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Geological and geotechnical modeling for the organization and utilization of subsurface space in urban areas: an application to the São Paulo metropolitan area

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Technical Note

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Abstract

The demand for underground construction to support urban development is growing in major metropolitan centers worldwide. As Brazil's economic hub, São Paulo faces significant infrastructure challenges, prompting the need for expanded underground networks. Understanding the geotechnical characteristics of subsurface materials is therefore essential. In this context, three-dimensional geological modeling tools—widely adopted in the petroleum and mining industries—are increasingly relevant but remain underutilized in civil construction. In contrast, countries such as the United Kingdom and Finland have consistently applied 3D models to support urban tunneling, as seen in the London and Thames Valley projects. This paper presents a portion of a 16.8 km^2 3D geological and geotechnical model of the São Paulo Metropolitan Area—specifically for Metro Lines 3 and 4—developed using Leapfrog Geo software. The complete model is based on 703 borehole records provided by the São Paulo Metro Company (CMSP), characterizing the sedimentary basin in which the metro system is located. The software uses an implicit modeling method based on Radial Basis Functions (RBFs), similar to dual kriging. It supports continuous updates without the need for full re-interpretation, enhancing the planning and design of future subway lines. The study also outlines the benefits and challenges associated with the broader adoption of such tools for underground infrastructure projects. This initial model serves as the foundation for a growing geological and geotechnical database designed to support future tunneling initiatives in São Paulo and its surrounding metropolitan region.

1. Introduction

In 2022, the global population reached 8 billion people, more than three times the number in 1950. In this context, the demand for better living conditions drives the migration of rural populations to large cities, creating serious issues related to urban infrastructure (Campos et al., 2006, 2024a, b). The construction of access ways, parking facilities, road and pedestrian tunnels, water supply systems and metro networks aims to improve the quality of urban life by freeing surface areas for housing and recreational use. The challenge of enhancing urban infrastructure is an ongoing effort to address spatial constraints faced by major cities such as London, New York, Shanghai, São Paulo, and others.

The expansion of underground infrastructure networks (for water, sewage, transportation, etc.) can impact on the population and even pose risks during construction, particularly by limiting people's mobility. Therefore, it is essential to have a detailed understanding of the behavior of soils and rocks that support civil constructions to minimize these risks. Following examples of countries like the United Kingdom and Finland, the idea of generating 3D models of different soil and rock layers to assist in urban underground construction is both promising and overdue in Brazil.

Projects for São Paulo metro lines are a technical benchmark in Brazil. Tunnels have also been adopted for other types of infrastructure networks, generating subsurface information. However, this information has not been shared among different users. The primary objective of this article is to demonstrate the

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use of borehole profile data from sections of five metro lines to create an integrated 3D model using Leapfrog software. Part of this model is presented here. The model is intended to be a publicly accessible platform to be permanently updated with information from future projects, similar to previous successful initiatives in other countries, as previously mentioned.

This article aligns with the achievements recently published in Revista Engenharia in celebration of the 50th anniversary of the São Paulo Metro system (Alvarenga et al., 2024). The results presented are part of the research reported Alvarenga (2025).

2. São Paulo metropolis context

Historical records of underground constructions in Brazil indicate that such endeavors began in the second half of the 19th century. However, it was in the late 1960s that planning and construction activities for São Paulo underground metro culminated in the city's first metro line (Line 1), connecting neighborhoods from north to south (Celestino & Rocha, 2011). According to Bilfinger et al. (2012), various tunnels were constructed in São Paulo over the 20 years preceding their publication featuring projects with equivalent diameters exceeding 5 meters, utilizing Tunnel Boring Machines (TBMs) or the New Austrian Tunneling Method (NATM), also known as Sequential Excavation Method.

Underground construction has been active in São Paulo lately, mainly including tunnels for road and metro. Currently, São Paulo metro system is operated by private entities (Lines 4 and 5) and by the São Paulo Metro Company (Lines 1, 2, 3, and 15). As mentioned, the city has five underground (Line 3 partially underground) metro lines in operation, along with the ongoing construction of a sixth line, the Orange Line (Line 6), the expansion of existing lines (Lines 2 and 4), two elevated lines (Lines 17 and 15), and additional lines in the design phase (Line 19) (CMSP, 2023).

