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

GEOLOGY

Geotechnical Cartography Applied to Territorial Planning: A Pedo-Geotechnical Approach

Cartografia Geotécnica Aplicada ao Planejamento Territorial: uma Abordagem Pedogeotécnica

Helena Polivanov[1], Emilio Velloso Barroso[1], Renan da Silva Ramos[1], Victor Augusto Hilquias Silva Alves[1], Felipe Polivanov Ottoni[2] & Rian Lucas Porto[1]

[1] Universidade Federal do Rio de Janeiro, Instituto de Geociências, Departamento de Geologia, Rio de Janeiro, RJ, Brasil
[2] Universidade Federal do Maranhão, Centro de Ciências de Chapadinha, Chapadinha, MA, Brasil

E-mails: hpolivanov@gmail.com; emilio@geologia.ufrj.br; renan.r3@gmail.com; victor.alves@sgb.gov.br; fpottoni@gmail.com; rianportodm@gmail.com

Abstract

Occupying territories without prior knowledge of the physical environment often leads to problems arising from inadequate planning. On April 10, 2012, Law No. 12,608 was enacted, establishing the National Policy on Protection and Civil Defense (PNPDEC). Article 3 of this law outlines territorial planning policies, highlighting that geotechnical mapping is fundamental for risk mapping and territorial planning. This study aimed to develop a methodology applicable to physical environment planning at a 1:50,000 scale, specifically for urbanization purposes. The proposed method involves creating a pedogeotechnical map, combined with physical indices, providing subsidies for creating of the geotechnical map. A practical application of this methodology was conducted in the municipality of Guapimirim, located in the state of Rio de Janeiro, southeastern Brazil. The choice of this test area is justified by its diverse physiographic and environmental conditions, allowing validation of the method in various environmental contexts. The results suggest that developing a pedogeotechnical map, with its pedogeotechnical units and including physical indices as a precursor to the geotechnical map, is a practical and straightforward approach. This methodology enables the identification of suitable and unsuitable areas for urban expansion and indicates potentials and limitations related to their use. Ultimately, implementing this approach contributes to more sustainable urban planning, considering the characteristics of the physical environment, promoting risk prevention, and ensuring community safety.

Keywords: Urban planning; Pedogeotechnical map; Municipality of Guapimirim

Resumo

A utilização do território sem o conhecimento prévio das características do meio físico frequentemente induz problemas decorrentes da ocupação sem planejamento adequado. Em 10 de abril de 2012 foi criada a Lei no 12.608, que instituiu a Política Nacional de Proteção e Defesa Civil (PNPDEC). Em seu artigo 3°, citam-se as políticas de ordenamento territorial, onde o mapeamento geotécnico é uma base para gerar as cartas de risco e para o planejamento territorial. Este trabalho teve como objetivo elaborar uma metodologia aplicável ao planejamento do uso do meio físico na escala de 1:50.000, para fins de urbanização. O método conta com a confecção de um mapa pedogeotécnico, associado aos índices físicos, que fornece base para a realização do mapa geotécnico. Para a aplicação da metodologia utilizou-se como área teste o município de Guapimirim, localizado no Estado do Rio de Janeiro, sudeste do Brasil, pois suas condições fisiográficas e ambientais são bastante diversificadas, o que permite a validação do método em diversas condições ambientais. Por fim, conclui-se que a realização do mapa pedogeotécnico com suas unidades pedogeotécnicas, associado aos índices físicos como antecessor ao mapa geotécnico, é uma metodologia prática e de simples execução, onde pode-se estabelecer áreas propícias e impróprias para a expansão urbana, bem como indicar suas potencialidades e limitações quanto ao uso. . Em última análise, implementar essa metodologia contribui para o planejamento urbano mais sustentável. Em última análise, implementar essa metodologia contribui para o planejamento urbano mais sustentável.

Palavras-Chave: Planejamento urbano; Mapa pedogeotécnico; Município de Guapimirim

Received: 07 March 2024; Accepted: 07 September 2024

1 Introduction

Geotechnical cartography is a comprehensive tool for various engineering purposes: subsidence zonation (Rozos, Apostolidis & Xatzinakos 2004), accessing landslides instabilities (Da Silva, Talamini & Zuquette 2021), the construction of three-dimensional subsurface models (Kim & Ji 2022) and the definition of terrain suitability classes for sustainable urbanization (Al-Ghorayeb et al. 2023; Moisa, Babu & Getahun 2023). It is indispensable for the territorial zoning of administrative areas (Moura &Canil 2018; Nola & Zuquette 2021; Souza & Sobreira 2015). It is the key to planning and occupying the physical environment, providing in-depth knowledge about the territory's physiographic characteristics, including geological, geomorphological, pedological, and geotechnical aspects. Its primary objective is to organize information about the physical environment, creating distinct units of homologous behavior. These units are then used to identify potentialities and limitations, thereby supporting all activities related to engineering projects and territorial development.

To reinforce the importance of geotechnical cartography, on April 10, 2012, Law No. 12,608 was enacted in Brazil, establishing the National Policy on Protection and Civil Defense – PNPDEC (PNPDEC 2012, no. 12 608). Article 3 of this law outlines territorial planning policies, highlighting that geotechnical mapping is fundamental for risk mapping and territorial planning.

The available methodologies and applications of geotechnical cartography have been discussed from the last century to the present day. Langem (1913, cited by Zuquette & Gandolfi 2004) presented a document to guide constructions in floodable areas. Since then, and still, in the twentieth century, numerous articles have been published on geotechnical cartography or engineering geology maps for general purposes (Anon 1972; Dearman & Fookes 1974; Eckel 1952; Fookes 1967; Popov et al. 1950; Simpson 1938; Varnes 1974) and on territorial use planning (Cratchley & Denness 1972; Matula, 1979). Considering the variety of geotechnical cartography methods used worldwide, a guide was published to standardize procedures for this type of map (IAEG, 1976).

In Brazil, awareness of mapping for geology applied to engineering works dates back to 1907 during the extension of the Northeast Brazil Railroad (Ruiz 1987). Energy sector companies produced geotechnical maps for the implementation of hydroelectric plants in the 1960s (Barroso, Barroso & Cabral 1998). Notably, a pioneering publication is the prototype with the geotechnical map of the Laranjeiras neighborhood in the city of Rio de Janeiro published by professor Haberlehner in 1966 (Barroso, Barroso & Cabral 1998). Since then, the production of geotechnical maps in Brazil has been concentrated in universities since the 1970s and, from the second half of the past decade, also by the Brazilian Geological Survey. The majority of these cartographic products are applied to territorial planning, identifying areas susceptible to physical processes and risk reduction.

The research group at the Institute of Geosciences of the Federal University of Rio de Janeiro (IEGO/UFRJ) is one of the pioneers in Brazil. Initially, the group used municipalities in the Rio de Janeiro metropolitan region as research laboratories for cartography applied to territorial planning (Cabral 1979; Cabral 1983; Barroso et al. 1986; Amaral 1988; Barroso and Barroso 1996), with scales ranging from 1:10,000 to 1:50,000. These maps were called geological-geotechnical maps, and their preparation was based on the method proposed by the IAEG (1976), with modifications depending on the availability and scales of the pre-existing geological and topographic maps (Barroso 1989). Subsequently, the research extended to other municipalities in the State of Rio de Janeiro, such as Petrópolis (Barroso and Lino 1984), Saquarema and Maricá (Barroso and Pedroto 1984), and Campos dos Goytacazes (Costa et al. 2011). The same group produced geotechnical maps on larger scales (1:2,000 to 1:5,000) aimed at solving instability issues in densely populated slopes (Barroso, Cabral & Fernandes 1987; Rego-Neto 1988; Sobreira, 1989).

The research group at the School of Engineering of São Carlos (EESC/USP) was also established during the same period, with its first master's theses defended in the 1980s (Zuquette 1981; Taveira 1986; Pejon 1987; Aguiar 1989). This group developed its own methods for geotechnical cartography, structured in three phases: preliminary, office and field, and conclusive (Zuquette 1993). In the EESC/USP mapping method, the definition and delimitation of geotechnical units can be carried out using different procedures and sets of attributes, potentially resulting in cartographic documents across eight different hierarchical levels: (I) fundamental synthesis, (II) interpretative and derivative, (III) basic analytical, (IV) prognostic, risk, and limitation, (V) procedural, (VI) potential viability, (VII) and (VIII) conclusive orientations. A recent example of this methodological approach is the map related to the suitability for the implementation of sustainable drainage systems, based on attributes reflecting infiltration conditions and controlling the construction and functional aspects of these systems (Failache et al. 2022).

The Institute for Technological Research of the State of São Paulo (IPT) has been conducting geotechnical mapping since 1979, beginning with the mapping of the hills of Santos and São Vicente at scales of 1:5,000 and 1:1,000, with the objective of proactively addressing the instability of their slopes. The IPT method focuses on solving or mitigating existing and potential problems in the study areas. Once these problems are identified, data is collected objectively to define different geotechnical units. Each geotechnical unit should specify practices for solving each identified problem in the study area (Prandini, Nakazawa & Campanário 1992). Currently, IPT's work has proposed methods for mapping susceptibility to landslides, flooding, mass movement, and flash floods (Bitar et al. 2021), although these maps are created without the support of geotechnical maps.

Researchers from the Geological Institute of the State of São Paulo (IG) produced maps for territorial management, defining mapping units based on the compartmentalization of the relief. In this method, the units are called geo-environmental and include geotechnical inferences (Oliveira et al. 2007, Vedovello et al. 2020). Researchers from the Federal University of Ouro Preto (UFOP) produced maps focusing on urbanization suitability (Carvalho & Sobreira 2016, Souza & Sobreira 2017a) and a flood susceptibility map based on the morphometric parameters of the terrain (Souza & Sobreira 2017b) for the Quadrilátero Ferrífero region in Minas Gerais. Meanwhile, UNESP in Ilha Solteira has been producing geotechnical cartography with various focuses: for soil collapse risk analysis (Oliveira, Rodrigues & Lollo 2007) and urban planning (Lollo, Santos & Curti 2013) in the Ilha Solteira region. In the State of São Paulo, starting in the 2010s, the Federal University of ABC also began producing geotechnical cartography for urban planning and disaster prevention (Nogueira et al. 2019), using the same method as IPT with some slight variations. Due to the disasters in the Serrana Region of Rio de Janeiro in 2013, the Geological Survey of Brazil started to develop geotechnical cartography (Ribeiro & Dias 2020), following the methodological procedures of Souza & Sobreira (2013).

While soil formation factors are of utmost relevance for geotechnical engineering, especially climate (controls rock weathering products and soil thickness), relief (regulates the ratio infiltration to run-off and outlines areas of material transport and deposition) and source material (influences the soil composition and its physical properties); almost none of previous cited work has pedology as a central key or a main attribute for geotechnical cartography production. Despite this fact, some pioneers researchers have discussed the use information to underpin geotechnical data (Barroso et al. 1981, Dias, R.D. & Gehling, Y.Y.W. 1982, Dias, R.D. & Gehling, Y.Y.W. 1985, Polivanov et al. 1984; Salomão 1984, Santos & Salomão 1981). Regarding application of soil maps to geotechnical cartography, the very first attempts relate to the published articles by Barroso (1986), Antunes et al. (1987) and Dias (1995).

More recently, Mendonça-Santos et al. (2009) published work correlating pedology and geotechnics for the Municipality of Rio de Janeiro. Antunes et al. (2013) established geo-pedological units to explore the relationship between pedology and geotechnics. Calderano Filho et al. (2013) applied geo-pedological unit methodology and introduced the term pedogeotechnical units. Luz et al. (2015) presented a morphopedological approach to support the design of infrastructure projects and minimize impacts on water resources. In the international literature, noteworthy works (Calitz & Hattingh 2007; Fanourakis 2022, 2012; Harmse 1977; Lee & Griffiths 1987; Paranhos et al. 2019; Rutka 1961; Wilson 1973) address pedological mapping and geotechnical cartography.

