E5	kNm²/m
Normal stiffness	1,4E7	kN/m
Poisson ratio	0,15	-

Source: Authors

Results and discussion

Data obtained from the statistical analysis

The results obtained are of great value, not only for this research, but also for future studies on the behavior of Bogotá's soil. The values obtained to build the stratigraphic column of Section 1 (Table 6) were compared with data gathered from other projects in order to verify their reliability. These values were used as soil layer inputs of the numerical model (Figure 6).

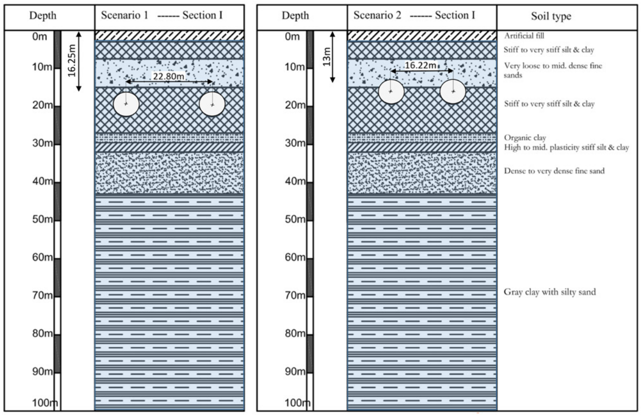


Figure 6. Illustration of modeling condition for Scenarios 1 and 2
Source: Authors.

Table 6. Soil parameters along Section I of the alignment

No.	Name of soil	Thickness [m]	Unit weight [kN/m3]	Modulus of deformation	μ Poisson ratio	Cohesion [kPa]	Angle of internal friction [°]
1	*Artificial fill*	3	17,64	18,24	0,1	0	25,00
2	*Stiff to very stiff silts and clays*	4,5	20,18	33,05	0,4	2	20,25
3	*Very loose to mid. dense fine sands*	7,5	18,14	52,26	0,3	0	33,00
4	*Stiff to very stiff silts and clays*	12	20,18	33,05	0,4	2	20,25
5	*Organic silt clay*	2,5	14,01	6,85	0,4	7	10,00
6	*High to mid. plasticity stiff silts and clays*	2,5	18,63	0,83	0,4	15	0,59
7	*Dense to very dense find sands*	11	19,5	97,27	0,3	0	33,47
8	*Grey clay with silty sands*	7,5	20,18	82,24	0,4	6	16,11

Source: Authors.

Numerical analysis

The soil values obtained were entered in the model, and the geometry of the mesh was built. The water table remains at -3 m (being the surface at 0 m) in both scenarios for Section I of the alignment. The geometry of the mesh also remains the same; only the position of the tunnel in the x- and y-directions changes for each scenario (Figure 7).

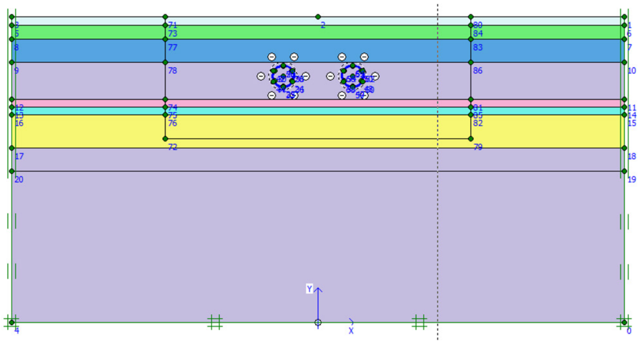


Figure 7. Mesh geometry and boundary conditions (Scenario 1)
Source: Authors

Vertical displacements: In the first scenario, the maximum surface settlement induced by the excavation of the two parallel tunnels is 8,96 mm. The excavation of the RT is expected to start once the construction of the LT has finished. Therefore, the immediate displacements will have already occurred, and they will have no influence on the excavation of the RT. The cumulative surface settlements induced by the excavation of both tunnels for Scenario 1 is estimated to be 8,96 mm. The heave of the surface is estimated to happen with a maximum value of 0,29 mm in a range of 40-50 m away from the tunnel axis in the x-direction (Figures 8 and 9).