3. Material and methods

The database described here is based on 703 borehole logs from a total of 1,175 profiles provided by the Companhia do Metropolitano de São Paulo, covering six metro line projects within the São Paulo Metro system over an area of 16.8 km^2 (Figure 1). The modeling was conducted using

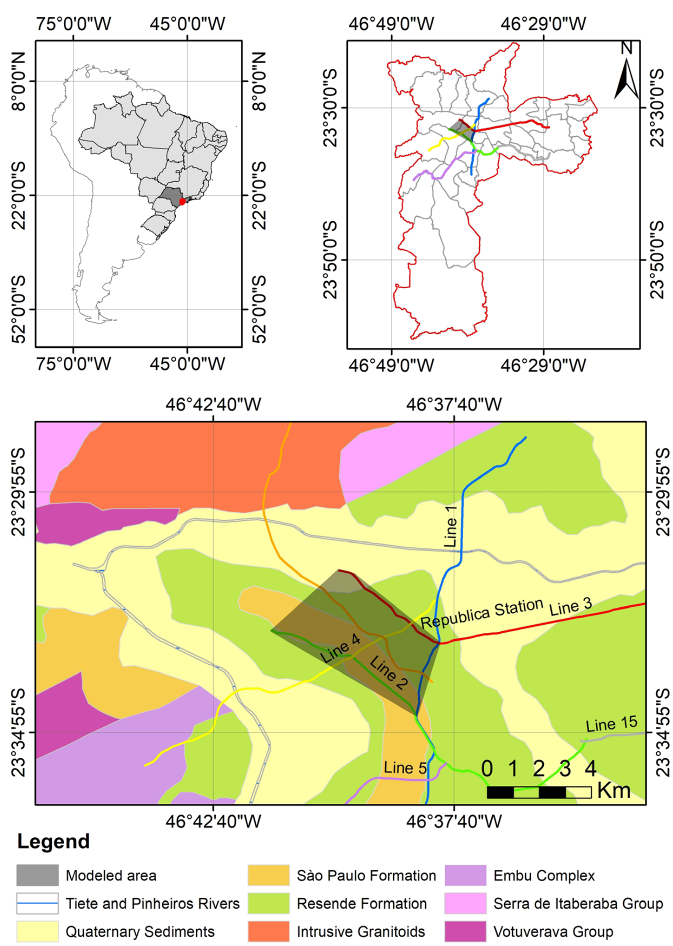

Figure 1. Modeled area (bottom) covering 16.8 km^2 within the city of São Paulo (top right, city boundary in red), located in southeastern Brazil.

Leapfrog Geo software, version 2023.2.3 (kindly provided by Seequent for academic purposes).

The construction of geo-objects in the software is based on an implicit method that uses finite approximations of surfaces, which exist only as mathematical representations within a volumetric function—hence the term "implicit" (Cowan et al., 2003). The software applies Radial Basis Functions (RBFs) for interpolation, which is grounded in the theory of regionalized variables on which kriging is also based (Stewart et al., 2014).

The dataset consists of scanned PDF logs dating from the 1960s—when the first metro line in São Paulo was designed—through to studies of Metro Line 6 in the 2010s. Each scanned log was carefully selected based on corrected geographic information (all data had to be located near the constructed metro lines; otherwise, it was discarded) and legibility (some scanned logs were impossible to read). All valid data were digitized using spreadsheet software, georeferenced to the SIRGAS datum, UTM Zone 23S, and interpreted according to the geotechnical profiles (Figure 2)

