Anuário do Instituto de Geociências
Universidade Federal do Rio de Janeiro
https://revistas.ufrj.br/index.php/aigeo/

ISSN 0101-9759
e-ISSN 1982-3908

Construction of Buildings in Soft Clay Deposits: A Case Study in a Public School in Florianópolis/SC, Brazil

Construção de Edificações em Depósitos de Argila Mole: um Estudo de Caso em Escola Pública de Florianópolis/SC, Brasil

João André Martins[1], Lélia Santiago Custódio da Silva[1] & Fábio Effting Silva[2]

[1]Universidade de Campinas, Departamento de Geologia e Recursos Naturais, Campinas, SP, Brasil
[2]Universidade de Santa Catarina, Departamento de Geologia, Campinas, SP, Brasil

E-mails: joaoandregaropaba@hotmail.com; leliacustodiodasilva@gmail.com; fabio.effting@gmail.com
Corresponding author: João André Martins; joaoandregaropaba

Abstract

The gradual increase in the risks of constructions without structural planning in hillside areas characterizes the expansion of urbanization in Brazil. In this process of territorial occupation, constructions on soft clay soils represent significant structural hazards. This study aimed to evaluate structural instabilities in a public school in Florianópolis (SC, Brazil), using integrated geology, geotechnics, and geophysics data. This is a case study in an area characterized by the urbanization process of the West Side of the Costeira do Pirajubaé Massif. Geologically, the study area is composed of granitic rocks, soft clay deposits, and colluvial soils, in an environment of the upper third to the middle of the slope. For data analysis, geophysical, geotechnical, and geological methods were used. In the results, it was identified upstream colluvium, evidenced by the wide variety of soils (sandy, yellowish silt clay, of medium consistency), as well as gray clay deposits, ranging from very soft to hard, with distinct characteristics of the residual soils of the granitoid downstream, which are normally medium consistency brown to yellowish clays, expected for the B horizon. The results indicate a potential slip surface, which corresponds to a layer of soft clay deposits. Thus, it can be concluded that the observed instabilities, characterized by footing displacement, cracks, and subsidence demonstrate subsoil fragilities related to human interventions and the insufficiency of the drainage system, even when existing.

Keywords: Urbanization; Slope; Colluvium

Resumo

O aumento gradativo dos riscos de construções sem planejamento estrutural em áreas de encostas caracteriza a expansão da urbanização no Brasil. Nesse processo de ocupação territorial, as construções em solos de argila mole representam perigos estruturais significativos. Este estudo teve como objetivo avaliar as instabilidades estruturais em uma escola pública de Florianópolis (SC, Brasil), a partir de dados integrados de geologia, geotecnia e geofísica. Trata-se de um estudo de caso em uma área caracterizada pelo processo de urbanização da Vertente Oeste do Maciço da Costeira do Pirajubáe. Geologicamente, a área de estudo é composta por rochas graníticas, depósitos de argilas moles e solos coluvionares, em ambiente de terço superior a médio de encosta. Para a análise dos dados, os métodos geofísicos, geotécnicos e geológicos foram usados. Nos resultados, identificamos um colúvio a montante, evidenciado pela ampla variedade de solos (argila siltico arenosa, amarelada, de consistência média), bem como depósitos de argila cinza, variando de muito mole a rija, com características distintas dos solos residuais dos granitoides a jusante, que é normalmente uma argila marrom a amarelada de consistência média, esperados para o horizonte B. Os resultados apontam que existe uma superfície potencial de escorregamento, que corresponde a camada de depósitos de argila mole. Dessa forma, pode ser concluído que as instabilidades observadas, caracterizadas por deslocamento de sapata, rachaduras, trincas e subsidências demonstram fragilidades do subsolo em relação as intervenções antrópicas e a insuficiência do sistema de drenagem, mesmo quando existente.

Palavras-chave: Urbanização; Encosta; Colúvio.

Received: 07 May 2022; Accepted: 29 September 2023

1 Introduction

In Brazil, the increase in the urbanization rate tends to favor the occupation of risk areas. This is because, during its constitutive process, increasing urbanization involves risks and dangers arising from the difficult relationship between the production of urban space and natural systems (Marandola Jr et al. 2013). However, the problem with urbanization is its disorderly occurrence (Grostein 2001) and its uneven territorial distribution (Ojima 2013). Therefore, urbanization has an intense impact on the process of territorial occupation, the result of which is the gradual increase in the risks of constructions without structural planning.

The occupations located on urban slopes represent areas of geological risk, due to recurrent slope slides (Faria 2011). For Marandola Jr et al. (2013), there is a strong relationship between urbanization and risk, since urban sprawl, unconnected with the effects of natural systems, tend to extend over unstable areas, such as slopes and valley bottoms. Dai et al. (2002) argue that as areas on unstable slopes are occupied under the pressure of increasing urbanization, human activities become important triggers for the occurrence of landslides. In this territorial mismatch, the danger of urban settlements, together with the access and economically unequal occupation of urban territory, causes profound transformations in urban centers. This situation is further aggravated by the accentuated occupation of unfavorable soils for construction.

The distribution and quality of buildings constructed in urban areas are indicators of disaster risk (Cui et al. 2019). For Cardona et al. (2012), disaster risk has different levels and effects, with catastrophic levels related to major disasters. However, small-scale disasters are more frequent, although often neglected (Velásquez et al. 2014). Although ignored, small-scale disasters are frequent and represent a significant cost expense (Marulanda, Llera & Cardona 2022). Consequently, governments must be aware of the cumulative effect of small disasters on society (Velásquez et al. 2014).

Within this context, constructions on soft clay soils pose significant structural hazards. Buildings built on clay soils tend to be subjected to intense, non-uniform movements of soil moisture, which cause cracks in their structures (Li, Cameron & Ren 2014; Kamal, Inel & Cayci 2022). Therefore, the degree of soil stability seriously compromises the structural safety of buildings (Zhang et al. 2018).

To assess soil behavior, the combination of geological, geotechnical, and geophysical data makes it possible to determine the depth of the instability zone and its lateral extent (Mezerreg et al. 2019). Geophysical methods are effective in characterizing landslides (Lissak et al. 2014; Mezerreg et al. 2019; Pasierb, Grodecki & Gwóźdź 2019). Furthermore, among the existing geophysical methods, electroresistivity (ER) stands out, which is frequently applied in the determination of geological strata. The technique allows for the investigation of the subsoil indirectly, without the need for sampling or direct reconnaissance (Lago, Elis & Giacheti 2006). However, although geoelectrical and geotechnical parameters can provide information on soil water content, few studies have sought to associate these parameters in recent decades (Friedel, Thielen & Springman 2006; De Vita et al. 2012; Piegari & Di Maio 2013; Uhlemann et al. 2017; Crawford & Bryson 2018; Mezerreg et al. 2019; Di Maio et al. 2020). Finally, the integrated analysis of geological, geotechnical, and geophysical factors offers insights into the mechanisms that cause landslides (Di Maio et al. 2020). Thus, the objective of this article is to evaluate the structural instabilities in a public school in Florianópolis (SC, Brazil), based on integrated geology, geotechnics, and geophysics data.

In the present study, it is considered as a case study the structural condition of a public school (Anísio Teixeira Municipal School – ATMS) in the West Side region of the Costeira do Pirajubaé Massif, in Florianópolis/SC. The school is situated on a steep and densely urbanized slope. In 2019, beams and column breakages were found in classrooms and bathrooms at the school, which showed risk in its structure. From these data, it became relevant to develop a structural analysis of the school, through geological, geotechnical, and geophysical assessments.

The municipality of Florianópolis is a dense urban agglomeration, which integrates the Santa Catarina mesoregion (IPEA 2000). The urbanization process of the West Side of the Costeira do Pirajubáe Massif was associated with disorderly growth, referring to the construction of irregular housing and the degradation of the physical environment, which contributed to the emergence of geological risk areas (Martins 2021). The West Side of the Costeira do Pirajubaé Massif corresponds to another Brazilian region, characterized by sub-habitations and urban disorder, in addition to a lack of technique in the construction of housing.