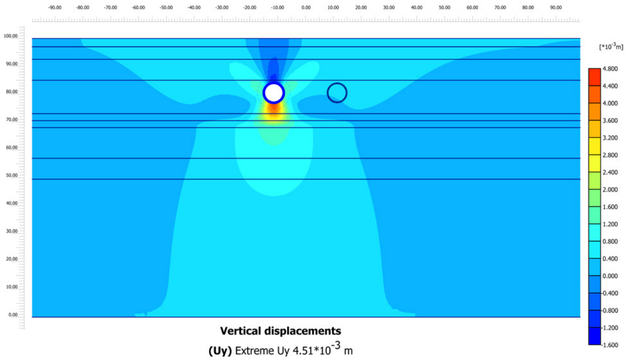


Figure 8. Vertical displacements induced by tunneling (Scenario 1 – Phase 1)
Source: Authors

The same procedure and assumptions were applied for Scenario 2. The maximum surface settlement estimated by the excavation of the two tunnels was 7,87 mm. The heave of the surface is a common phenomenon during tunneling, which is due to the stresses released from excavation. In this scenario, the maximum heave is greater than the one in Scenario 1, with a value of 0,53 mm. The soil moves upwards in a range of 0-40 m from side to side from the middle point of each tunnel, which, in the model, corresponds to the coordinates (x=0, y=100) (Figures 10 and 11).

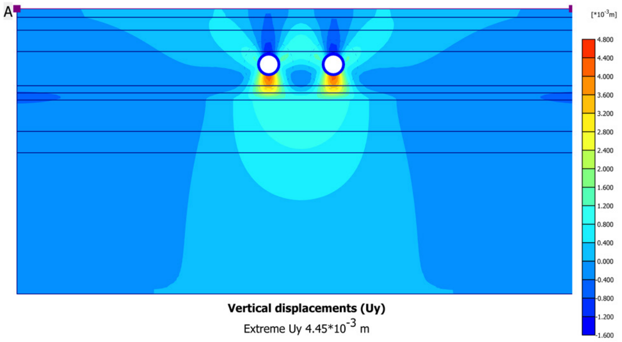


Figure 9. Vertical displacements induced by tunneling (Scenario 1 – Phase 2)
Source: Authors

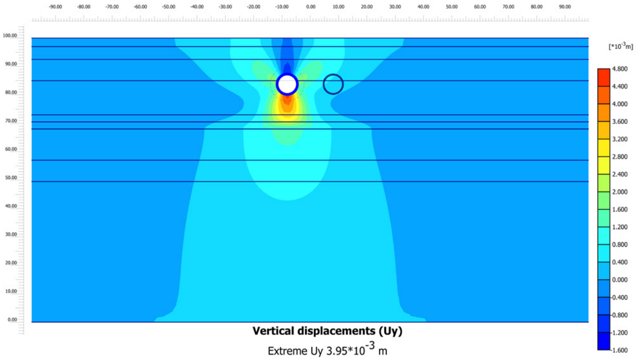


Figure 10. Vertical displacements induced by tunneling (Scenario 2 – Phase 1)
Source: Authors

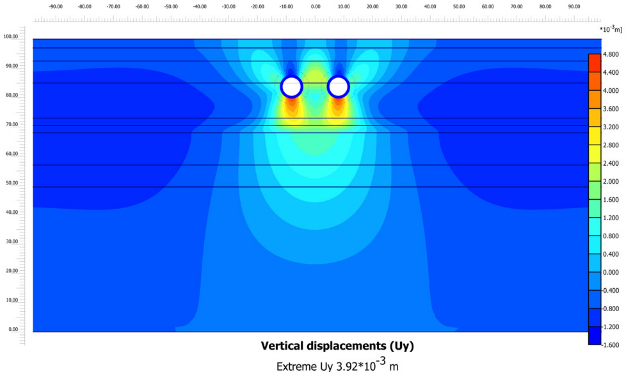


Figure 11. Vertical displacements induced by tunneling (Scenario 2 – Phase 2)
Source: Authors

Consolidation analysis: A consolidation analysis was performed (Phase 3) to evaluate the development or dissipation of pore pressures as a time function. This elastoplastic consolidation analysis was made possible by the features of PLAXIS2D. The maximum vertical displacement for Scenario 1 was 3,16 mm whereas the maximum value for Scenario 2 was 172,68 mm (Figure 12b).