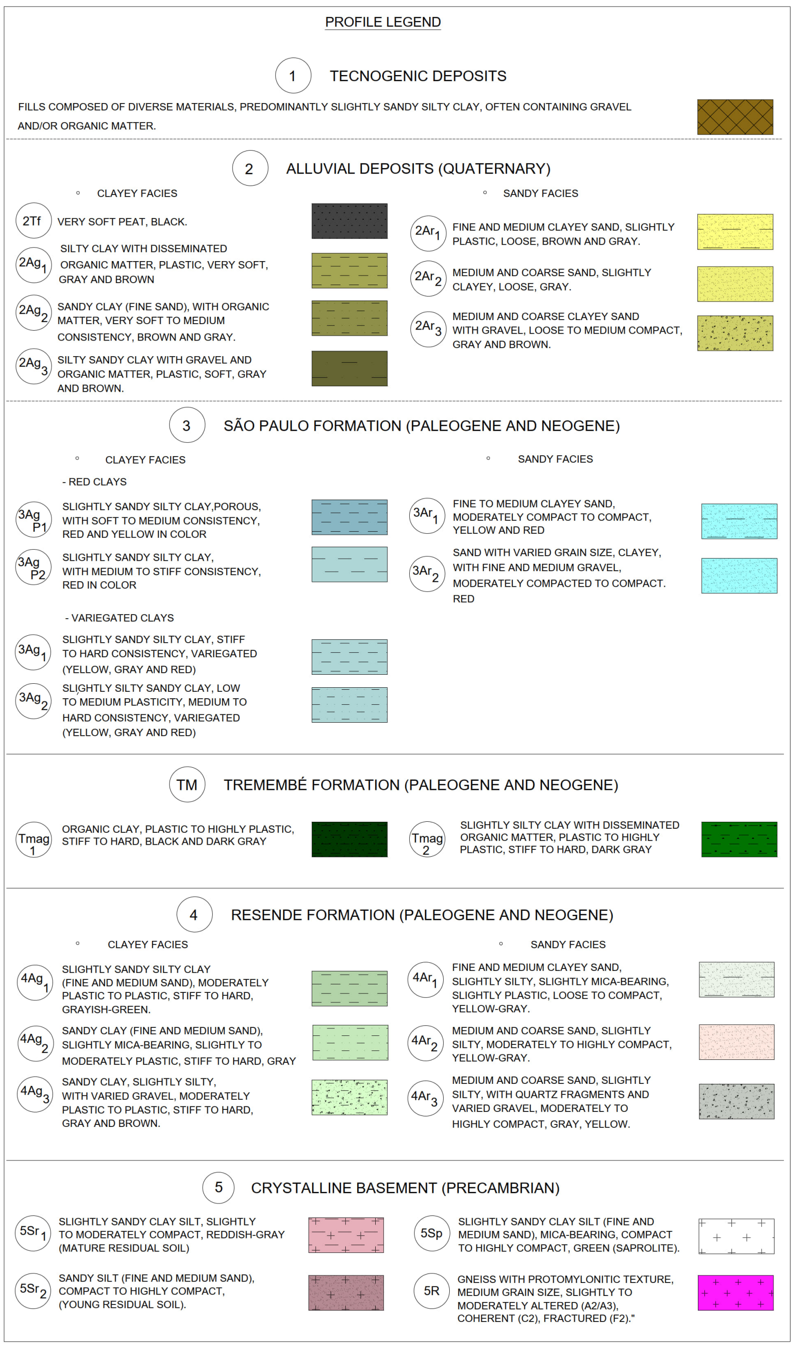

Figure 2. Geological and Geotechnical units of São Paulo's Basin (Modified after CMSP and Kutner & Bjornberg, 1997).

commonly used by the engineering community to describe the geology of the São Paulo Basin.

The Digital Elevation Model (DEM) was obtained from the GeoSampa website (São Paulo, 2023), an open-access city information platform, using LIDAR scans of a point cloud originally containing over 100 million points in a ca. 52 km^2 area, which was reduced to approximately 10 million points and interpolated using Civil 3D software.

The Technogenic, Alluvial, São Paulo, and Resende Formation deposits were modeled using deposit algorithms available in Leapfrog Geo, while the bedrock was generated using an intrusion algorithm. The geological facies within each deposit were refined with intrusion algorithms to create 'pancake'-shaped layers that mimic the typical intercalation of clay and sand facies commonly found in sedimentary basins. Geostatistical methods embedded within the intrusion algorithm were applied to prevent overestimation in areas distant from actual data points.

Although certain workflows still need to be better established for geological and geotechnical modeling to become routine practice in construction engineering (Monteiro et al., 2024), recent efforts, such as those by Miranda (2021), have leveraged geostatistical techniques to analyze geological and geotechnical data from the São Paulo basin, highlighting the potential for further advancements in this field.

4. Condensed history and applications of geomodeling in urban areas

Computational modeling for sedimentary basins began in the 1980s, initially focused on the hydrocarbon sector. Not until 1998, fully three-dimensional reservoir models became possible, though still limited by computational constraints (Hantschel & Kauerauf, 2009). The 2000s marked a turning point as improved software compatibility with personal computers lowered processing costs and expanded access to sectors such as civil construction (Kessler et al., 2008).