Understanding risks is a necessary process and an early stage for risk management (Carreño et al. 2017). Studies that seek to identify or map these areas in detail are of great importance for the prediction of events and the adoption of public measures of territorial organization. These territorial policies are possible through a contextualized analysis of the production of urban-regional space and the geography of risks, at different scales (Marandola Jr et al. 2013; Andriamamonjisoa & Hubert-Ferrari 2019; Ali & Shakir 2022; Kokkala & Marinos 2022). In such a way that the knowledge of the patterns of urban buildings must be integrated into the environmental planning of the Municipality. There are some previous studies that evaluated pathologies and risks on buildings in Santa Catarina's coast (Dal-Bó & Soares 2020; Reichert & Noda 2020; Guckert & Schons 2021), however none of them considered the integration between geological and geotechnical data.

2 Study Area

The study area is located in southern Brazil, in the municipality of Florianópolis, in the state of Santa Catarina (Figure 1). This region is known as the West Side of the Costeira do Pirajubaé Massif (Pereira 2018). The investigated area corresponds to the Anísio Teixeira Municipal School (27º38'00''S, 48º31'20''W), located at Rua João Câncio Jaques, in the Costeira do Pirajubaé neighborhood. The institution was an educational space frequented by more than 400 students, which was interdicted in 2019, after evidence of cracks in its structure.

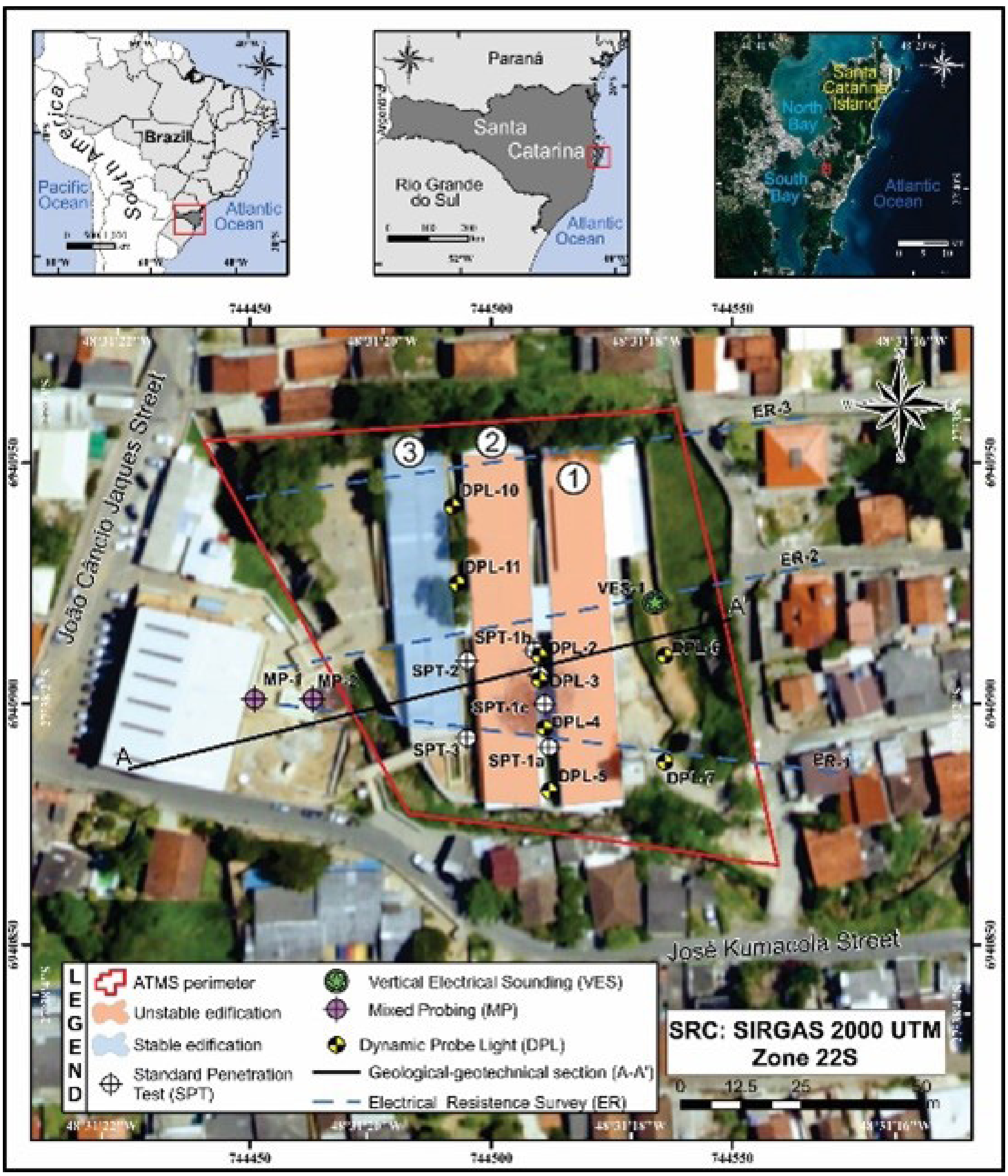

Figure 1 Location map of the study area and geotechnical and geophysical investigation points.

3 Methodology

The study was carried out within a proposal of integrated application of geological, geotechnical, and geophysical data. In field inspections, it was carried out surveys on geological aspects, as well as identify the main types of human interventions in the area, such as cuts, landfills, garbage disposal, pits and drainage system (sewage and rainwater), deforestation, cracks, and water surges. In the field inspections, it was also defined the main contacts of each geotechnical unit.

For drilling and geophysical analysis, it was performed the SPT (Standard Penetration Test), DPL (Dynamic Probe Light), MP (Mixed Probing), Electrical Resistence Surveys (ER), and Vertical Electrical Surveys (VES) (Figure 1).

The SPT corresponded to the dynamic driving of the sampler with a cutting shoe tip, performed concomitantly with the advance by auger every meter drilled. The SPTs were developed aiming at the acquisition in the field of a soil resistance measure (N) and quick characterization of soils, according to the NBR 6484 and ABGE (1999) standards.

The DPL also corresponded to a piece of equipment used to acquire a soil resistance measure (N10) in the field. According to Martins (2021), the equipment consists of a guide rod, in which a weight with a mass of 10 kg, moves in free fall along a standard height of 50 cm. The rods had an external diameter of 22 mm and a length of 1.0 m, being graduated every 10 cm to facilitate the reading of their penetration. The energy transmitted by each blow of the weight was 50 J, considering the total efficiency of the equipment. The drilling process involves the 10 kg load to be lifted, to fall in a free fall of 50 cm, to the upper portion of the rods. The recording of the number of blows necessary for driving 10 cm defined the standard penetrometric index, generically called N10, for the records obtained with the tip of 10 cm² and NDPL-5 for those obtained with the cone of 5 cm². These records were plotted on graphs, showing the penetration required for the penetration of every 10 cm of the composition or cumulatively.

The ESs were plotted in the direction of the slope dip, passing through the school facilities and the existing stream in the area. The VES was located in the topographically higher back portion. For the study, it was also considered 2D electrical imaging. This is because 2D electrical imaging contributes to the definition of the different soils that occur along the profile, providing a (partial) profile/section view of the area (Whiteley et al. 2019). All ESs had a Dipole-Dipole Arrangement and 5.0 m spacing with up to 15 investigation levels (up to approximately 20.0 m depth). EW interpretations were performed using the RES 2D INV software. In the VES, it was sought to recognize the thickness of the soil and its probable formation, as well as the rock depth and the presence of underground water. For VES, the arrangement used was the Schlumberger, with a maximum AB of 80m, reaching a depth of 20 m (¼ of AB).

Finally, it was developed the geotechnical profile, arranged in the study area as shown in Figure 1, based on the topographic survey, drilling data, and geophysics. In this way, it was defined the depths and characteristics of the soils of each layer.

4 Geological Setting

The study area is located in the Dom Feliciano Belt, dominated by associations of granitic rocks arranged in a NE direction strip that extends from Santa Catarina to Uruguay, designated Batólito Pelotas in the Sul-Rio-Grandense Shield, Aiguá Batholith in the Uruguayan Shield and Florianópolis batholith in the Santa Catarina Shield (Bitencourt et al. 2008). The latter is restricted to the state of Santa Catarina. This strip comprises successive granitic pulses, often linked to mantle activity in the form of mafic microgranular enclaves, synplutonic dykes, as well as synchronous diorite and gabbroic bodies.

Bitencourt et al. (2008) emphasize that Plutonic magmatism is closely associated with transpressive tectonics at the end of the Brasiliano Cycle, being interpreted in the typical post-collision environment by Bitencourt and Nardi (1993, 2000) and Bitencourt et al. (2008). Alternatively, the Florianópolis Batholith is interpreted as part of an ensialic orogenic belt (Basei 1985) or as a magmatic arc root (Basei 2000; Corrêa 2016).