In short, as we can see from the previous paragraph, while several schools of geotechnical cartography were emerging and developing in Brazil between the 1970s and 1980s, there were studies aimed at incorporating pedological information to understand the geotechnical behavior of soils. After this phase, starting in the 2000s, the search for the inclusion of pedological information in the practice of geotechnical cartography was once again resumed.

However, the incorporation of pedological knowledge into geotechnical cartography is not yet widely disseminated and nor entirely established. In light of the aforementioned considerations, this article proposes a methodological adaptation to support geotechnical maps. The approach involves creating a preliminary pedogeotechnical map with predefined units, developed based on the pedological map and incorporating pertinent geotechnical interpretations. This pedogeotechnical map is supplemented with a legend defining its units. When coupled with physical soil characterization tests, it facilitates the generation of the geotechnical map.

This methodology was tested in an area within the municipality of Guapimirim, State of Rio de Janeiro (RJ), southeastern Brazil, situated in one of the valleys of the Serra dos Órgãos mountain range, with a history of geological disasters such as mass movements and floods. The physiographic aspects of the chosen area for testing the method are highly diverse. The municipality is located partly in the Serra dos Órgãos to the north, in the coastal lowlands bordering the Guanabara Bay to the southwest, and in transitional terrains between these two compartments. These terrains are characterized by fluvial sedimentary plains, partially affected by tidal fluctuations, colluvial sediments, and residual soils derived from different lithotypes. This diversity makes the area particularly intriguing for testing the methodology proposed in this study. Additionally, the municipality's population (approximately 61,000 inhabitants) and its steadily increasing municipal human development index over the last three decades (IBGE 2020) add further significance to this research.

Due to this physiographical diversity, in addition to the proximity to the city of Rio de Janeiro (approximately 50 km), the state capital, it is assumed that there will be significant demographic growth and land occupation in the coming decades. It is worth noting that the municipality of Guapimirim is currently considered part of the metropolitan region of the city of Rio de Janeiro. In addition to the themes above, a portion of the municipal territory is encompassed by the Serra dos Órgãos National Park, where the "Dedo de Deus" peak stands as its primary natural and touristic landmark. The park headquarters in the municipality hosts historic and protected structures. Therefore, the pressure exerted by the growing tourist activity must also be considered concerning urban expansion planning and the relevant economic activities for the municipality.

In light of the above, the main objective of this work was to test and adapt a geotechnical cartography methodology that includes a pedogeotechnical map and its units, supplemented with physical indices, in a complex area with respect to its geological and geomorphological frameworks.

When we consider the 5,565 Brazilian municipalities in a broader national context, it becomes clear that the vast majority are grappling with a significant issue. They either lack technical staff or have an insufficient workforce for studies focused on territorial planning, both urban and rural. On the other hand, the geotechnical cartography methods developed by Brazilian universities and research institutions are technically excellent but often too specialized and time-consuming. As a result, they require a specialized workforce, which most municipalities and state agencies lack in their technical teams. This underscores the urgent need for a simple, cheap, and fast geotechnical cartography method to address Brazil's territorial management challenge. These are the main characteristics of the geotechnical cartography method that is now presented in this research.

2 Materials and Methods

2.1 Study Area

The municipality of Guapimirim is situated in the Baixada Fluminense, a metropolitan region in the state of Rio de Janeiro, southeastern Brazil. Its geographical coordinates are 22º31'57" South latitude and 42º59'24" West longitude (municipal seat). The altitude varies from sea level to 700 meters (Prefeitura de Guapimirim 2000). The region has a hot and humid tropical climate, classified as Aw according to Köppen (1948), with a rainy season in spring-summer and a dry winter. Figure 1 illustrates the location of the study area.

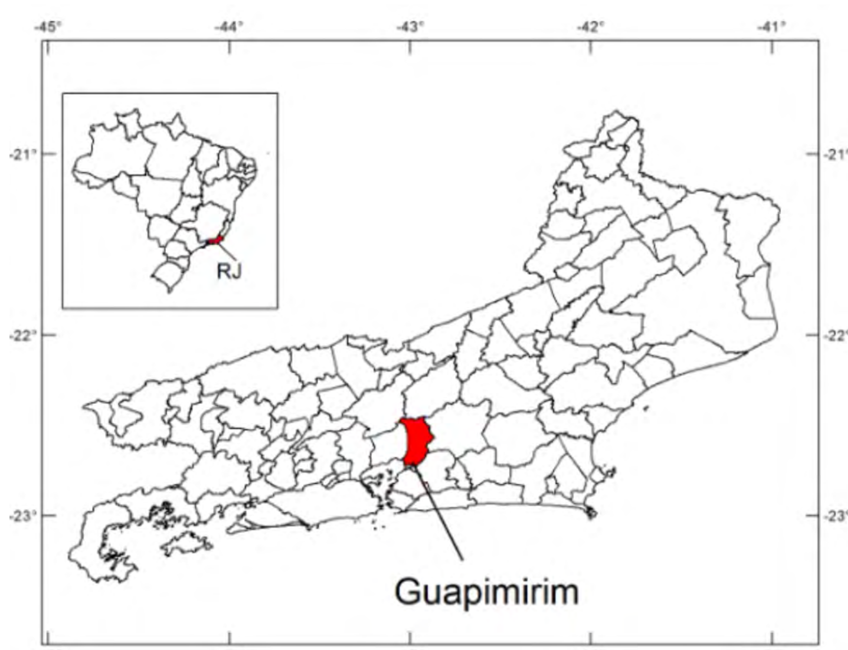

Figure 1 Location map of the Municipality of Guapimirim.

The municipality in question is located in a valley at the base of the Serra dos Órgãos, with approximately 95% of its territory inserted into the Sedimentary Basin of Rio Macacu. The basin's basement is composed of paragneisses and alkaline rocks, and the basin is primarily constituted by the Macacu Formation, followed by Quaternary deposits: marine, fluvio-marine, and colluvial-alluvial (CPRM 2001). The northern portion of the municipality is composed of the Serra dos Órgãos unit, represented by biotite granites, granodioritic gneisses, leucogranitic gneisses, and granites; and Santo Aleixo, consisting of migmatites. Meanwhile, the central region of the municipality has a transitional contact with the Santo Eduardo Unit, composed of banded lenticular gneisses with the presence of biotite and hornblende (Grossi Sad et al. 1980).

Cenozoic deposits consist of marine, transitional, and fluvial sediments. The southern part of the municipality is predominantly composed of fluvio-marine deposits and, to a lesser extent, marine deposits, sediments from the Macacu Formation, and floodplain deposits (UFF/FEC 2010).

Geomorphological units are characterized to the north by the Serra dos Órgãos unit, featuring a mountainous escarpment relief along with ridges and stepped terraces. In the central and southern regions, the geomorphological unit of the Guapi-Macacu Basin prevails, with hilly reliefs dominating the center and extensive fluvio-marine plains to the south of the municipality (Dantas et al. 2012).

Pedological units in the municipality are constituted by eight soil classes: RED-YELLOW LATOSOLS (Oxisols) in hilly reliefs; HYDROMORPHIC PLANOSOLS (alfisols) in flat terrains and river terraces; FLUVIC NEOSSOLS (Fluvisols) in lowland areas and coastal plains; MELANIC GLEYSOLS (Entisols) and THIOMORPHIC SOILS, as well as undifferentiated mangrove soils at elevations close to sea level, on fluvio-marine sediments; and HAPLIC CAMBISOLS (Inceptisols) and LITHIC NEOSSOLS (Leptosols) in association with mountainous and steep reliefs (Secretaria Estadual do Ambiente - RJ 2011).

2.2 Applied Methodology

A synopsis of the methodology tested and employed in the pilot area is presented in Figure 2.

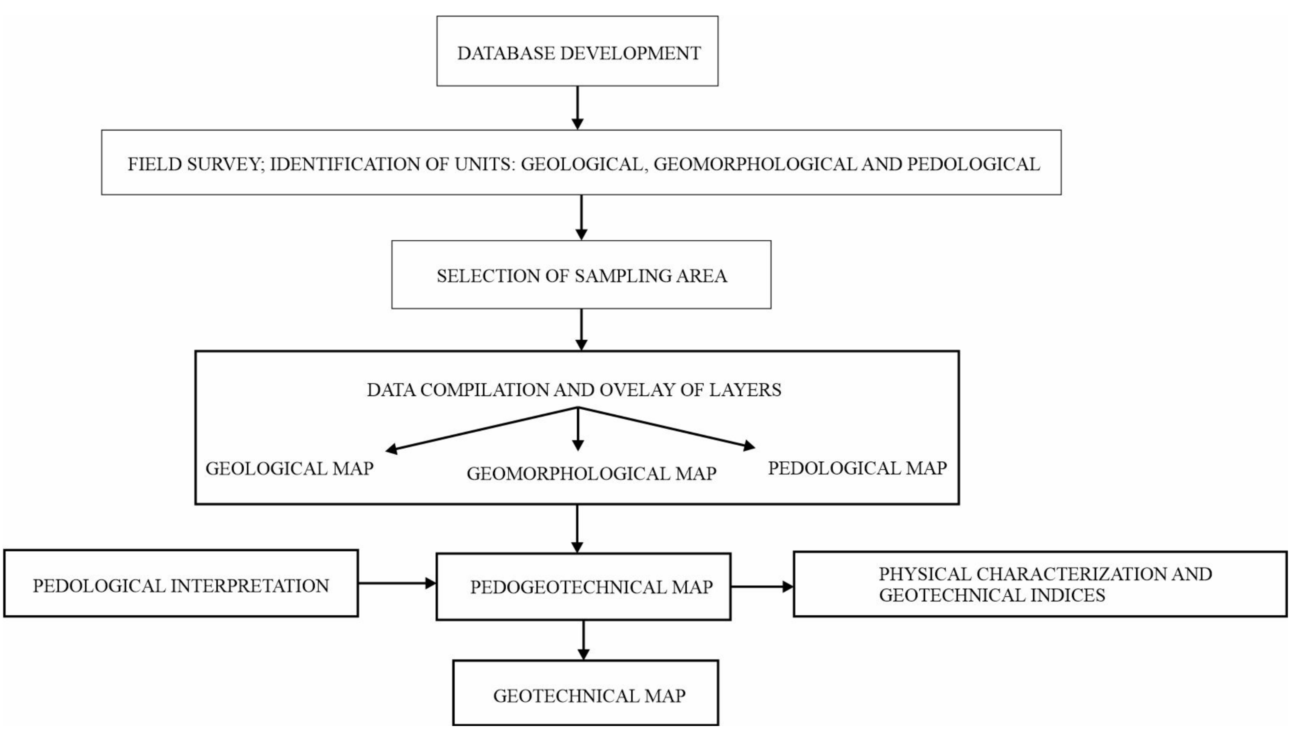

Figure 2 Flowchart of the methodology employed in geotechnical mapping.

2.2.1. Database Construction

The data utilized in this research were obtained from the following sources: (1) digital cartographic base of the municipality of Guapimirim and a geomorphological map (1:50.000) obtained from CPRM (2015), encompassing information on susceptibility to gravitational mass movements and flooding, topography, pedology, urban areas, drainage, roads, and environmental protection areas. (2) Geological maps (1:50.000) of the State of Rio de Janeiro from the Department of Mineral Resources (DRM 1972; 1980; 1981; 1984) used to prepare the geological map and (3) pedological maps (1:100.000) from Secretaria Estadual do Ambiente do Rio de Janeiro (2011).

The scales of most geological, geomorphological and pedological maps available in Brazil are not the most appropriate for geotechnical applications, which generally require much larger scales. However, in the case of geotechnical mapping for territorial planning, this issue, while relevant, is less critical when the geotechnical map is designed and executed with this specific purpose in mind. This reiteration of the map's intended use is particularly true for municipalities with large areas available for expansion and when those pre-existing information is at 1:50,000 scale.