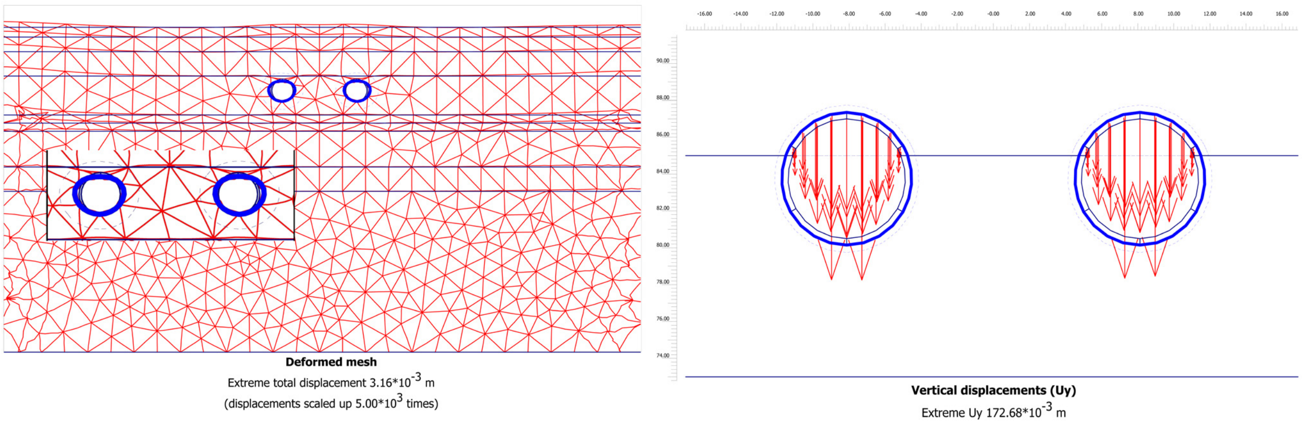


Figure 12. Consolidation analysis: a) deformed mesh for Scenario 1, and b) vertical displacements for Scenario 2
Source: Authors

Discussion

Surface settlements: The results show that the excavation depth of tunnels affects the deformation of the soil (Table 7). The heterogeneity of the subsurface plays a key role in the primary and secondary consolidation, so the behaviour of soils shall be carefully studied to choose an appropriate excavation depth. For example, in Scenario 1, the immediate settlements are slightly higher than those of Scenario 2, but the estimated secondary consolidation is significantly smaller than that of Scenario 2. This could be explained by the characteristics of the crossing layers: soft soils have low hydraulic conductivity, which means that consolidation processes in sands happen much faster than in clays.

Table 7. Surface settlements induced by excavation of metro tunnels for the BML1.

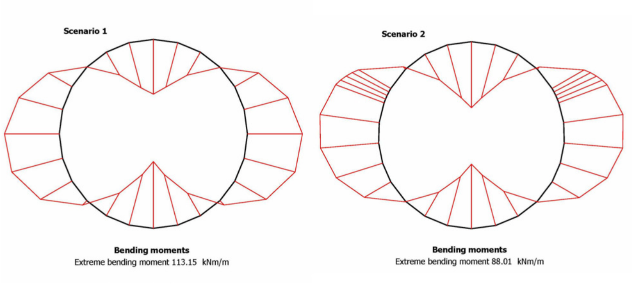
Scenario	Phase 1	Phase 2	Phase 3
1 (at -16,25 m)	4,51 mm	4,45 mm	3,16 mm
Cumulative settlements	4,51 mm	8,96 mm	***12,12 mm***
2 (at -13 m)	3,95 mm	3,92 mm	172,68 mm
Cumulative settlements	3,95 mm	7, 87 mm	***180,55 mm***

Source: Authors

Secondary consolidation: Although the consolidation values for Scenario 1 are lower, it is important to acknowledge that consolidation in clays will continue to happen over a long period. Secondary consolidation would mainly affect the settlement of the tunnel structure. Liao *et al*. (2011) and Cui *et al*. (2015) studied the cumulative settlement of Shanghai's Metro Line 1 during the 1995-2009 period. The maximum and minimum cumulative settlements were 287,8 mm and 5,8 mm, respectively, according to *in-situ* monitoring data of the Metro Line 1 in Shanghai (Cui *et al*., 2015). It is worth mentioning that the maximum allowed settlement value for construction of underground metro lines in Shanghai is 20 mm. There, the subsoil can also be characterized as low strength soft soil with friction angles in the range of 8,5-16,9°. Numerical analysis showed cumulative settlements lower than 10 mm induced by the excavation of two parallel tunnels at different depths and tunnel clearance. Thus, shield tunneling in Bogotá soil is viable.