The Florianópolis batholith can be divided into four units: Águas Mornas Suite, São Pedro de Alcântara Suite, Pedras Grandes Suite and Cambirela Suite. Santa Catarina Island presents exposures of these units, being the Pedras Grandes Suite (SPG), represented in the study area by the Ilha and Itacorubi Granites, as can be identified in Figure 2. For Corrêa (2016), these granitoids represent high-K calc-alkaline magmatism and the main formation mechanism for such rocks is the crustal reworking of materials extracted in the middle and deep levels of the crust. However, for Tomazzoli and Pellerin (2015), Colluvial-Alluvial Deposits occur in the study area (Figure 2).

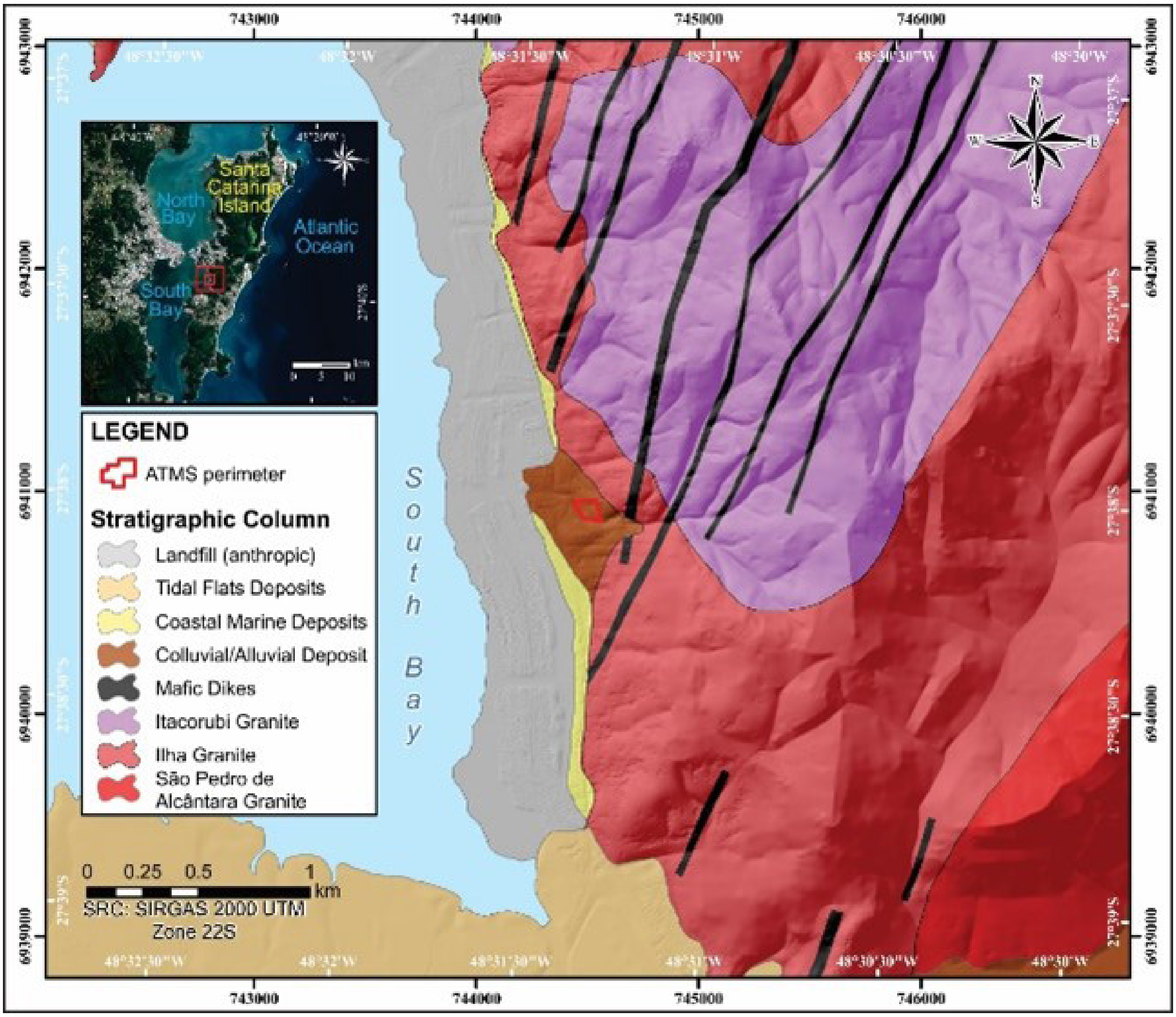

Figure 2 Geological context of the study area. Adapted of Tomazzoli & Pellerin (2015).

5 Results e Discussion

5.1 Field Geology

From the data collected, in the study area, it is observed the occurrence of colluvial deposits. It is verified the presence of rocky outcrops, in the form of blocks/boulders, upstream of the study area, and downstream, as slabs, blocks, and boulders. The area is located in a hillside environment (middle to lower third) with cuts and landfills resulting from human occupation, such as the construction of the school (Figure 3). In the upstream area, there is disorderly growth and housing with little construction technique (Figure 4). The occupation of this slope follows an Azorean pattern with roads perpendicular to the contour lines.

It is also identified degradation of Permanent Preservation Areas – PPA, involving the suppression of native protective vegetation or even the dumping of sewage into water courses associated with the sources of the Itacorubi Granite. The watercourse intercepts the studied area in the SE-NW direction, runs in the open (Figure 4D), and has a bed of blocks/boulders with concreted margins (Figure 4B).

There are not efficient drainage systems in human interventions, nor efficient works to contain slopes. It is observed stone walls in some cuts made without an associated drainage system, some of them with the presence of water pouring (Figure 4B).

Figure 3 Anísio Teixeira Municipal School (ATMS - study area) inserted in the middle to lower third of the slope: A. Water tank and classrooms; B-C. Cuts and landfills resulting from human occupation with the aim of building the School; D. Walkway over the watercourse.

Figure 4 Drainage and slope containment works are inefficient: A. Stonewall in some cuts made without associated drainage system; B. Stone wall with the presence of water pouring; C-D. Masonry wall without an associated drainage system.

5.2 Characterization of Instabilities

The ATMS has three classroom blocks distributed on the steep slope (Figure 1). In only two of them (1 and 2), the one upstream (Figure 5) and in the central portion (Figure 6), it is observed several cracks and fissures, as well as a possible rupture in the sidewalk located between the two aforementioned blocks (Figure 7 A-B) and the inclined trees (Figure 7 C-D).

Another extremely serious finding is an excavation of approximately 2 meters, carried out next to a foundation pillar inside the classroom of the block that showed deterioration (Figure 8). In the area, it is noticed an empty space between the footing and the starting column, with no presence of water in this location, which is configured as the displacement of the footing (Figure 8D).

At the same level as the buildings that showed great deterioration of the structure (20 m), in an area close to the school, it is identified cracks with millimeter to centimeter openings. Downstream of the buildings, there aren't any cracks, fissures, wall blockage, inclined poles, and/or significant water surges.

5.3 SPT Sounding

It was analyzed the Standard Penetration Tests called SPT-1, SPT-1A, SPT-1B, and SPT-1C, at 21 m (Figure 1), upstream of the central classroom block (2) that presented the cracks.

In SPT-1, it is observed a predominance of 0.70 m fill material, followed by a sandy, yellowish silt clay, with an average consistency of up to 1.5 m. From this depth, it is identified the predominance of gray clay, ranging from very soft to medium, up to normally 3.5 m. From 3.5 m, up to 4 m (impenetrable to percussion), it is found gray clay with gravel. The survey did not reach the water level.

In SPT-1A, it is identified a predominance of 0.70 m fill material, followed by a sandy, yellowish silty clay, with an average consistency of up to 1.7 m. From this depth, it is observed a predominance of gray clay, ranging from very soft to hard, up to normally 3.5 m. From 3.5 m to 4.8 m (impenetrable to percussion), it is possible to identified a yellowish clay with gravel. The survey did not reach the water level.

Figure 5 Upstream block (1) of Anísio Teixeira School: A. Inclined crack with a thickness of 0.5 mm; B. Horizontal crack with a thickness of 0.7 mm; C. Horizontal crack with a thickness of 0.4 mm; D. Inclined crack with a thickness of 0.6 mm.