2.2.2. Field survey, Identification of Geological, Geomorphological, Pedological Units and Selection of Areas for Sample Collection

After obtaining cartographic documents from the various sources listed in the previous section, fieldwork began to recognize the general characteristics of the study area. The purpose of this research phase was to identify regions susceptible to gravitational mass movements and flooding. This initial phase allowed for the verification of the main geological, geomorphological, and pedological characteristics described in the consulted cartographic documents. In regions with rugged terrain, colluvium, mature and saprolite soils were delineated, and soil profiles were opened to identify B and C horizons. This initial set of information guided the mapping work and the soil sampling strategy for physical characterization tests in the laboratory.

Regarding soil sampling for characterization tests, in the lowland regions, the terrain was cleared using traditional field tools, and disturbed samples were collected by augering with a Dutch auger, reaching maximum depths of up to 80 cm. In contrast, in regions with higher relief, the selected profiles for sampling were properly prepared, and samples were extracted from the B and C horizons of the profile. All samples were meticulously identified, stored to maintain moisture content, and transported to the laboratory.

To enhance understanding of the study, the symbolizes of soil horizons are briefly explained: A represents a mineral horizon with varying proportions of organic matter; Ap denotes a horizon with pedoturbation; E is a light-colored where materials have been removed, Bw designates the highly weathered horizon; Bp is formed by clay accumulation through translocation in a reducing environment; Bi represents a slightly weathered horizon with incipient pedogenetic processes; Cr represents the C horizon directly derived from the parent rock, related to the saprolite soil; and the C horizon is the material giving rise to the soil profile, with a number to the right indicating materials with distinct morphological characteristics.

2.2.3. Laboratory Analyses

Laboratory analyses were performed to characterize the physical properties of the soils, encompassing assessments of natural and hygroscopic moisture content (W) (ABNT 2024), grain density (ρ)(ABNT 2017b), particle size analysis (ABNT 2018), Liquid Limit (LL) (ABNT 2017a), and Plastic Limit (PL) (ABNT 2016). The outcomes of these analyses were employed to compute Skempton's Activity Index (AI) (Skempton 1953) and the consistency index (CI) following Terzaghi (1944).

Table 1 presents the values of Skempton's AI, Equation 1, and its corresponding classification (Skempton 1953), the CI, Equation 2, and its classification (Caputo 2015), along with empirical correlations between CI and the Standard Penetration Test (SPT), as well as unconfined compressive strength (qu) according to Terzaghi & Peck (1968). It is important to emphasize that these empirical relationships have limited applicability (Souza Pinto 2016) and are exclusively employed in preliminary studies.

$$AI = \frac{PI}{\%clay} \quad (1)$$

$$CI = \frac{LL - Wnatura}{PI} \quad (2)$$

Where AI is Activity Index, LL is Liquid Limit, W humidity or soil water content and, PI Plasticity Index.

The materials were classified based on the data obtained from physical characterizations, utilizing the Unified Soil Classification System - USCS (Wagner 1957).

Table 1 Classification Activity Index (AI), Consistency Index (CI), empirical correlations between CI and the Standard Penetration Test (SPT) and unconfined compressive strength (qu). SPT and qu values estimated from CI, according Terzaghi and Peck (1968).

AI	AI Classification	CI	CI Classification	SPT	qu (kgf/cm²)
<0.7	inactive	0	Very soft	<2	<0.25
0.7-1.25	moderately	0 <CI<0.50	soft	3-5	0.25-0.5
>1.25	active	0.50 <CI<0.75	medium	6-10	0.5-1.0
		0.75 <CI<1.00	stiff/very stiff	11-19	1.0-4.0
		CI>1.00	hard	>19	>4.0

2.2.4. Development of Maps

With the pre-existing data (CPRM 2015), maps were developed, including the map of field descriptions and sampling points, geological, geomorphological, pedological, pedogeotechnical and geotechnical maps, utilizing ArcGIS 10.3.1 software. We capture the field points geographical coordinates where soil profiles were described and sampled using the Garmin Etrex 22x GPS.

The geological map was created by integrating geological maps (DRM 1972, 1980, 1981, 1984), with adjustments made between the contacts of each geological map, aiming to reduce the discrepancies found in the contacts between the maps. Fieldwork was conducted for the refinement and final production of this map.

The geomorphological map was crafted utilizing the CPRM (2015) databases and field adjustments were carried out for the final production of this map.

Initially, we conducted field validation of the pedological map used as the source for this research. In this phase, we identified and corrected any inconsistencies between the pedological units on the map and those observed in the field. Next, we compared the geomorphological map with the adapted pedological map to assist in delineating unit boundaries, as relief is a soil formation factor and a valuable parameter for verifying pedological unit limits.

In the subsequent step, the construction of the pedogeotechnical map followed the recommendations of Antunes et al. (2013) to assign general geotechnical characteristics to the pedological units, considering the association of soil classes with landforms and parent material.

The geotechnical map was developed through interpretations of the pedogeotechnical map and its legends, supplemented by physical characterization data and indices. These pieces of information were instrumental in defining the units presented in the legend of the geotechnical map.

3 Results and Discussion

3.1 Points and Collection of Samples

Table 2 displays the locations of the 26 points and the 54 samples collected for laboratory testing.

Figure 3 depicts the locations of sampled points, illustrating their density and distribution.

Table 2 Point locations in study area (P – Point, S – Sample, Hz – Horizon and, UTM coordinates: N – North and E – East).

P	S	Hz	UTM-N	UTM-E	P	S	Hz	UUTM-N	UTM-E
1	1	C1	7505890	714085	15	28	C	7490966	708136
	2	C2	7505890	714085	16	29	C	7489052	710256
2	3	C1	7505396	712758	17	30	C	7490539	710567
	4	C2	7505396	712758	18	31	Bw	7503401	715792
3	5	C1	7506343	711886		32	Cr	7503401	715792
	6	C2	7506343	711886	19	33	Bw	7506903	716030
4	7	C1	7505254	715918		34	Cr	7506903	716030
	8	C2	7505254	715918	20	35	Bw	7503049	711103
5	9	C1	7505535	717253		36	Cr1	7503049	711103
	100	C2	7505535	717253		37	Cr2	7503049	711103

Table 2 Cont.

P	S	Hz	UTM-N	UTM-E	P	S	Hz	UUTM-N	UTM-E
6	11	C1	7506933	716189	21	38	Bw	7502517	713545
	12	C2	7506933	716189		39	Cr1	7502517	713545
7	13	C1	7503480	718196		40	Cr2	7502517	713545
	14	C2	7503480	718196	22	41	Bw	7501078	716646
8	15	C1	7502722	716180		42	Cr1	7501078	716646
	16	C2	7502722	716180		43	Cr2	7501078	716646
9	17	C1	7501751	716425	23	44	Bw	7495259	707923
	18	C2	7501751	716425		45	Cr	7495259	707923
10	19	A	7498311	707481	24	46	Bw	7499881	711923
	20	Bp	7498311	707481		47	Cr1	7499881	711923
11	21	E	7501235	711437		48	Cr2	7499881	711923
	22	Bp	7501235	711437	25	49	B	7505222	715216
12	23	E	7502292	709591		50	Cr1	7505222	715216
	24	Bp	7502292	709591		51	Cr2	7505222	715216
13	25	A	7500381	716821	26	52	Bi	7504767	708187
	26	C	7500381	716821		53	Bw	7504767	708187
14	27	C	7493861	712112		54	Cr	7504767	708187

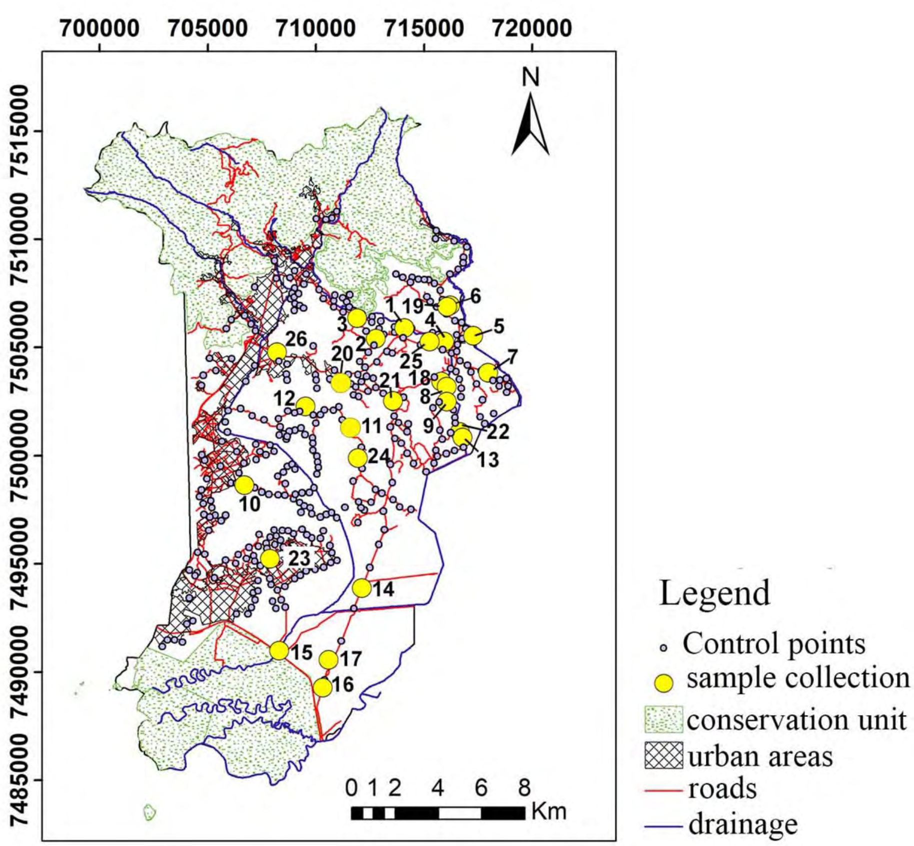

Figure 3 Distribution and density of the sampled and control points of the Municipality of Guapimirim, State of Rio de Janeiro, Brazil. (SIRGAS 2000/ UTM ZONE 23S).

3.2 Geological, Geomorphological, Pedological and Pedogeotechnical Maps

3.2.1. Geological Map

The geological map is presented in the Figure 4, in which all the units, accesses and the urban polygons can be observed.

The northern portion of the municipality is composed of the Serra dos Órgãos Suite, housing the state's largest exposed batholith—the Serra dos Órgãos Unit. This unit is characterized by biotite granites, gneissic granodiorites, leucogranitic gneisses, and post-collisional granites (Andorinha and Nova Friburgo granites). Adjacent to the batholith is the Santo Aleixo Unit, consisting of both heterogeneous and homogeneous injection migmatites (CPRM 2001).

A transitional contact occurs with the Santo Eduardo Unit in the central municipality region. As documented by Grossi Sad et al. (1980), this unit is classified as part of the Paraíba do Sul Complex, featuring banded lenticular gneisses with biotite and hornblende, exhibiting a diverse granulitic to mylonitic texture.

The Cenozoic deposits in the Guapimirim region consist of marine and fluvial sediments derived from surrounding geological units, including the Macacú Formation, reworked by recent erosional-depositional processes (UFF/FEC 2010). Fluvial sediments predominantly characterize the region, occasionally occurring in association with relic coastal sediments. To the south, the geological framework of the municipality is prominently composed of fluvio-marine deposits, with lesser representation of marine deposits, sediments from the Macacu Formation, and floodplain deposits.

3.2.2. Geomorphological Map

The Figure 5 depicts the geomorphological units observed in Guapimirim area.