Urban geological modeling gained prominence in countries like the UK, where the British Geological Survey (BGS) developed 3D subsurface models for London and the Thames Valley (Ford et al., 2008; Mathers et al., 2014), environmental remediation projects in Glasgow (Entwisle et al., 2008; Monaghan et al., 2012), and geothermal-focused models in Cardiff (Kendall, 2015). In Finland, geological research has deep historical roots, with the Geological Survey of Finland (GTK) playing a leading role in managing national geodata and supporting mineral resource development (Haapala, 2005).

5. Geological model of São Paulo Metro lines 3 and 4

Alvarenga (2025) developed a 3D geological and geotechnical model based on percussion borehole profiles provided by CMSP, using Leapfrog Geo software. The complete model covers a portion of the city of São Paulo delineated by Lines 1, 2, 3, 4, and the preliminary design of Line 6. This paper presents two longitudinal sections: Line 3 (between Sé and Barra Funda stations) and Line 4 (between Paulista and República stations). In the presented segment, the nomenclature of the geological and geotechnical units follows the same system used in the metro projects of São Paulo, initially proposed by CMSP for Line 4 with contributions made by Kutner & Bjornberg (1997) as shown in Figure 2, and extended to subsequent designs for Lines 5 and 6. The geotechnical context is based on the Precambrian bedrock of granite-gneissic rocks, covered by Paleogenic and Neogenic sediments from the São Paulo Basin and unconsolidated Quaternary sediments.

Figure 3 shows a segment of the typical model in the vicinity of Line 3 of the São Paulo Metro. The data used in this model is derived from borehole profiles along Line 3 between Sé and Palmeiras-Barra Funda stations, as well as from Line 1 at its integration with Sé station and from Line 4 at its integration with República station.

The detailed 2D profile draws attention to the significant concentration of sands from the Resende Formation described in this region. Vargas (1992) and Feliciani (1989) characterize these occurrences as typical examples of the so-called 'basal sands'. Rocha (1995) analyzed samples collected from the locations described by Vargas, concluding that sands from the Anhangabaú Valley exhibit a narrower grain size distribution and are classified as pure sands, whereas those from Praça da República contain higher levels of silt and clay, classifying them as silty or clayey sands.

Figure 4 shows a segment of the 3D model in the vicinity of Consolação Street, based on borehole data from Line 4 of the São Paulo Metro. Under Paulista station, deposits of porous red clays ($3AgP_1$ and $3AgP_2$) with an average thickness of 10 meters predominate around elevation 800 along the Paulista Avenue ridge axis. The contact between the São Paulo and Resende Formations occurs between elevations 750 and 740 m, with crystalline basement rocks also described near elevation 740 m beneath Higienópolis-Mackenzie station.

It is important to note the process of collecting borehole profile data spanning different time periods. Borehole profiles of Line 1 (from the late 1960s) and Line 2 (from the 1970s and 1980s), allow for relatively easy interpretation, including the recognition and distinction of sediment layers from the São Paulo and Resende Formations. These distinctions began to be widely developed in the technical field, particularly in Metro projects from the 1990s (Lines 4 and 5), with major contributions from Riccomini (1989), Riccomini & Coimbra (1992), Rocha (1995), Kutner & Bjornberg (1997), Monteiro et al. (2013) and Gurgueira (2013).

6. Proposed geotechnical model

In addition to the importance of digitizing data (borehole profiles, geophysical information, etc.) for the creation of