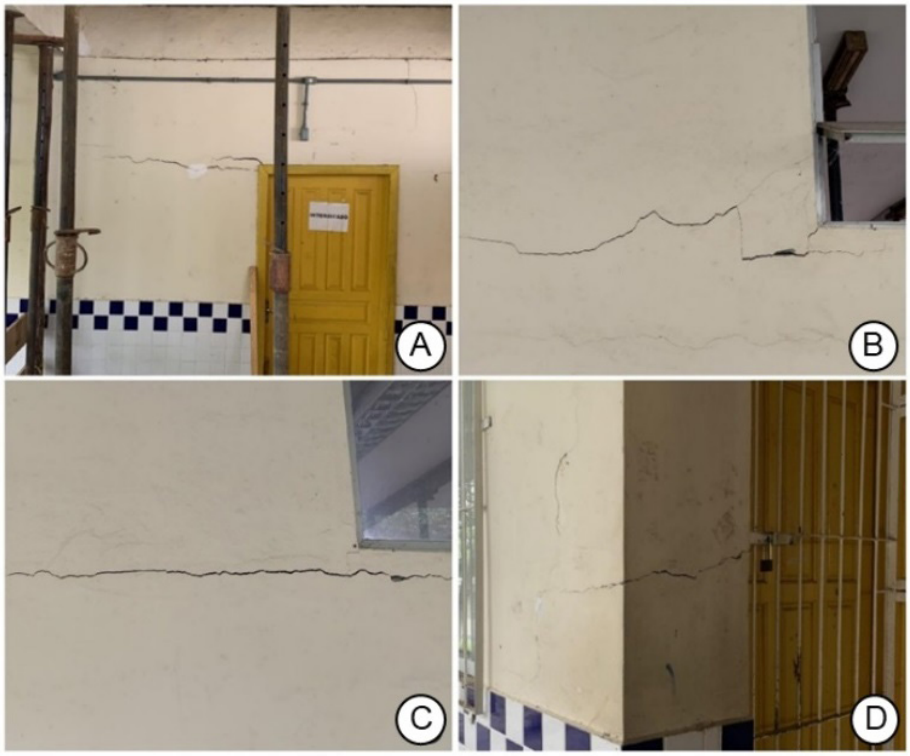

Figure 6 Central block (2) of Anísio Teixeira School: A. Horizontal crack with a thickness of 0.7 mm near the door; B-C. Horizontal crack with a thickness of 0.6 mm near one of the windows; D. Horizontal cracks with a thickness 0.7 mm close to a door.

Figure 7 Space between the most upstream and central block (1-2) of the Anísio Teixeira School: A-B. Sidewalk located in front of this classroom showing a possible rupture; C-D. Leaning trees showing a possible rupture.

Figure 8 Central block (2) of the Anísio Teixeira School: A-B. Several longitudinal cracks in the sidewalk located in front of this classroom show a possible rupture; C. Shoring throughout the classroom, allowing the evaluation of the severity of the rupture of the beams, and walls; D. Excavation of approximately two meters, carried out next to a foundation pillar inside the classroom of the block that showed the deterioration, in which an empty space was found between the footing, and the starting pillar.

Regarding the Number of Blows (N), analyzing the SPT-1 and SPT-1A soundings, it was identified a low resistance layer, associated with soft gray clay, at an approximate depth of 2 m (2 blows), normally followed by a gain of resistance of up to 20 blows (Figure 9).

In SPT-1B, it is observed a predominance of fill material 0.8 m, followed by a sandy, brown clay, of medium consistency up to 1.6m. From this depth, it is also identified the predominance of gray clay, ranging from very soft to hard, up to normally 4.9 m (impenetrable to percussion). The survey did not reach the water level.

In SPT-1C, it is also observed a predominance of backfill material, however, up to 0.4 m, followed by clay with reddish gravel, with an average consistency of up to 1.5 m. From this depth, it is identified the predominance of a very soft gray clay, up to 3.6 m. From this depth, it is found clay with pebbles, reddish hard, up to 4.85 m (impenetrable to percussion). The survey did not reach the water level.

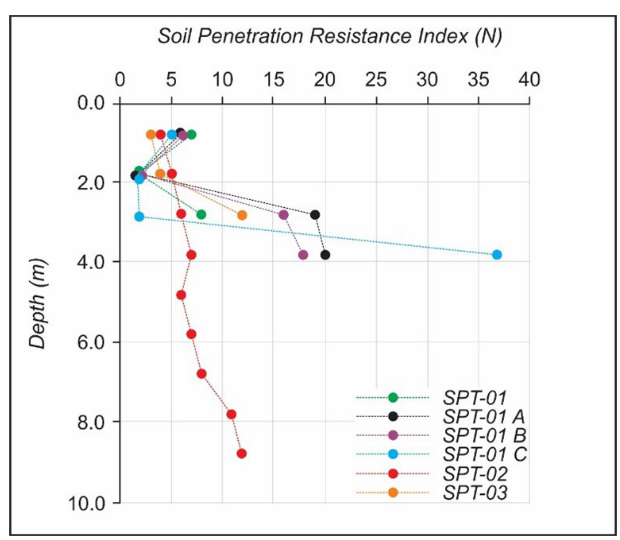

Figure 9 Soil Penetration Resistance Index (N) graph of the SPT-01, SPT-01A, SPT-01B, SPT-01C, SPT-02, and SPT-03 soundings.

Still regarding N, analyzing the SPT-1B and SPT-1C soundings, it was identified a low resistance layer, associated with soft gray clay, at an approximate depth of 2 to 3 m (2 blows), normally followed by a resistance gain of up to 37 blows.

In SPT-2 (Figure 1) it is observed a soft brown clay up to 2.6 m, followed by a yellowish silty clay of medium consistency up to 7.9 m. From this depth, it is found a sandy clay silt, moderately compact up to 10m, where the impenetrable to percussion was reached, according to NBR-6484.

In SPT-3 (Figure 1), it is found a backfill layer up to 0.6m, followed by a brown clay of soft consistency, up to 2.6m, followed by a yellowish silty clay of medium consistency, up to 4m. At this depth, the impenetrable to percussion was reached, being developed the trepanning test by washing, according to NBR-6484.

Finally, regarding the number of blows (N), analyzing the soundings, it did not find layers of low resistance, which could be associated with very soft gray clay, but a gain in resistance with depth, suggesting residual soil, according to the Figure 9.

5.4 DPL Sounding

The analysis' results of the Penetrometric Soundings DPL-6 and DPL-7 (22 m elevation), upstream of the classroom that presented the cracks (block 1) (Figure 1), it is exposed by Figure 10.

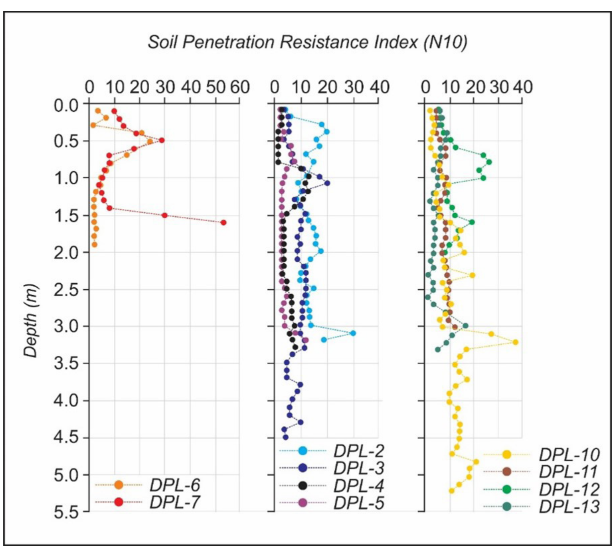

Figure 10 Soil Penetration Resistance Index (N10) graph of DPL-6, DPL-7, DPL-2, DPL-3, DPL-4, DPL-5, DPL-10 and DPL-11.

Regarding the Number of Blows (N10) of the DPL-6, at a depth of up to 1m, it is found a wide variation of the N10 (between 1 and 25 blows), as well as a low resistance layer (2 blows), normally between 1, 3 and 1.9 m. Differently, the DPL-7, presented at a depth of up to 1.7m, a wide variation of the N10 (between 4 and 54 blows).

The DPL-2, DPL-3, DPL-4, and DPL-5 (20 m elevation) (Figure 1), upstream of the classroom that presented the cracks (block 2), concerning N10, analyzing the soundings, no low resistance layers were identified, as shown in Figure 10.