Grant and Taylor (2000), Wilson *et al*. (2011), and Sahoo and Bibhash (2019) numerically and experimentally studied the support pressure of circular tunnels in cohesive soils and the effect of an overlying sand layers on the stability of tunnel excavation in the lower clay layer, as it is the case of the BML1. These studies can be used to decide the thickness and stiffness of the lining required to support the surrounding soil for the BML1.

Forces acting on the lining: The performance of the lining is considered as a whole system, whose ultimate goal is to provide an overall stability of the opening. As for the tunnels excavated in soft ground by shield machines, segmental lining should maintain the structural integrity of the excavation opening as the shield moves forward and minimize the immediate movement of the surrounding ground. Larger forces are expected to act on the lining for Scenario 1 because the overburden pressure is higher. These values can be considered for reference by engineers in order to determine the future design of the segmental lining of Bogotá's metro (Figures 13, 14, and 15).



Bending moments Max. value 113,15kN*m/m	**Bending moments** Max. value 88,01kN*m/m

Figure 13. Lining bending moments for Scenarios 1 and 2
Source: Authors

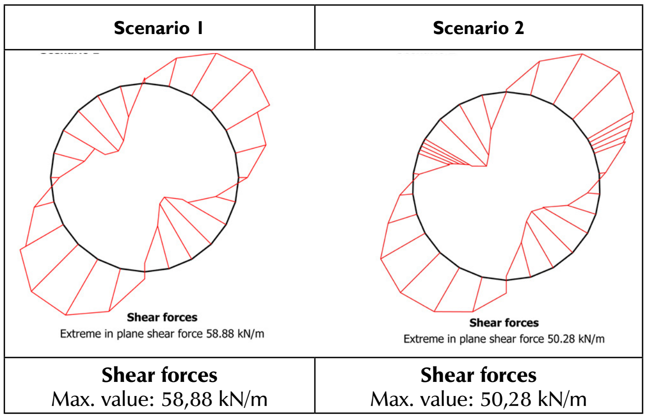


Figure 14. Lining shear forces for Scenarios 1 and 2
Source: Authors

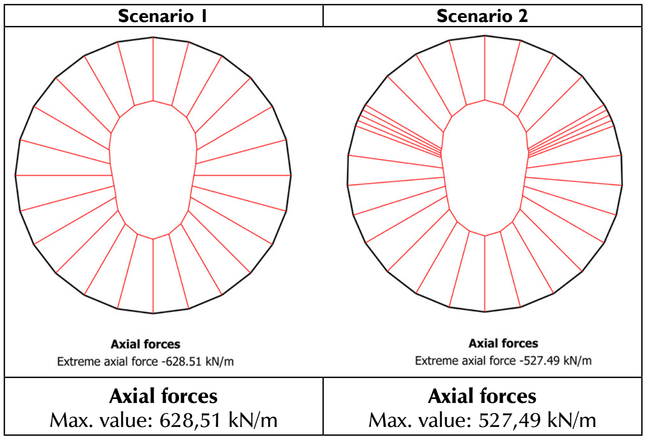


Figure 15. Axial forces acting on the lining for Scenarios 1 and 2
Source: Authors

Conclusions

The application of statistical analysis to define the soil characteristics of Bogotá's subsoil gave green light for the numerical analysis to estimate settlements induced by tunneling. An extensive analysis was performed to make use of the laboratory and *in situ* test results obtained in 2014, which resulted in the stratigraphic profile of the BML1's first 6,6 km. The numerical analysis showed cumulative settlements lower than 10 mm induced by the excavation of two parallel tunnels at different depths and tunnel clearance. Thus, shield tunneling in Bogotá soil is viable. As in Shanghai, the consolidation phenomenon shall be considered by the contractors of future metro tunnels in Bogotá, with sufficient long-term monitoring of settlements. Throughout the course of this research, the authors found valuable technical facts that can be used for future metro projects in Bogotá, Colombia.

Acknowledgements

The authors are grateful to the Statistics and the Civil Engineering Department of USTA University (Colombia) and the Tongji University's College of Civil Engineering for their financial support on the software needed to conduct this analysis. Thanks are owed to Germán Pardo for providing information, to Steven Zhou for proofreading this paper, and to the Colombian Institute of Urban Development (IDU) and Empresa Metro de Bogotá for making the data available for public use.

CRediT author statement

All authors: Conceptualization, methodology, validation, formal analysis, investigation, writing (original draft preparation, review, and editing), data curation, supervision, project administration, resources, and funding acquisition.

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