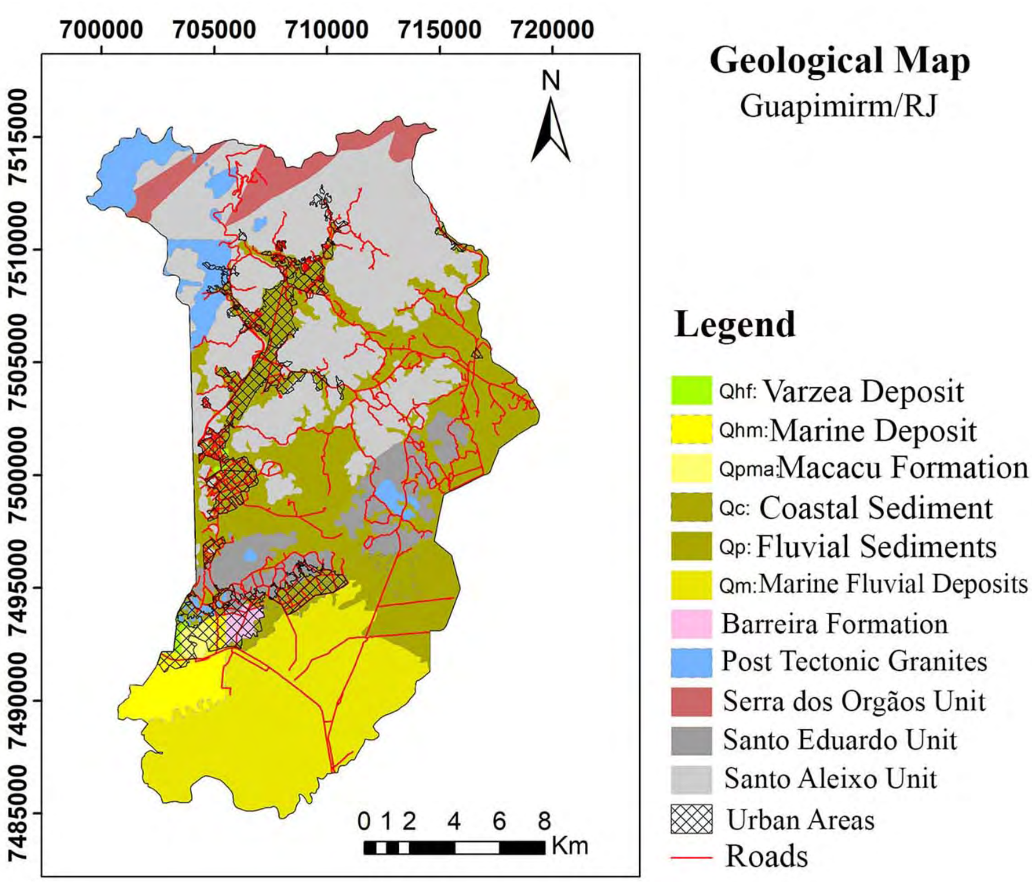

Figure 4 Geological Map of the Municipality of Guapimirim, State of Rio de Janeiro, Brazil. Compiled through the integration of geological maps from DRM (1972, 1980, 1981, 1984), with adjustments made by the authors. (SIRGAS 2000/ UTM ZONE 23S).

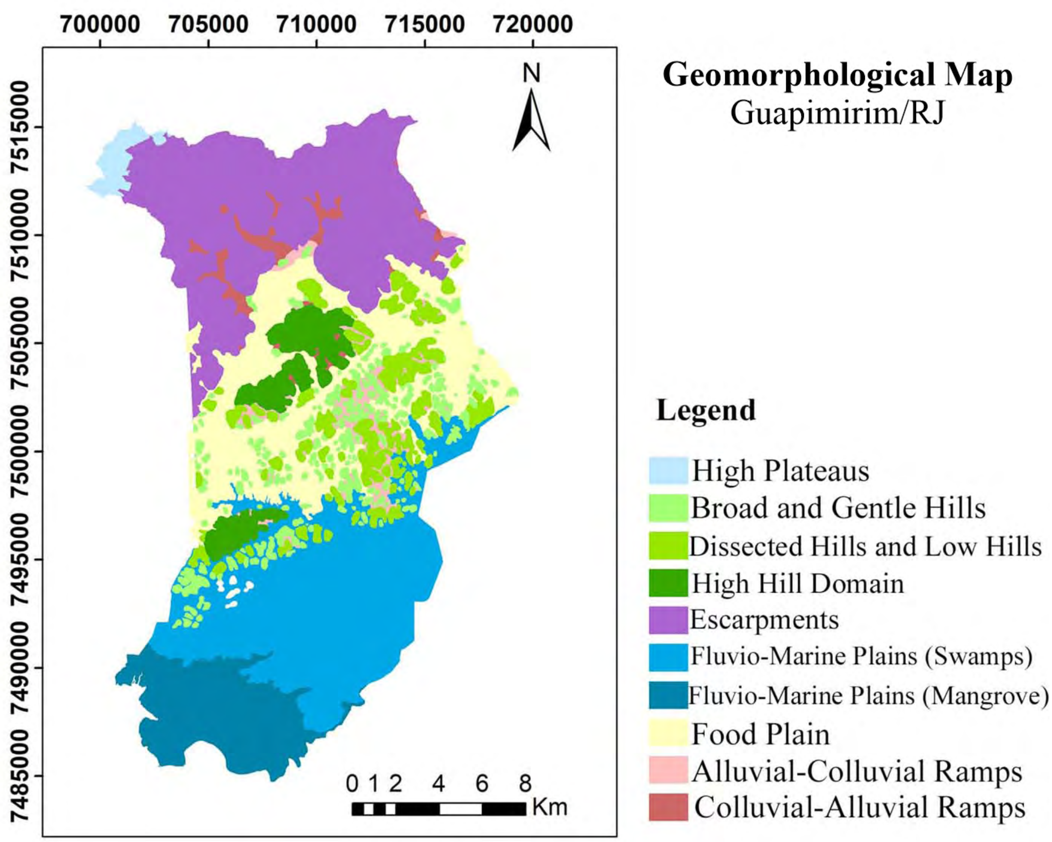

Figure 5 The Geomorphological Map of the Municipality of Guapimirim, State of Rio de Janeiro, Brazil, was developed utilizing the CPRM (2015) datasets, with field adjustments made by the authors. (SIRGAS 2000/ UTM ZONE 23S).

Guapimirim's geomorphology is characterized by distinct features, including the Serra dos Órgãos plateaus in the northwest, marked by flattened rock surfaces and sub-vertical cliffs (Dantas et al. 2012). The Guapi-Macau basin dominates the region with a varied terrain, encompassing hilly terrains, fluvio-marine plains, and alluvial-colluvial ramps. Coastal dynamics reveal a transition from hilly terrains to extensive alluvial and fluvio-marine plains, featuring sub-horizontal surfaces and mangrove areas (Dantas et al. 2012). The geological foundation, comprising the Serra dos Órgãos Suite and Santo Aleixo Unit, adds complexity to the landscape. Cenozoic deposits, influenced by the Macacú Formation, contribute to the region's dynamic geomorphological evolution.

3.2.3. Pedological Map

Soil units that occur in study are in the Figure 6. The pedological units, along with their corresponding symbols, and their relationships with the pedogeotechnical units are available in Table 3.

In the central part of the municipality of Guapimirim, Red-Yellow LATOSOLS (Oxisols) predominate. PLANOSOLS (alfisols) are present in flat reliefs and river terraces, with the majority occurring in urbanized areas. There is a minimal occurrence of YELLOW ARGISOLS (Ultisol) in the south-southwest area of the municipality, and they are situated within urbanized areas (ICMBio 2012).

FLUVIC NEOSSOLS (Fluvisols) occur in the coastal plains near the Macacu and Guapiaçú rivers. These soils develop from recent alluvial deposits. In low-lying areas near the sea, MELANIC GLEYSOLS (Gleysols) and THIOMORPHIC GLEYSOLS (Gleysols) are present, along with UNDIFFERENTIATED MANGROVE SOILS. These soils are hydromorphic and occur predominantly in mangrove environments.

It is noteworthy that the NEOSOLS (Entisols) (order) pedological legend, represented by the code R, is differentiated by the suborders FLUVIC (U), LITHIC (L), REGOLITHIC (R), and QUARTZARIC (Q). The suborders of soil classes are presented in Tables 4 and 5, where LATOSOLS (L) (Oxisols) are differentiated

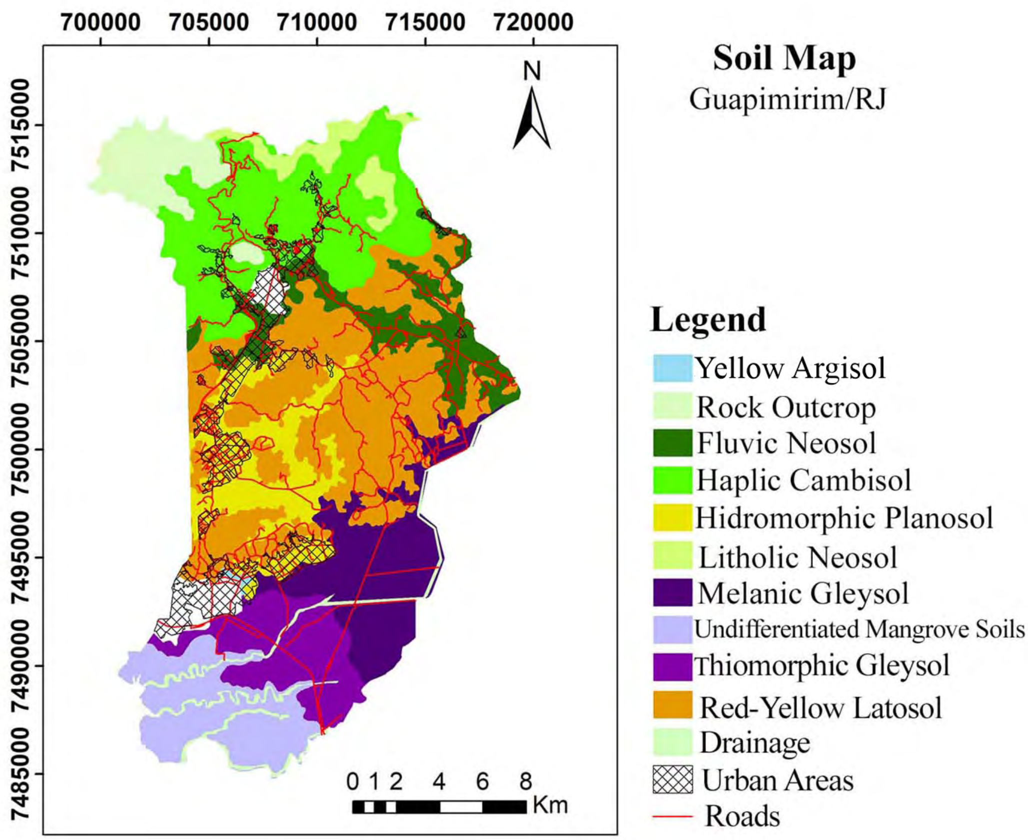

Figure 6 Soil Map of the Municipality of Guapimirim, State of Rio de Janeiro, Brazil. It was produced based on data from Rio de Janeiro (CPRM 2015), with adaptations made by the authors from field observations. (SIRGAS 2000/ UTM ZONE 23S).

by the numbers 1, 2, and 3, based on the relief. Here, 1 corresponds to those occurring in flat and gently undulating terrain, 2 to undulating terrain, and 3 to strongly undulating, mountainous, and rugged terrain. Similarly, the suborders of CAMBISOLS (C) (Inceptisols) are distinguished by the numbers 1, 2, and 3, based on the relief, where 1 corresponds to those occurring in flat and gently undulating terrain, 2 to undulating terrain, and 3 to strongly undulating, mountainous, and rugged terrain.