Finally, in the DPL-10 and DPL-11 Penetrometric Soundings (18 m elevation), downstream of the classroom that presented the cracks (Figure 1), concerning the Number of Blows (N10), a tendency to gain strength with depth is identified (Figure 10). In the DPL-10, the water level was observed at a depth of 5.4 m.

5.5 Mixed Probing

It was evaluated 2 Mixed Probings (MP), developed downstream of the classroom that presented the cracks (Figure 1), at 17 m, on the occasion of the Sports Gym project. This area had great relevance for understanding the geology of the study area (Figure 1). In the Mixed Probings analyzed MP-1 and MP-2, it is identified landfill material up to 1.15 m, followed by a pinkish-gray granite (ranging from very altered to little altered). The MP-1 was finished at a depth of 11.51 m, and the MP-2, at 18.29 m. In both soundings, the water level was 1m deep, as shown in Figure 11.

6 Geophysics

It was performed the VES-1, which is important, mainly, for defining the water level, as well as the soil type and rock alterability along the profile, upstream of the classroom that presented cracks (Figure 1). Through the geophysical survey, it is identified landfill up to 0.7 m, followed by soil up to 3.2 m (Figure 12). From this depth up to 13.5 m, it is observed a hard weathered rock, followed up to 20 m by soft weathered rock. It was determined the water level at the contact between the soil layer and hard altered rock, at a depth of 3.2 m.

The electric surveys ER-1 (Figure 13), ER-2 (Figure 14), and ER-3 (Figure 15) were important in the determination of the geometry of the layers, the strength of materials, and geological structures. The underground flow is arranged in soil-rock contact. Low resistances, between

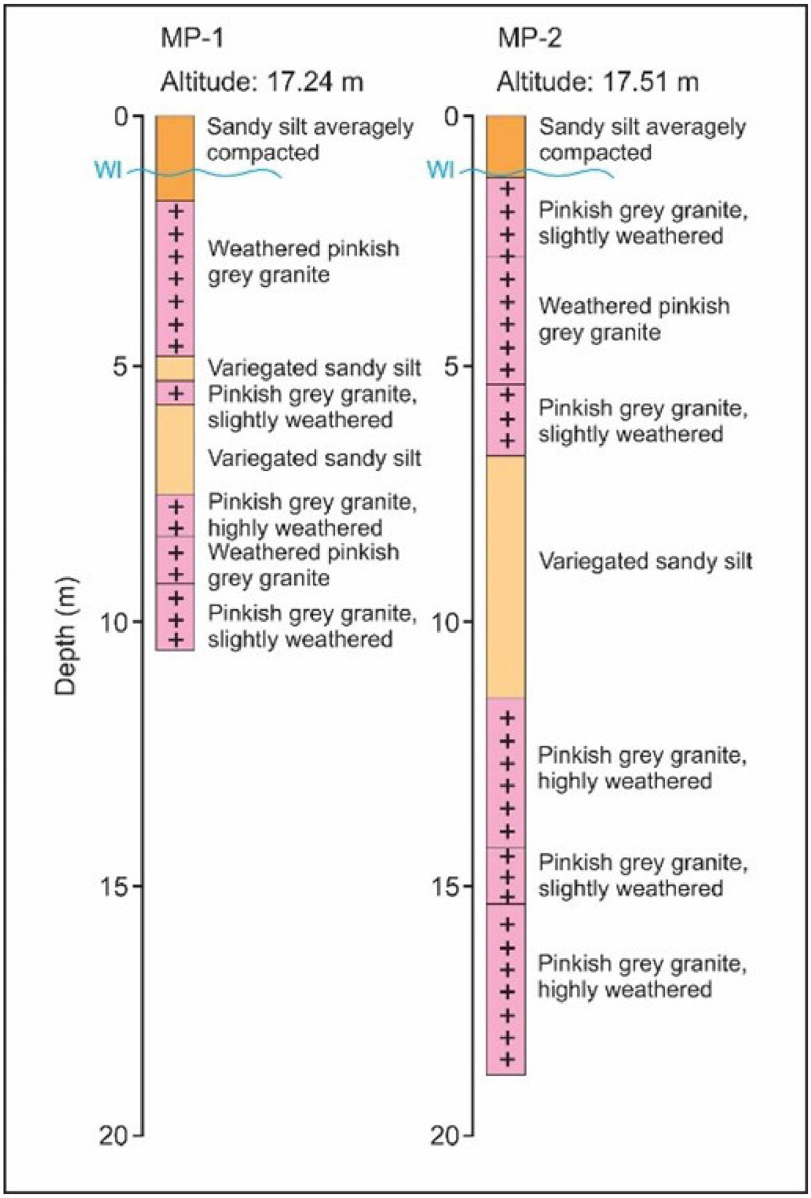

Figure 11 Mixed probings carried out at 17 m, downstream of the classroom that showed cracks, corresponding to MP-1 and MP-2, respectively.

10 and 20 ohm.m, indicate predominantly clayey soils, which are identified locally, mainly between 20 and 15 m. It is identified slightly higher resistances, between 20 and 40 (ohm.m) clayey sand soils, 40 and 60 (ohm.m) sandy clay soils, and 60 to 300 (ohm.m) sandy soils, more frequently, both downstream and upstream from the classroom that presented the cracks, between 35 and 15 m. It is was also identified high resistivities, higher than 1000 (ohm.m), which indicate a rock of igneous composition, mainly between 15 and 5 m.

It is identified the blocks, upstream of the classrooms that have cracks, through geophysics (Figure 14).

6.1 Geological-Geotechnical Section Discussion

For the elaboration of the geological-geotechnical section of the study area, it is determined a straight line aiming at the representation of the section perpendicular to the contour lines, as it presents the greatest dip of the studied slope. Subsequently, it was analyzed the SPT, DPL, MP, and VES, and prepared the geological-geotechnical section (Figure 16). This section it was made with a similar approach developed by Ali and Shakir (2022) and Kokkala and Marinos (2022), integrating geological, geotechnical and soundings data on GIS environment.

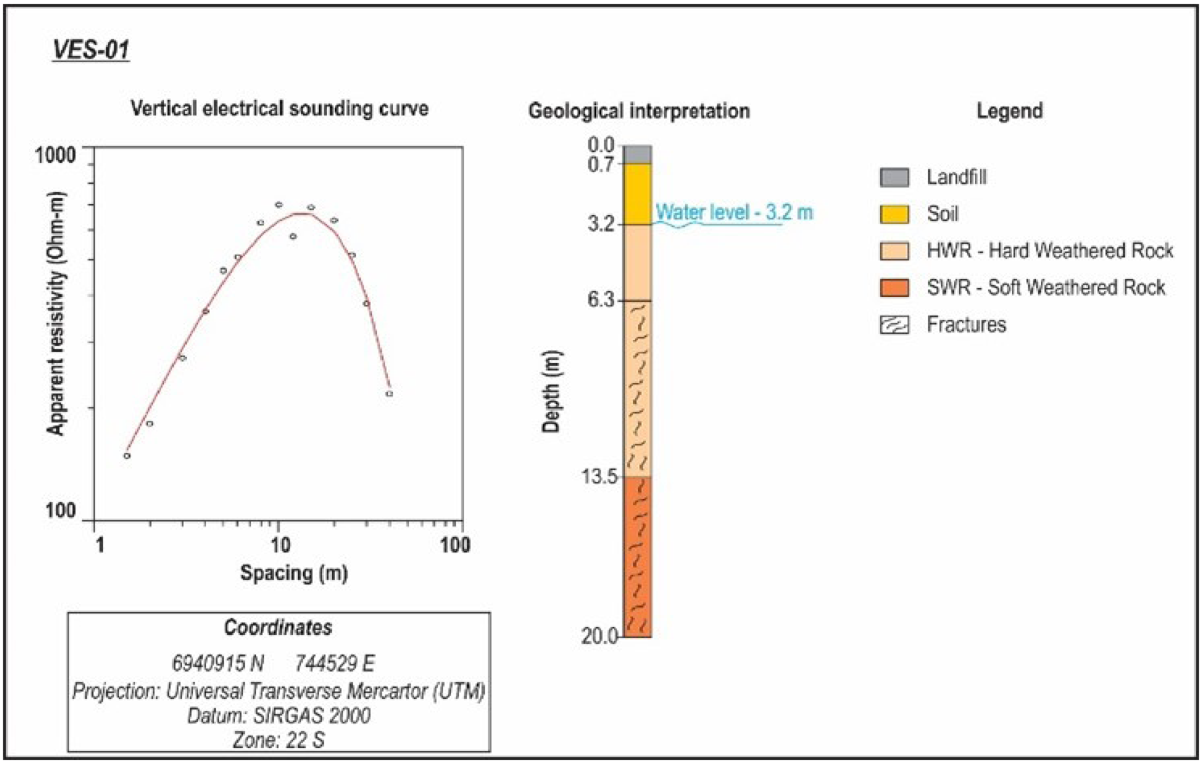

Figure 12 Vertical Electrical Survey (VES) (TECGEO 2019).