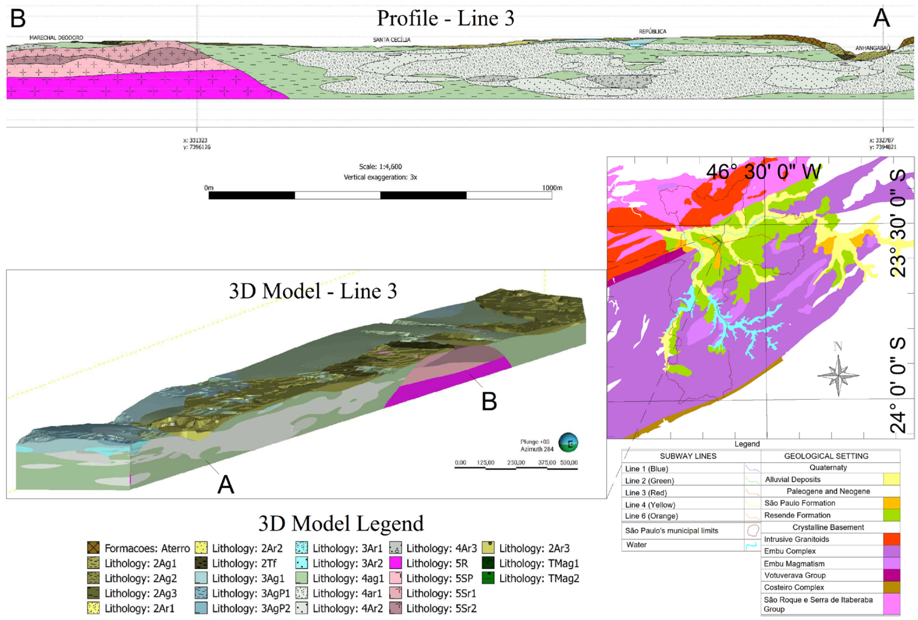

Figure 3. Model developed for Line 3 of the São Paulo Metro; at the top: segment of the model line between Marechal Deodoro and Anhangabaú stations; bottom left: a 3D longitudinal section; lower right: the geological setting, subway lines and city boundaries.

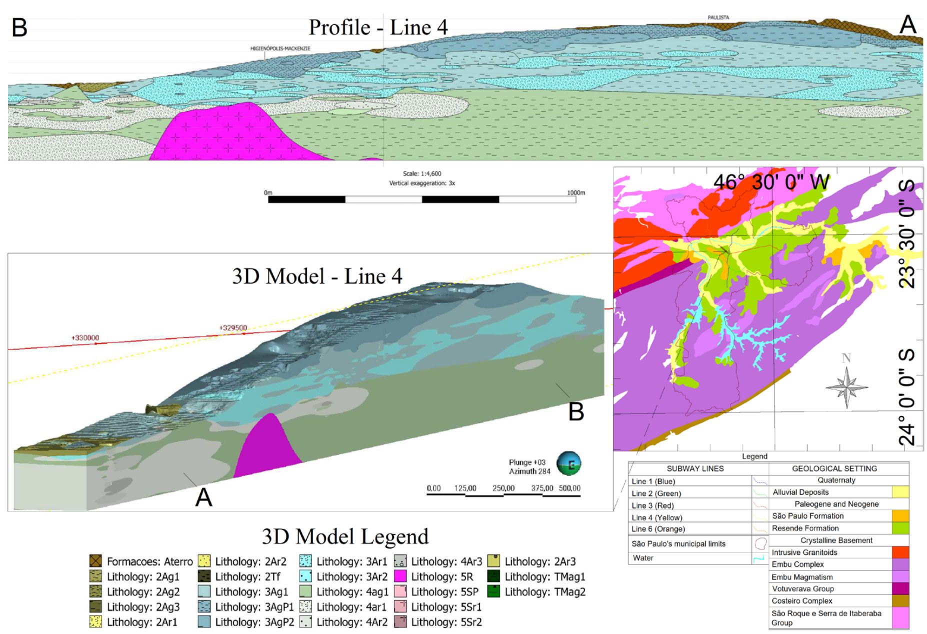

Figure 4. Model developed for Line 4 of the São Paulo Metro: at the top, the segment of the modeled line between Higienópolis and Paulista stations; bottom left, a 3D longitudinal section; lower right, the geological setting, subway lines and city boundaries.

geological models, data related to material strength (SPT, CPTu, etc.) can also be incorporated into the models. The data can be compared to classifications available in the literature (e.g. ABNT, 2020) about the states of compactness and consistency of sands and clays.

A material resistance model based on Standard Penetration Test (SPT) sampler is proposed for Lines 3 and 4 (Figure 5). The relative density of sands and the consistency of clays (predominant materials in sediments and weathering products of rocks) provide a better understanding of the expected