The Saline Gleysoils (Gleysols) SALINOS (Gz) are characterized by salinity, while the THIOMORPHIC (Gj) exhibit the presence of sulfidic materials and sulfides; both soil types occur in coastal areas. MELANIC GLEYSOLS (Gm) is distinguished by soils with a horizon A rich in organic matter. In contrast, the HÁPLICOS (Gx) do not exhibit any of these specific characteristics.

3.2.4. Pedogeotechnical Map

Figure 7 depicts the pedogeotechnical map, with the pedogeotechnical legend crafted following the methodology outlined by Antunes et al. (2013), albeit with modifications introduced by the current authors. As described in the Introduction, several authors have worked on extracting geotechnical information from the soil pedological classes in Brazil. However, the work by Antunes et al. (2013) was groundbreaking in systematizing the interpretation of pedological data for geotechnical applications, which justifies its use in this research.

A detailed exposition of the legend's interpretation is available in Table 3.

3.3 Pedogeotechnical Units

The association of attributes defines the geotechnical units presented on the pedogeotechnical map, giving them homologous characteristics from a geotechnical perspective. It is important to note that terrains with homologous geotechnical characteristics exhibit the same systemic functionalities. This characteristic should not be confused with the homogeneity of the unit, a concept associated

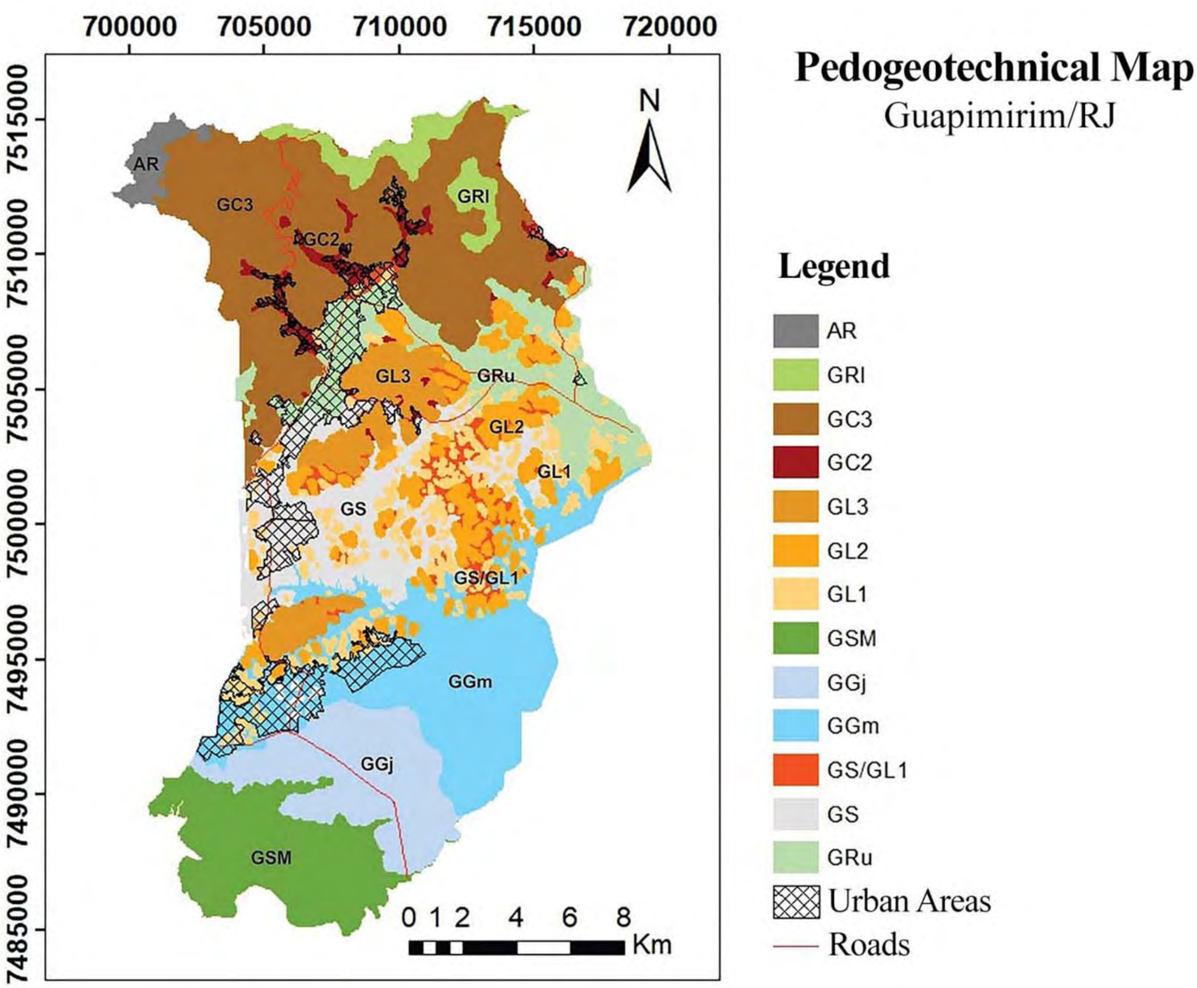

Figure 7 Pedogeotechnical Map of the Municipality of Guapimirim, State of Rio de Janeiro, Brazil. (SIRGAS 2000/ UTM ZONE 23S).

Table 3 Correspondence between the Pedological and Pedogeotechnical legend, with modifications made by the authors.

Pedogeotechnical unit	Pedogeotechnical legend	
	legend	**Sub-legend**
CAMBISOLS (C)	GC	1, 2, 3 Related to the topography
Colluvial-Talus Slopes *	* Introduced by the authors	
NEOSOLS (R)	GR	L (Litholic); R (Regolithic); U (Fluvic); Q (Quartzarenic)
LATOSOLS (L)	GL	1, 2, 3 Related to the topography
colluvial-talus ramp *	* Introduced by the authors	
PLANOSOLS (S)	GS	
GLEYSOLS (G)	GG	J (Thiomorphic); Z (Saline); M (Melanic); X (Haplic)
UNDIFFERENTIATED MANGROVE SOILS *	GSM	* Introduced by the authors
ROCK OUTCROP	AR	* Introduced by the authors

with the variability of each attribute or property within the same. Thus, different pedogeotechnical units may exhibit varying internal degrees of homogeneity or heterogeneity.

The classification distinguishes between units representing lowland environments, typically characterized by reducing conditions, and those associated with high-altitude environments, marked by oxidizing conditions. Detailed definitions for these units can be found in Antunes et al. (2013). The subsequent section comprehensively describes the pedogeotechnical units associated with this map.

3.3.1. Description of Attributes and Geotechnical Behavior in Lowland Environments

Unit GRU - Fluvic Neosols - This unit comprises Fluvic Neosols (Ru), which are characterized as transported soils with limited development and the absence of a B horizon. These soils occur in flat terrain, originating from fluvial processes, typically situated along watercourses. The granulometry of these materials is highly diverse due to the overlay of sedimentary deposits from various facies, lacking pedogenetic relationships. A notable feature relevant to urbanization is their susceptibility to flooding during periods of heavy rainfall. Understanding these characteristics is crucial for urban planning and environmental management in the designated areas.

Unit GS - Planosols (S)This unit is represented by Planosols (S), characterized by the presence of a Bp horizon distinguished by a high clay concentration formed through the translocation of this fraction within the soil profile. The pedogenetic translocation process in this soil class results in high compaction of the B horizon, where previous pores are filled with clay, imparting very low permeability to this horizon. This significant textural difference between the Bp and overlying horizons, especially in flat terrain or depressions, makes these areas prone to flooding during periods of intense precipitation. Additionally, in alluvial-colluvial ramps, they become susceptible to surface erosion. Understanding these soil characteristics is pivotal for land-use planning and erosion control strategies.

Units GGm and GGj – Gleysols- These units are hydromorphic soils. They occupy flat reliefs, fluvio-marine terraces, alluvial plains, and mangroves. The water table is close to the surface for a significant part of the year, rendering these soils saturated and prone to flooding, especially during periods of intense precipitation.

Melanic Gleysols (GGm): These Gleysols exhibit high organic matter percentages in the upper layers, making them potentially suitable for agriculture with proper management.

Thiomorphic Gleysols Gj): These soils are characterized by the presence of sulfidic materials and sulfides, accompanied by acidic pH. They are typically found in coastal areas associated with mangroves. This soil class is characterized by high compressibility, potential corrosiveness due to acidity, and susceptibility to inundation. In geotechnical terms, they are known as very soft to soft soils or organic clays. Understanding these soil characteristics is crucial for agriculture, coastal regions' land-use planning, and geotechnical engineering.

This unit comprises undifferentiated mangrove soils, consisting of saturated clayey sediments with high organic matter content and lacking developed pedogenetic processes. These soils are prevalent in flat relief areas near sea level, strongly influenced by tidal actions. The absence of pedogenetic development and the proximity to water level make them distinctive components of coastal environments. Understanding the characteristics of undifferentiated mangrove soils is crucial for assessing their role in coastal ecosystems and planning sustainable land use in these areas.

3.3.2. Description of Attributes and Geotechnical Behavior in High-Altitude Environments

Unit GL - Latosols (L) - This unit is represented by Latosols (L), known for their highly weathered nature, homogeneity, and limited horizon differentiation. A low-activity clay fraction with varying amounts of kaolinite, iron oxides, and aluminium oxides and hydroxides characterizes them.

These soils occur in different relief phases, and the legend assigns numerical designations as follows: GL1 for flat and gently undulating reliefs, GL2 for undulating reliefs, and GL3 for strongly undulating, mountainous, and escarpment reliefs. They can also be found in alluvial-colluvial ramps with steeper slopes near hills. Under natural conditions, these materials typically do not exhibit stability issues. However, due to the terrain characteristics, the GL3 class (strongly undulating and mountainous relief) presents the potential for mass movement occurrences. Understanding the variations within Latosols is essential for assessing their stability and geotechnical considerations in diverse relief scenarios.

Cambisols (C) - This unit is characterized by Cambisols (C), which consist of materials with low weathering alteration and less pronounced pedogenetic characteristics. They can occur in various relief phases, where GC1 represents flat and gently undulating relief, GC2 undulating relief, and GC3 strongly undulating, mountainous, and escarpment relief. These soils indicate areas with the presence of saprolite soils and/or colluvial and/or talus deposits.

These areas are susceptible to mass movements, especially in the case of CG3. The GC1 class, not belonging to high-altitude soils, is developed from unconsolidated sediments designated as Fluvic Cambisols.

Understanding the characteristics of Cambisols is essential for assessing their potential for mass movements and identifying areas prone to such occurrences, providing valuable insights for land-use planning and geotechnical considerations.

Unit GRl - Litholic Neosols (Rl) - This unit is represented by Litholic Neosols (Rl), predominantly found in mountainous terrain and commonly associated with Cambisols and rock outcrops. These soils are characterized by an A horizon directly overlaying rock or a thin layer of saprolite soil.

The occurrence of Litholic Neosols in mountainous reliefs, often in conjunction with Cambisols and rock outcrops, highlights their unique pedological characteristics. The direct contact between the A horizon and rock or a thin layer of saprolite soil distinguishes them within the landscape. Understanding these soil features is crucial for assessing the geotechnical implications and informing land-use planning in mountainous regions.

Unit AR - Rock Outcrops - This unit comprises rock outcrops, representing the association of various geological units, including Santo Aleixo, Santo Eduardo, Serra dos Órgãos, and post-tectonic granites.

Rock outcrops within this unit showcase the diverse geological formations, encompassing different rock types and geological units. Including geological entities highlights the complexity of the terrain and provides valuable insights for geological mapping and land-use planning. Understanding the specific characteristics of each geological unit is crucial for a comprehensive assessment of the terrain and its geotechnical implications.