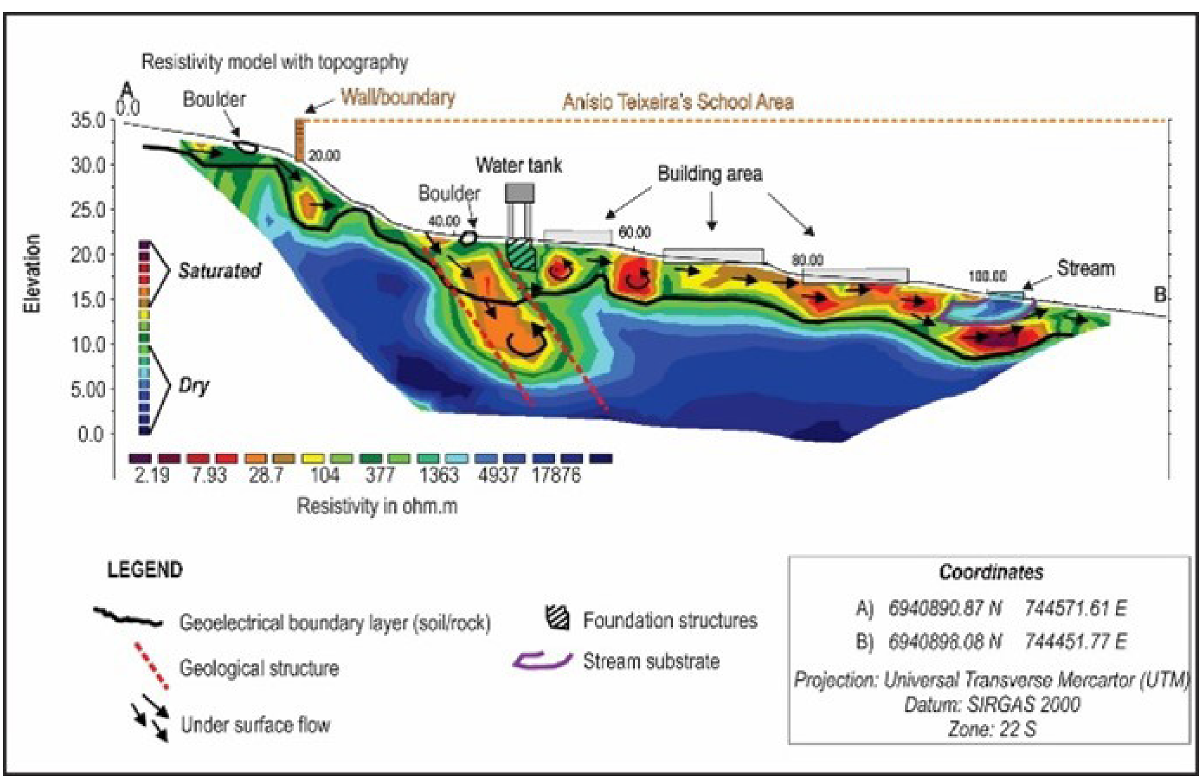

Figure 13 ER-1 - 2D Electrical Imaging (TECGEO 2019).

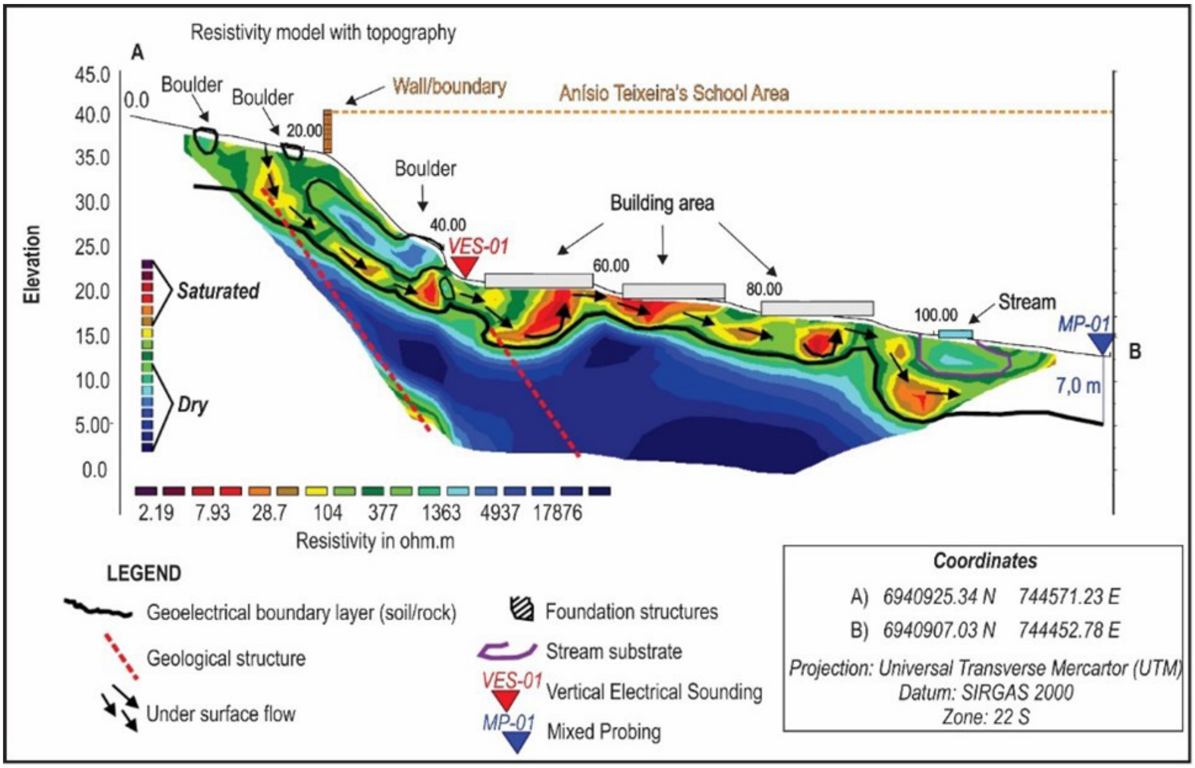

Figure 14 ER-2 - 2D Electrical Imaging (TECGEO 2019).