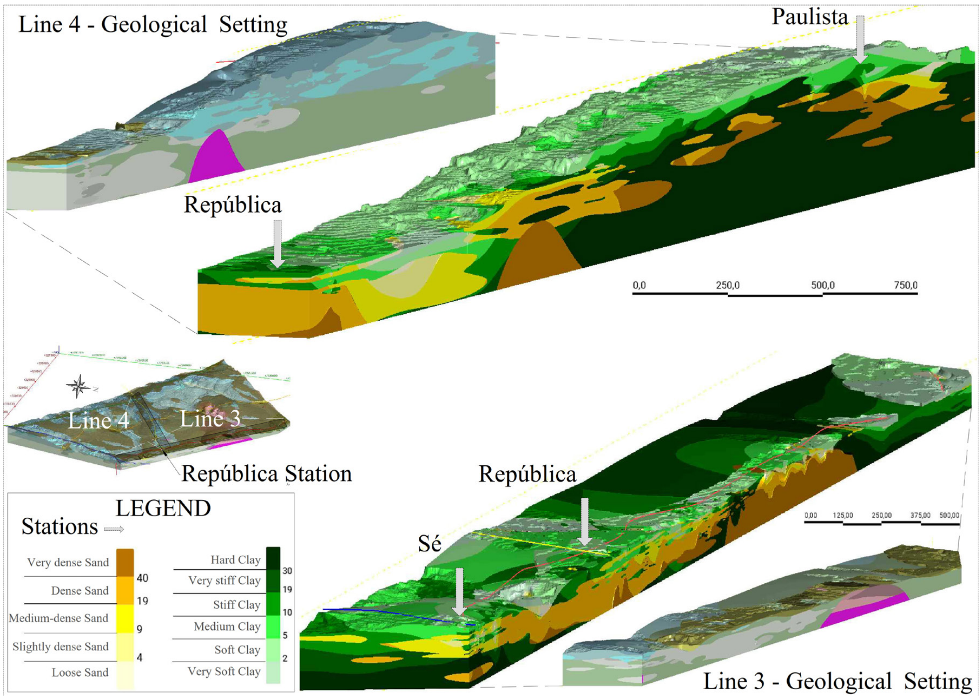

Figure 5. Geotechnical models of Lines 3 (bottom) and 4 (top).

behavior at depth. This model represents a more valuable piece of information when considering the behavior of a structure supported by such materials.

7. Conclusion

For the development of underground structure projects, subsurface 3-dimensional modeling has been showing a highly promising and fast processing instrument, particularly as it is already an established tool in the petroleum and mining industries. However, the use of the tool for shallow lithological covers and widely spaced data remains a challenge.

As observed in the geotechnical models of São Paulo Metro Line 3 and Line 4, a concentration of medium to loose sand beneath the area between Higienópolis-Mackenzie and República stations may pose a significant challenge to subsurface excavations. The high concentration of sand identified in the geological profiles of Lines 3 and 4 serves as a warning for the need for more detailed investigations in these regions.

There is a notable lack of studies focused on 3D modeling for civil construction in the city of São Paulo, particularly when compared to advancements in the mining industry and subsurface modeling in metropolitan areas (e.g. United Kingdom and Finland). While 3D models in São Paulo remain underdeveloped, thousands of investigations performed for urban infrastructure projects (such as bridges and buildings) represent a valuable resource for establishing a robust geological and geotechnical database. However, these data are often lost. In its current stage of development, the model is still limited for planning future underground works due to the lack of spatially comprehensive data. For geological and geotechnical modeling to become a routine practice in construction engineering, it is essential to further establish and refine certain workflows. The standardization and digitization of lithological investigation data, along with its maintenance in a database managed by public authorities or concessionaires, as done in Finland, will significantly increase the amount of information available for creating increasingly accurate and detailed models.

The 3D subsurface model developed will allow for continuous updates with the inclusion of information from new boreholes, aiming to enhance the detailing of the ground mass three-dimensional composition. Interpolation tools are available for practically any type of geological environment. The findings of this study will serve as a foundation for future regional projects, including underground constructions and building foundations.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

João Paulo Mantovani Alvarenga: data digitization and interpretation, modeling, visualization, writing – original draft, software acquisition. Wilson Shoji Iyomasa: data interpretation and supervision, visualization, formal analysis, validation, writing – review & editing. Tarcísio B. Celestino: conceptualization, methodology, research supervision, validation, formal analysis, funding acquisition. Marcelo Denser Monteiro: data curation, interpretation, supervision, validation, resources.

Data availability

Data generated and analyzed in the course of the current study is not publicly available due to company data sharing policy, but a complete or limited dataset can be made available by CMSP upon formal request.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) ChatGPT and Claude with the aim of misspelling checking and proofreading. The entire process of using this tool was supervised, reviewed and when necessary, edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

BGS	British Geological Survey
CMSP	São Paulo Metro Company
DEM	Digital Elevation Model
GTK	Geological Survey of Finland
NATM	New Austrian Tunneling Method
RBF	Radial Basis Function
SPT	Standard Penetration Test
TBM	Tunnel Boring Machines

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