3.4 Physical Characterization

This section details the physical characteristics of the soil and geological units within the mapped region. This comprehensive physical characterization is a foundation for understanding the terrain, aiding in various applications such as land-use planning, geotechnical assessments, and environmental management.

The results of the lowland soil physical characterization tests are presented in Table 4, and the empirical correlations between the SPT and the qu are provided in Table 5, as per Terzaghi & Peck (1968). It is emphasized that the CI and qu values are utilized solely as empirical indicators of material characteristics.

The pedogeotechnical unit is represented by the letter G and the pedological legend associated with each soil class. The sample legend includes the pedogeotechnical unit/pedological horizon (Tables 4 and 5). It is noteworthy that at point 12 (PLANOSOL), there is no pronounced leaching observed in horizon A, as it is an anthropogenic horizon.

Table 4 Physical characterization tests and empirical indices of lowland materials (flat relief).

PU	P/hz	C (%)	S (%)	Sd (%)	G (%)	S/C	Wn (%)	Wh (%)	LL (%)	PL (%)	PI (%)	AI	CI	qu (kgf/cm²)
GRU	1/C1	33	42	25	0	1.3	40.8	1.8	68	36	32	0.97	0.85	MH
	1/C2	34	56	10	0	1.6	56.9	4.0	67	41	26	0.76	0.39	MH
	2/C1	36	17	47	0	0.5	22.6	3.5	46	19	27	0.75	0.87	CL
	2/C2	44	14	42	0	0.3	26.2	3.8	56	20	36	0.82	0.83	CH
	3/C1	29	45	25	1	1.6	32.5	5.2	48	20	28	0.97	0.55	CL
	3/C2	8	16	76	0	2.0	16.7	2.0	NP	NP	NP	NP	NP	SC-SM
	4/C1	21	18	61	0	0.9	21.4	2.2	40	22	18	0.86	1.04	SC
	4/C2	22	15	63	0	0.7	20.6	1.9	36	18	18	0.82	0.85	SC
	5/C1	31	17	52	0	0.5	21.0	3.0	42	6	36	1.16	0.58	SC
	5/C2	26	10	64	0	0.4	15.3	2.2	NP	NP	NP	NP	NP	SC-SM
	6/C1	20	9	71	0	0.5	23.1	4.8	NP	NP	NP	NP	NP	SC-SM
	6/C2	29	9	62	0	0.3	25.0	4.0	NP	NP	NP	NP	NP	SC-SM
	7/C1	25	16	59	0	0.6	21.0	3.9	NP	NP	NP	NP	NP	SC-SM
	7/C2	30	9	61	0	0.3	20.5	1.5	50	33	17	0.57	1.74	SM
	8/C1	35	41	24	0	1.2	39.9	4.1	58	32	26	0.74	0.70	MH

Table 4 Cont.

PU	P/hz	C (%)	S (%)	Sd (%)	G (%)	S/C	Wn (%)	Wh (%)	LL (%)	PL (%)	PI (%)	AI	CI	qu (kgf/cm²)
	8/C2	26	37	37	0	1.4	38.8	3.2	45	33	12	0.46	0.52	CL
	9/C1	10	34	56	0	3.4	31.1	1.8	NP	NP	NP	NP	NP	SC-SM
	9/C2	36	27	37	0	0.8	44.0	2.9	35	23	12	0.83	0.83	SC
GS	10/Ap	17	14	69	0	0.8	16.2	1.4	NP	NP	NP	NP	NP	SC-SM
	10/Bp	29	11	60	0	0.4	20.7	1.6	35	23	12	0.41	1.19	SC
	11/Ap	17	10	69	4	0.6	14.3	0.7	NP	NP	NP	NP	NP	SC-SM
	11/Bp	29	22	48	1	0.8	28.2	1.2	50	36	14	0.48	1.56	ML-MH
	12/Ap	26	14	59	1	0.5	20.0	1.2	NP	NP	NP	NP	NP	SC-SM
	12/Bp	27	11	60	2	0.4	25.3	1.2	38	31	7	0.26	1.82	SM
GCM	13/A	28	51	21	0	1.8	50.4	4.4	61	33	28	1.00	0.38	MH-CH
	13/C	9	4	87	0	0.4	20.9	1.0	NP	NP	NP	NP	NP	SC-SM
	14/C	64	35	1	0	0.5	67.1	52.3	109	76	48	0.75	0.87	MH
GGJ	15/C	15	20	64	1	1.3	56.2	7.7	NP	NP	NP	NP	NP	SC-GM
	16/C	22	24	54	0	1.1	99.7	83.5	88	60	28	1.27	0.00	SM
	17C	57	39	4	0	0.7	95.7	80.3	141	83	58	1.02	0.78	CH

Legend: PU= pedogeotechnical unit; P/hz=point/horizon; C=clay; S=silt; Sd=sand; G=gravel; Wn= natural humidity; Wh= hygroscopic humidity; LL= Liquid Limit; PL= Plastic Limit; PI=Plastic Index; AI= Activity Index; CI= consistency index

Table 5 Correlations between Standard Penetration Test (SPT) and unconfined compressive strength (qu) for lowland materials (flat relief).

PU	P/hz	SPT	qu (kgf/cm²)	PU	P/hz	SPT	qu (kgf/cm²)
GRU	1/C1	11-19	1.5-4.0	GS	11/A	-	-
	1/C2	3-5	0.25-0.5		11/Bp	>19	>4
	2/C1	11-19	1.5-4.0		12/A	-	-
	2/C2	11-19	1.5-40		12/Bp	>19	>4
	3/C1	6-10	0.5-1.5	GS	13/A	3-5	0.25-0.5
	3/C2	-	-		13/C	-	-
					14/C	11-19	1.5-4.0
	4/C1	>19	>4				
	4/C2	11-19	1.5-4.0	GGJ	15/C	-	-
					16/C	<2	<2
	5/C1	6-10	0.5-1.5		17C	11-19	11-19
	5/C2	-	-				
	6/C1	-	-				
	6/C2	-	-				
	7/C1	-	-				
	7/C2	>19	>4				
	8/C1	6-10	0.5-1.5				
	8/C2	6-10	0.5-1.5				
	9/C1	-	-				
	9/C2	11-19	1.5-4.0				
	10/A	-	-				
	10/Bp	>19	>4				

Legend: PU = pedogeotechnical unit; P/hz = point/horizon; SPT= Standard Penetration Test; qu = unconfined compressive strength (qu)

Table 6 Physical characterization tests and empirical indices of high-altitude materials.

PU	P/hz	C (%)	S (%)	Sd (%)	G (%)	S/C	Wn (%)	Wh (%)	LL (%)	PL (%)	PI (%)	AI	CI	USCS
GRU	18/Bw	60	8	32	0	0,1	17,1	4,7	61	39	22	0,37	2,00	MH
	18/Cr	39	37	24	0	1,0	43,2	13,5	77	33	44	1,13	0,77	CH
	19/Bw	43	11	46	0	0,3	11,2	6,9	36	23	13	0,30	1,91	CL
	19/Cr	6	28	66	0	4,7	13,8	0,6	NP	NP	0	0,00	0,00	SC-SM
	20/Bw	48	7	44	1	0,2	8,5	1,7	57	26	31	0,65	1,56	CH
	20/Cr1	11	31	58	0	2,8	22,5	1,5	63	33	30	2,73	1,35	SC/SM
	20/Cr2	8	34	58	0	4,3	26,6	1,5	NP	NP	NP	0,00	0,00	SC-SM
	21/Bw	53	10	37	0	0,2	20,7	2,7	71	30	41	0,77	1,23	CH
	21/Cr1	20	38	42	0	1,9	11,7	1,2	55	32	23	1,15	1,88	MH
	21/Cr2	9	24	67	0	2,7	19,0	1,3	0	0	0	0,00	0,00	SC-SM
	22/Bw	44	7	46	3	0,2	14,8	3,9	69	44	25	0,57	2,17	MH
	22/Cr1	9	21	58	12	2,3	5,9	1,9	0	0	0	0,00	0,00	SC-SM
	22/Cr2	32	36	32	0	1,1	35,5	1,9	60	38	22	0,69	1,11	MH
GL2	23/Bw	55	10	35	0	0,2	23,1	7,0	58	35	23	0,42	1,52	MH
	23/Cr	25	32	40	3	1,3	28,1	7,2	56	32	24	0,96	1,16	MH-CH
	24/Bw	47	19	34	0	0,4	21,8	1,9	69	39	30	0,64	1,57	MH
	24/Cr1	14	44	42	0	3,1	27,2	1,5	55	38	17	1,21	1,63	MH
	24/Cr2	12	40	48	0	3,3	28,9	1,5	60	43	17	1,42	1,83	MH
	25/Bw	16	27	54	3	1,7	10,5	0,6	51	23	28	1,75	1,45	SC
	25/Cr1	2	15	83	0	7,5	2,4	0,8	0	0	0	0,00	NP	SC-SM
	25/Cr2	3	14	83	0	4,7	3,8	0,7	0	0	0	0,00	NP	SC-SM
GL3	26/Bi	15	28	56	1	1,9	4,6	1,4	37	27	10	0,67	3,24	SM
	26/Bw	40	10	46	4	0,3	9,9	1,4	44	25	19	0,48	1,79	CL
	26/Cr	8	28	64	0	3,5	19,9	1,2	0	0	0	0,00	-	SC-SM

Legend: PU= pedogeotechnical unit; p/hz= point/horizon; C=clay; S=silt; Sd=sand; G=gravel; Wn= natural humidity; Wh= hygroscopic humidity; LL= Liquid Limit; PL= Plastic Limit; PI=Plastic Index; AI= Activity Index; CI= consistency index.

Table 7 Correlations between the standard penetration test (SPT) and unconfined compressive strength (qu) for high-altitude materials.

	P/hz	SPT	qu (kgf/cm^2)		P/hz	SPT	qu (kgf/cm^2)
GL1	18Bw	> 19	>48	GL2	23/Bw	>19	>4,8
	18Cr	11 a 19 19	2,4 a 4,8		23/Cr	>19	>4,8
	19/Bw	> 19	>4,8		24/Bw	> 19	>4,8
	19/Cr	_	_		24/Cr1	> 19	> 4,8
					24/Cr2	> 19	>4,8
	20/Bw	> 19	>4,8				
	20/Cr1	> 19	> 4,8		25/Bw	>19	>4,8
	20/Cr2	_	_		25/Cr1	_	_
					25/Cr2	_	-
	21/Bw	> 19	>4,8				
	21/Cr1	>19	> 4,8	GL3	26/Bi	> 19	>4,8
	21/Cr2	-	_		26/Bw	> 19	>4,8

Table 7 Cont.

P/hz	SPT	qu (kgf/cm²)	P/hz	SPT	qu (kgf/cm²)
			26/Cr	_	_
22/Bw	> 19	>4,8			
22/Cr1	_	_			
22/Cr2	> 19	> 4,8			

Legend: PU = pedogeotechnical unit; P/hz = point/horizon; SPT= Standard Penetration Test; qu = unconfined compressive strength.

The characterization data and correlations between the penetration index and qu for highland soils are presented in Tables 6 and 7, respectively.

3.5 Geotechnical Map and its Units

The pedogeotechnical map, generated from physical and pedological characteristics, comprises six units and five subunits (Figure 8). These units are defined based on geological, geomorphological, and pedogeotechnical characteristics, supported by field and laboratory data.

3.5.1. Geotechnical Units of the Lowland Area in Guapimirim

Unit I

Located in the central north and northeast of the municipality, at altitudes from 13 to 40 meters, Unit I consists of floodplains formed from fluvial sediments, correlating with the pedogeotechnical unit GRu. The materials are heterogeneous, with varied grain sizes and plasticities, ranging from non-plastic to very high plasticities (Burmister 1949), and classified from ML-OL to CL, CH, and MH-OH (Table 4). The activity varies from inactive to normal, and the consistency ranges from soft to hard (Table 4). These diverse classifications underscore the dependency on the nature of the sedimented materials.