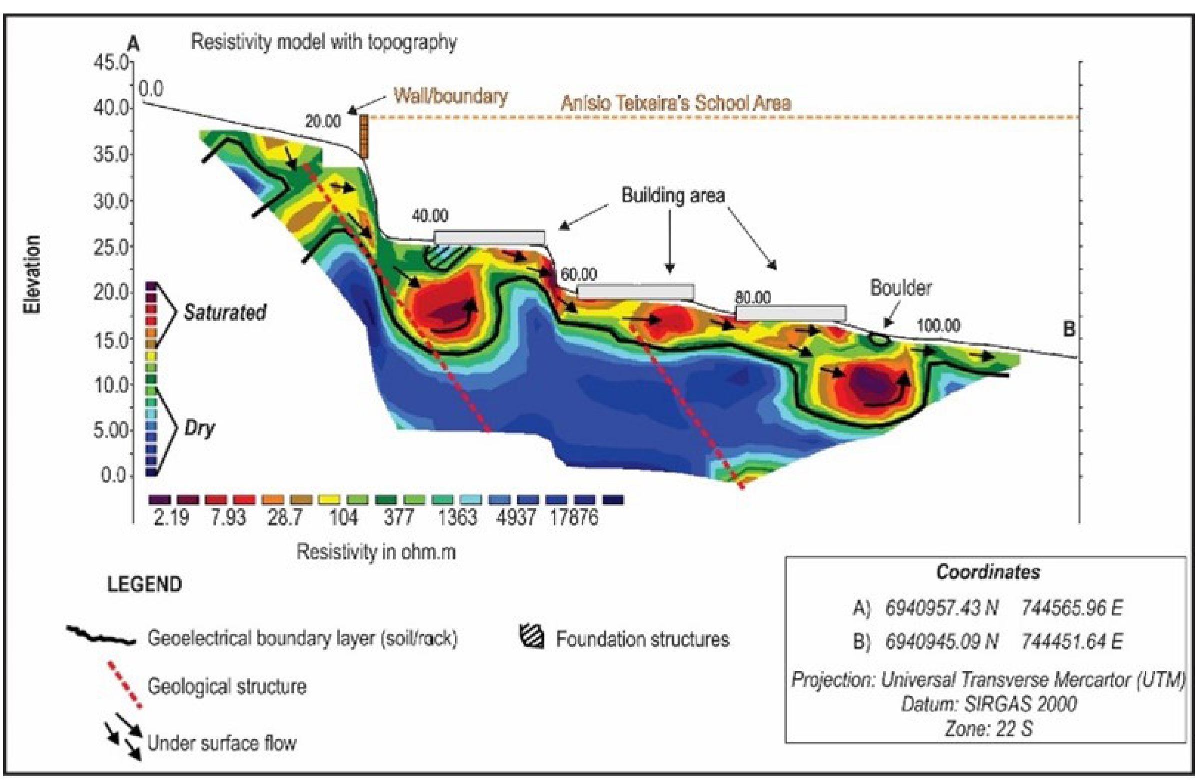

Figure 15 ER-3 - 2D Electrical Imaging (TECGEO 2019).

The integration of results involving the application of direct and indirect investigation methods (sounding and geophysical surveys, respectively) allowed the stratigraphic and structural elucidation of the study area. From this analysis, it can be highlighted a well-marked transition between crystalline rocks and sedimentary deposits. The stratigraphic column interpreted for the study region includes the plutonic basement rocks in their different levels of alteration, serving as a basement for the occurrence of sedimentary deposits on them. The geological-geotechnical profile (Figure 16) shows the plurality and lateral variation of these different deposits, which exhibit distinct structures, textures, and mineralogies, indicating the performance of different processes and events within the same sedimentation environment.

The geological and geotechnical surveys already carried out in the study region (Santos 1997; Tomazzoli & Pellerin 2015; Martins 2021) classified the surroundings of the ATMS as a region of occurrence of Colluvial-Alluvial Deposits (Figure 2). According to Tomazzoli and Pellerin (2015), this type of deposit is made up of poorly selected sediments, with proportions of gravel, sand, and mud, occurring along the slopes, as well as in fans and even at their foot. The description and characterization of the literature for Colluvial Deposits and Alluvial Deposits present sometimes ambiguous and unobjective character. This problem can be explained by the scale of the mapping being regional (aiming to cover the entire ATMS area) and by the historical confusion among geoscientists between the terms colluvial and alluvial (Miller & Juilleret 2020).

To trace the sedimentation environment of the deposits that constitute the substrate of the ATMS, it was considered the modern distinctions between the different types of sedimentary deposits whose genesis refers to the slope environment (Miller & Juilleret 2020; USDA 2015). The union of this information provided the individualization of four stratigraphic units along the local geological profile (Figure 17), namely: 1) Ilha Granite, 2) Residual soil of Ilha Granite, 3) Slope Alluvial Deposit, and 4) Colluvial Deposit.

The Ilha Granite (1) (Figure 17), which serves as the basement for the entire sedimentary package subsequently piled up, is characterized by a coarse porphyritic to equigranular biotite syenogranite, often sectioned by aplite veins (Tomazzoli & Pellerin 2015; Tomazzoli, Pellerin & Horn Filho 2018). The same is closely related to the genesis of the second stratigraphic unit, composed of residual soil resulting from the weathering of the Ilha Granite itself.

The unit of residual granite soils (2), outcropping downstream of the study area, is formed by medium consistency yellowish-brown clays. The origin of this unit refers to the product, mainly, from the chemical weathering acting on the massif (Ilha Granite), resulting in the alteration of k-feldspars in clay minerals. Analyzing the geological-geotechnical profiles (Figures 16 and 17), it was noticed that the rock layer is relatively shallow and sinuous. This morphology usually exhibits susceptibility to erosive flows with material carried underground, which, combined with the low maintenance of ATMS buildings (about 40 years of existence), are the cause of geotechnical problems.

The third unit, the Slope Alluvial Deposit (3), occurs locally below buildings 1 and 2 (Figure 17), which present the main geotechnical problems (cracks and displacement of shoes, ruptures, and leaning trees). This unit is composed of gray clays, very soft to soft, with the occurrence of rounded granules (pebbles are rare) in some layers. This unit has its genesis linked to sedimentation of continental origin, with deposition aided by a structural trap.

The analysis of electrical surveys resulted in the identification of a geological fault in the region of occurrence of gray clays, which had been elucidated as a structural trap to the Slope Alluvial Deposits, originating upstream of the study area. Slope Alluvial Deposits are a specific type of Alluvial Deposits (Miller & Juilleret 2020), and are those formed by the transport of clastic sediments downhill, initially by unchanneled (dispersed) water flows, grading into channels/drains along the slope, with selection increasing proportionally to the distance traveled over the slope. The lateral variation in grain size and selection of these sediments is commonly noticeable, which are presented in finer terms as they approach the end of the slope (Miller & Juilleret 2020; USDA 2015). According to the United States Department of Agriculture (USDA 2015), it can be differentiated Slope Alluvial Deposits from Colluvial Deposits by the presence of rock particles in the size of granules and rounded to subrounded pebbles in the middle of the deposited material, contrasting with the blocks and angular boulders verified in Colluvial Deposits.

Specifically for the layers of gray clay deposited below buildings 1 and 2 of the ATMS, the formation is attributed to floods events, creating a diffuse flow of water downhill, which may have been channeled by the drainage network. This water flow is responsible for erosion and transport of finer fragments of Ilha and Itacorubi granites, and even Colluvial Deposits, all located upstream of the study area. These sediments were deposited in the study area with the help of the structural trap formed by the geological fault. Because the fault is a structure that provides water percolation (by relieving the pressure exerted on the aquifer), it provided a condition of water saturation on the deposit, creating an anoxic environment. This condition implies the formation of a hydromorphic soil known as gley soil, causing the deposit to lose its original color and turn gray (Van Hooff & Jungerius 1984), giving rise to the very soft gray clays found in the study area.

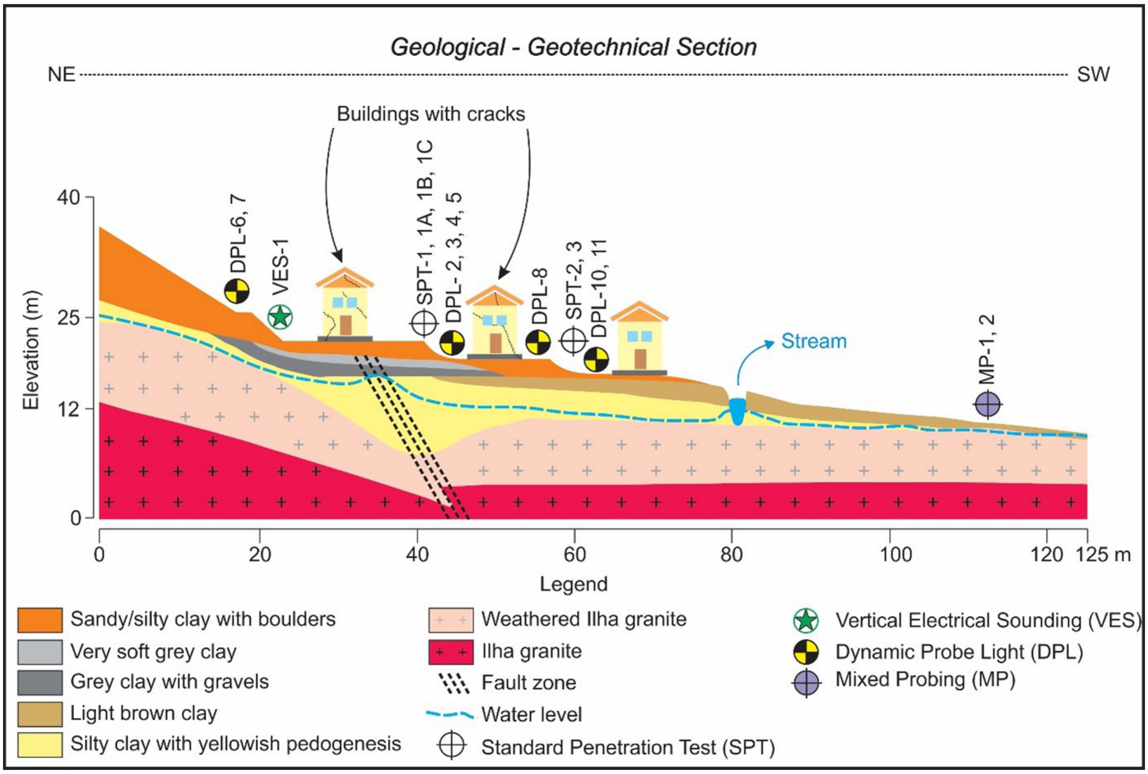

Figure 16 Geological-geotechnical section of the study area.