Based on the empirical relationships described in this article, this unit generally exhibits a low number of SPT blows and low qu (Table 5). The water table is frequently at or very near the surface, indicating a high susceptibility to flooding during rains (Figure 9).

One of the challenges we encountered during our field investigations was the flat terrain, which made it difficult to observe the thickness of the soil and sediments. Despite this, our auger investigations revealed that the water table is consistently close to the surface, at a maximum depth of 50 cm.

Unit II

Situated in the central-eastern region, at altitudes from 10 to 40 meters, Unit II includes valleys between hills and Planosols. It correlates with the pedogeotechnical unit GS, with a subunit II-A (Figure 10A) correlating with GS/GL1, distinguishing alluvial-colluvial ramps between the foothills and valley bottoms. The terrain exhibits sub-horizontal to gently undulating relief, with gentle slopes of 5 to 10 degrees. It is characterized by the interdigitation and/or covering of colluvial deposits by recent alluvial deposits.

Located at the highest part of those gentle slopes that extend to the Latosols, the Planosols show a textural contrast between horizons E (sandy) and Bp (clayey). The upper A and E horizons are non-plastic materials with low AI, while subsurface Bp horizons have medium to low plasticity, characterized by inactive clays and hard consistency. The Unified Soil Classification System classifies the A horizons of this unit as SC-SM, while the B horizons range from SC to ML-MH (Table 4). It is worth to emphasize the absence of pronounced textural differences in the A horizon at point 12 due to its anthropogenic origin (Ap).

Understanding these characteristics is crucial for any construction or engineering project in this area. For instance, the removal of the upper horizons (A and E) can lead to inundated areas when excavations (pits) expose the subsurface B horizon (Figure 10B). This unit is also prone to significant surface erosion during periods of intense precipitation due to drainage impediments in the Bp horizon and the non-cohesive A and E horizons. Empirical relationships with characterization data indicate high unconfined compressive strength and number of SPT blows, establishing better load-bearing capacity and more favourable conditions for shallow foundations when compared to Unit I.

In the same way, the thickness of this geotechnical unit was not possible to determine in the field, and the water table is at depths greater than 2.0 m at the top of the unit.

Unit III

Unit III is in the southeast and southwest, where urban settlement occurs, at altitudes from 7 to 25 meters, Unit III correlates with the pedogeotechnical unit GGm,

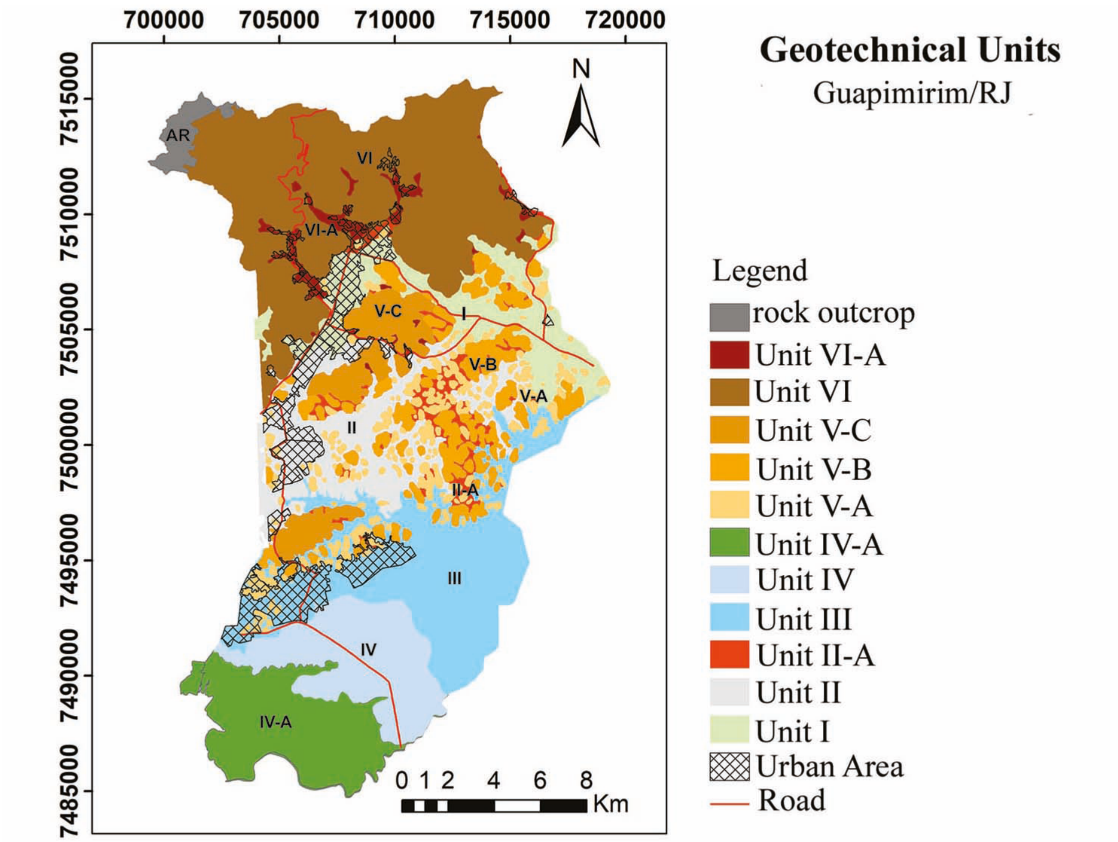

Figure 8 Geotechnical Units Map of Guapimirim Municipality, State of Rio de Janeiro, Brazil.

Figure 9 Typical flattened area corresponding to Unit I with floodable zones.

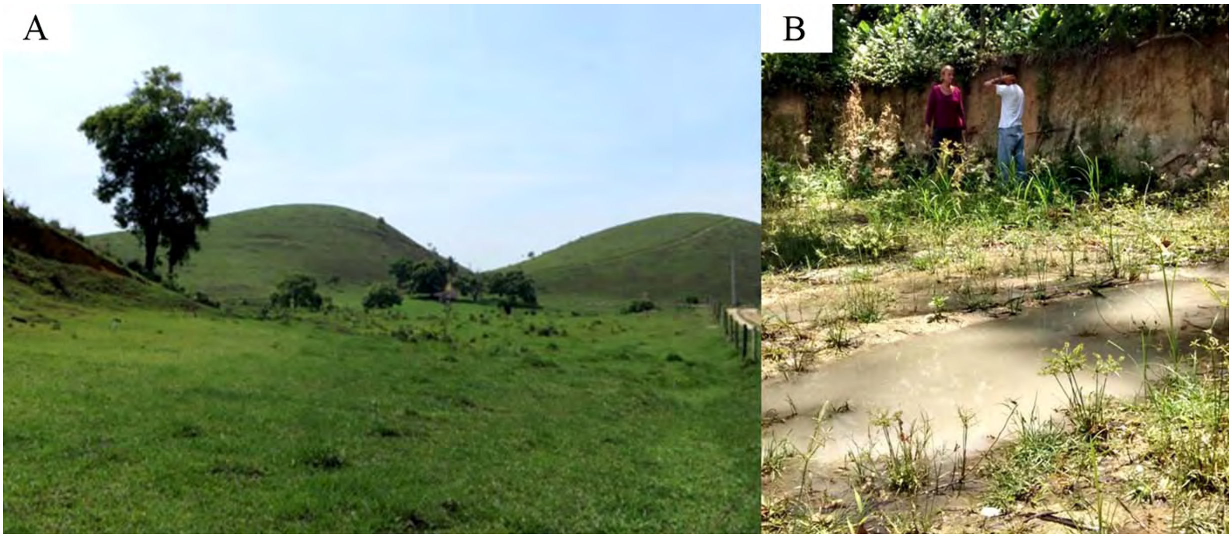

Figure 10 A. Depicts a sub-horizontal alluvial-colluvial ramp in Unit II-A; B. An area of Planosol with inundated excavations in Unit II.

which develops in plains and/or flood-prone areas during rainy periods (Figure 11A). It comprises mineral soils with potential organic and hydromorphic horizons, ranging from clayey-silty to sandy. The Atterberg limits exhibit high variability due to the influence of different sedimentary facies and textural variation in the samples (Table 4). Classified by USCS as SC-SM and MH, the GLEYSOLS present significantly elevated natural moisture content (Table 4), given that these soils are situated at low elevations, with the water table close to the surface, occupying extensive flat areas.

The CI varies from soft to firm, strongly influenced by seasonal moisture content. Consequently, the qu and SPT also exhibit corresponding variations (Table 4). This unit shows low strength and bearing capacity, mainly when classified as MH.

This geotechnical unit has the same characteristics as geotechnical unit I regarding soil thickness and water table depth.

Unit IV

Unit IV is in the extreme south, near sea level, at 0 to 7 meters, Unit IV correlates with the pedogeotechnical unit GGj, consisting of fluvial and marine sediments in consistently flooded terrains (Figure 11B). The materials vary from clayey to sandy, with plasticity ranging from very high to non-plastic. The PI varies from very soft to firm, directly dependent on natural moisture. The USCS classifies them as SC-SM, SM, and CH (Table 4), with natural moisture content almost always around 100%.

The materials' mechanical characteristics are poor, with low resistance and bearing capacity, comparable to soils designated as "soft" in Geotechnical terms. However, they become indurated when they eventually dry near the terrain surface and may display high strength. In addition to their mechanically unsuitable characteristics for direct loadings, their thiomorphic nature, containing sulfur in the form of sulfates, sulfides, and hydrogen sulfide acids, makes the materials in this unit acidic and corrosive.

Defined as a subunit, **IV-A** occurs at the mouths of rivers that flow into Guanabara Bay and consists of high-salinity mangrove areas. Its materials are constantly inundated and contained within a permanent environmental protection area. This subunit stands out for its saline nature, imposing its worst geotechnical characteristics regarding strength, acidity, corrosion, and heightened salinity. Sampling this unit was not feasible, as they are

Table 8 Summary of main characteristics of lowland geotechnical units.

Geotechnical Unit	Landform	Pedological Characteristics	Geotechnical Characterization
I	Fluvial Plains	GRu	ML-OL to CL, CH, and MH-OH
II	Fluvial Terraces and alluvial-colluvial fans	GS/GL1	SC-SM, SC to ML-MH
III	Fluvial Plains	GGm	SC-SM and MH
IV	Marine-fluvial plains	GGi	SC-SM, SM, and CH

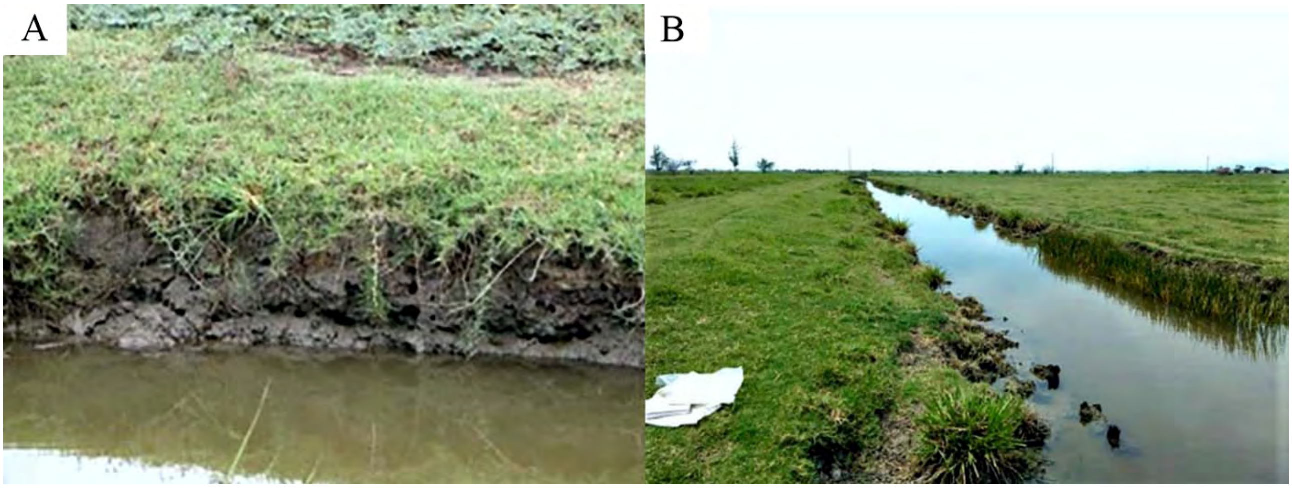

Figure 11 Depicts flood-prone areas in: A. Unit III; B. Fluvio-marine plain of Unit IV.

submerged. Its characteristics have been defined through pedological analysis.