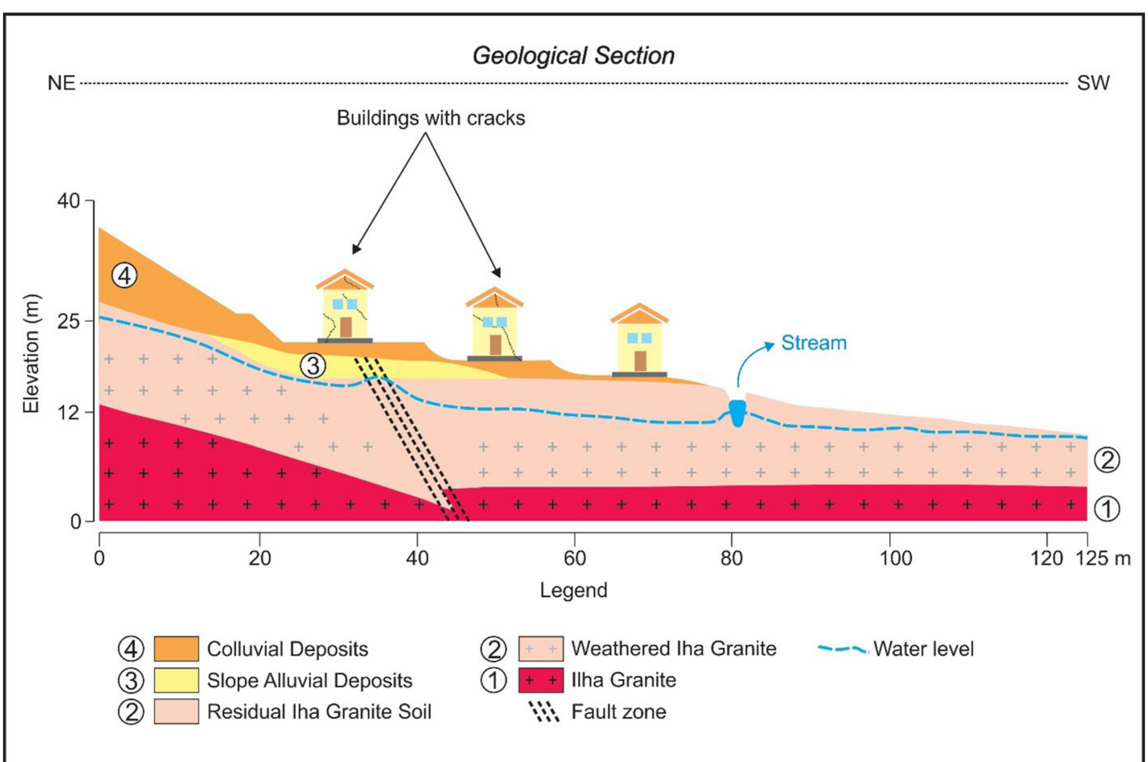

Figure 17 Geological section with the four major stratigraphic units individualized in the study area.

Consisting of the similarity in the genesis and characteristics of the Slope Alluvial Deposits mapped and sampled in this project in the ATMS region and by USDA (2015), it was interpreted them as contemporary analogs. Automatically, it was excluded the possibility of the formation of these clays associated with fluctuations in sea level along the Quaternary, which have records along the Brazilian coast. At the contrary of the results exposed by Coughlan et al. (2023) from the Holocene Sea level variation on the north Irish Sea, the mean sea level oscillations mapped by Suguio et al. (1985), Horn Filho and Livi (2013) for the southern Brazilian coast, and the Costeira do Pirajubaé region, respectively, do not reach the ATMS quotas, since it is inserted at an altitude of more than 20 m.

The topmost unit (4) (Figure 17), which spatially covers the subsequent ones, is characterized by poorly selected soils, with the presence of boulders and angular blocks, surrounded by a clayey-silty-sandy matrix, with a medium consistency, ranging from yellow to brown. This unit presents the typical characteristics of a deposit formed by gravitational mass movements with short transport, mapped as a Colluvial Deposit. So, in the same way as the Slope Alluvial Deposits, the Colluvial Deposit of the EMAT region is extremely compatible with the definition of colluvium imposed by Miller and Juilleret (2020).

Therefore, it was observed the major geotechnical problems found in the ATMS (cracks and displacement of shoes, ruptures, and leaning trees) in buildings 1 and 2. These deformations are associated with the presence of layers of soft gray clay that occur on them. A similar situation was described by Andriamamonjisoa and Hubert-Ferrari (2019) in the urban area of Antananarivo (capital city of Madagascar). The very soft to soft gray clays found in the region of the study area (Martins 2021) have a high cohesion value, however, they have low friction angles, making them materials of low competence and low shear strength. This peculiarity causes the layer to undergo constant deformations caused by the stresses imposed by deposits and structures beneath it. This overload induces the loss of water between the clay particles, and the consequent soil compaction, giving conditions for the occurrence of deformations and geotechnical problems verified in buildings 1 and 2. Because the layers of soft gray clays are associated with a fault zone, the deformations can also be related to its reactivation. Therefore, this movement can generate small mechanical waves, which, when interacting with the clayey soil of the Slope Alluvial Deposit, would increase its pore pressures, enabling the formation of liquefaction processes. According to Kamal, Inel and Cayci (2022), the effect of neighboring buildings positioned on soft soils must be taken in count, since they can magnify the deformation rate on the soft soil layer. Thus, future researches might considerer the EMAT nearby context to evaluate the influence of adjacent buildings on the soft gray clay layer.

7 Conclusion

From the data discussed, it was considered the school, which should correspond to a safe place for students, teachers, and staff, as an area of geological risk. It was identified these instability conditions through a series of cracks in its structure, which are related to the low-strength soft gray clay layer.

In the soundings and geophysical surveys, it was defined a geological-geotechnical profile, indicating the soil layers and underground water level. The observed instabilities, cracks, and subsidence showed the weaknesses of the subsoil (soil with the presence of blocks/boulders, winding basement top, and high flow due to the high slope) in the face of human interventions (cuts, landfills, construction of roads, buildings, sheds, waterproofing) and the incapacity/insufficiency of the drainage system, even when it exists.

Therefore, the results presented here allowed an integrated analysis of geological, geotechnical, and geophysical aspects to be carried out in the structural conditions of a school built on a steep slope. Even being a study on a specific location, these occupation conditions are similar to many urban territories in the country. It is expected that the results presented may contribute to the definition of the predisposing factors of the slope studied, through the identification of soil-rock contact, clayey soils of low resistance, preferential ways of infiltration of rainwater, and spatial distribution of water content in the soil.

8 Acknowledgments

The authors thank the Department of Civil Engineering at UFSC for their support and infrastructure; and Prosul, for all the data financed and made available through the contract with the Municipality of Florianópolis.

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Author contributions
João André Martins: conceptualization; formal analysis, methodology; validation; writing – original draft; writing review and editing; visualization. **Lélia Santiago Custódio da Silva:** validation; writing review and editing; visualization. **Fábio Effting Silva:** formal analysis; validation; writing review and editing; visualization.

Conflict of interest
The authors declare no potential conflict of interest.

Data availability statement
All data included in this study are publicly available in the literature.

Funding information
Not applicable.

Editor-in-chief
Dr. Claudine Dereczynski

Associate Editor
Dr. Márcio Fernandes Leão

How to cite:
Martins, J.A., Silva, L.S.C. & Silva, F.E. 2024, 'Construction of Buildings in Soft Clay Deposits: A Case Study in a Public School in Florianópolis/SC, Brazil', *Anuário do Instituto de Geociências,* 47:53330. https://doi.org/10.11137/1982-3908_2024_47_53330