The soil thickness is not observable, and the water table is on the terrain surface or at shallow depths around 50 cm. Table 8 summarizes the main characteristics of lowland units.

3.5.2. Geotechnical Units of Uplands in the Municipality of Guapimirim

Unit V

This **Unit V** is significantly relevant to the region and presents varying relief patterns, including GL1 (flat to gently undulating), GL2 (undulating), and GL3 (strongly undulating, mountainous, or escarpment) over migmatites and gneisses. It includes mature B horizons and saprolite Cr horizons.

Found in broad, gently sloping hills with amplitudes below 50 meters, covered by low vegetation (Figure 12), the **subunit V-A** correlates with the pedogeotechnical unit GL1. The B horizon soils are clayey and clayey-sandy, with plasticity ranging from medium to very high, AI from inactive to normal, and consistency indicating hardness and classifying as MH, CH, and CL (Table 5), according to USCS.

The Cr horizon has silty sand textures, PI from non-plastic to high, AI from normal to high, and CI indicating hardness, classifying as SC-SM, MH, and CH according to USCS. The Cr horizons are more sandy and/or silty than the mature B horizons, with a high silt/clay ratio (greater than 1), indicating a tendency toward erodibility. Excavations should avoid exposing the Cr horizon, and engineering projects should implement protective measures against erosion or slope instability.

This unit's soil thickness typically exceeds 15 m, and the water table cannot be directly visualized or determined in the field.

The **subunit V-B** occurs in dissected and low hills, with amplitudes from 50 to 100 meters and dense tree vegetation (Figure 13A), correlating with pedogeotechnical unit GL2. The B horizons (Figure 13B) have clayey, silty clay, and silty sand textures, high PI, AI ranging from inactive to active, and CI indicating hardness (Table 5). Soils classified as MH predominate in the B horizons of this subunit.

The Cr horizons are sandy, with AI from normal to active and CI indicating hardness. SC-SM soils of the USCS classification predominate on this horizon. The Cr horizons have a high silt/clay ratio, indicating a tendency toward erosion. Consequently, excavations conducted in this subunit should avoid exposing the Cr horizon, or appropriate protective measures must be implemented, such as erosion control or slope stability measures. This subunit is in higher relief areas, so erosional and stability issues are magnified, necessitating stricter precautions related to this issue.

The thickness of this geotechnical unit reaches an average of around 5.0 m and can vary between 2 and 10 m. We could not observe the water table in the field.

The **subunit V-C** occurs in high hills with amplitudes from 100 to 300 meters, correlating with pedogeotechnical unit GL, and includes Latosols (Oxisols) and sometimes Cambisols (Inceptisols). The B horizons vary from sandy to clayey, with PI from non-plastic to plastic, AI from normal to inactive, and CI indicating hardness (Table 5). The Bi horizons (less pedogenic) have high silt/clay ratios (greater

Figure 12 Broad hill - Subunit V-A.

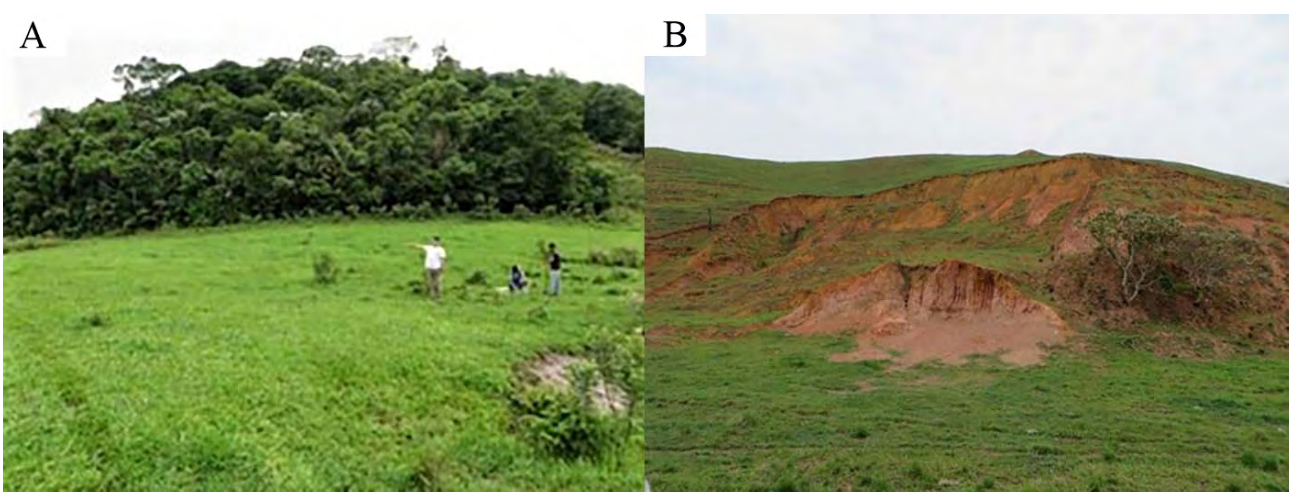

Figure 13 A. Low hill with dense vegetation of Subunit V-B; B. Broad hills highlighting colluvial B horizon over residual soil - Subunit V-B.

than 1), indicating erosion tendency, while Bw horizons (mature) have low ratios (lower than 1). The mature B horizons are classified as CL and Bi as SM. A sample from the Cr horizon was classified as SC-SM, also indicating a high erodibility characteristic. The presence of Bi over Bw horizons on steep terrain makes this subunit prone to erosion and slope instability processes (Figure 14A), recommending environmental preservation.

The third subunit, V-C, corresponding to the pedogeotechnical unit GL3, occurs in high hills with amplitudes ranging from 100 to 300 meters. It is distinguished by Latosols (Oxisols), sometimes associated with Cambisols (Inceptisols). Table 5 shows that the B horizons are characterized by sandy texture, PI ranging from non-plastic to plastic, AI ranging from normal to inactive, and CI indicating hardness. The B horizons in this unit are heterogeneous, varying from Bi (with little pedogenesis) to Bw (mature). The silty/clay ratios in Bi are above 1, and in Bw, they are below 1, indicating tendencies towards erosion (Bi) and those not prone to erosion (mature B). The mature B horizon is classified as CL, and Bi as SM.

In this subunit, only one sample test was conducted on the Cr horizon, where the silty/clay ratio (Table 5) is very high, indicating a significant tendency to be erodible. The material exhibited non-plastic behavior and was classified as SC-SM (Table 5). In fieldwork, a tactile-visual analysis revealed a pattern among the Cr horizons (saprolite soil), predominating of silty sand texture.

Subunit V-C is characterized by Bi horizon over mature Bw horizon in several locations. The association of these two B horizons, superimposed on saprolite soils in terrain with high slopes, makes this unit prone to erosion processes (Figure 14A) and issues related to slope instability. This subunit should be recommended for environmental preservation.

Due to this unit's rugged relief, the soil thicknesses are much smaller, reaching up to 2.0 m at maximum. The water table depth could not be determined in the field.

Unit VI

Unit VI covers a large area to the north of the municipality, comprising rocks of the Serra dos Órgãos Batholith, with granitic and granodioritic gneisses. The terrain is strongly undulating to mountainous, with steep slopes and high drainage density. Soils include Cambisols (GC3) and Lithic Neosols (GRL), with notable colluvial slopes and talus ramps (Figure 14B).

In these mountainous regions, soil thicknesses are minimal, reaching between 30 cm and a maximum of 1.0 m. The water table is not directly observable. Table 9 summarizes the main characteristics of upland units.

3.6 Territorial Planning: Discussion on the Potential and Weaknesses of Geotechnical Units

Each geotechnical unit represents a unique combination of geological, pedological, and geotechnical characteristics, distinct from other units. These characteristics allow for predicting the general behavior of these homologous land fractions in terms of territorial occupation

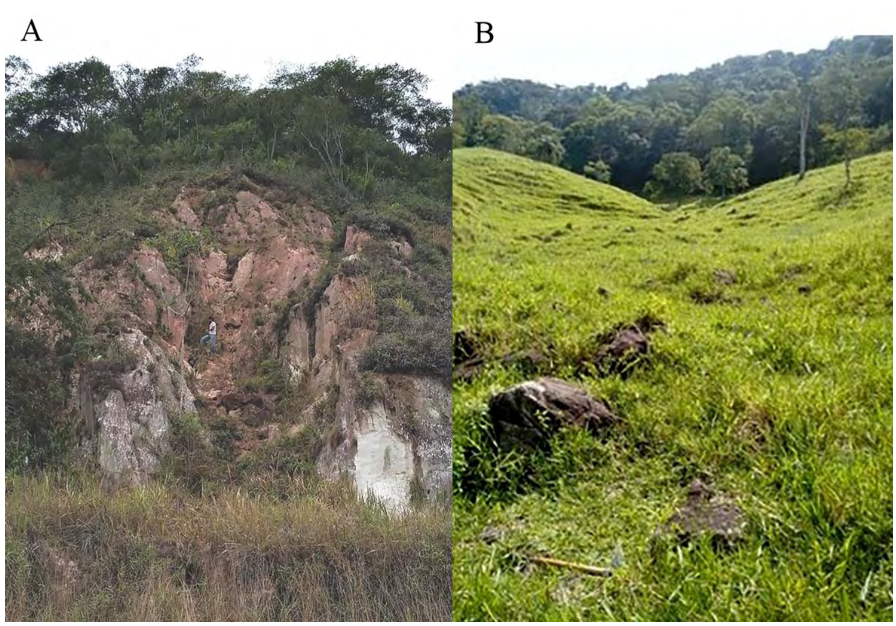

Figure 14 A. High hill of Subunit V-C with evidence of erosion; B. Colluvial slopes with subordinate talus - Unit VI.

Table 9 Summary of main characteristics of upland geotechnical units.

Geotechnical Unit	Landform	Pedological Characteristics	Geotechnical Characterization
V-A	Gently undulating	GL1	B: MH, CH, and CL C: SC-SM, MH, and CH
V-B	Undolating	GL2	B:MH C: SC-SM
V-C	Strongly undulating	GL3	B:CL, SM C: SC-SM
VI	Mountainous	GC3-GRL	

processes. Understanding the overall geotechnical behavior of these units enables legislators and municipal authorities to establish public policies that regulate land use and its economic and social functions. The Municipal Master Plan, which sets these policies according to Law 12.608, should include land subdivision, use, and occupation parameters to promote diverse uses and contribute to employment and income generation.

For the Municipal Master Plan to effectively manage territorial resources from social, economic, and environmental perspectives, it is essential to consider each geotechnical unit's potential and weaknesses. The following discussion focuses on the municipality of Guapimirim.

Generally, the lowland **units and subunits (I, II, III, and IV)** have similar restrictions. Soils and sediments with low bearing capacity require special attention for urban infrastructure development. Large commercial and residential buildings need deep foundations. Urban infrastructure near or on the surface (landfills, pavements, and water and sewage networks) may experience significant settlements in areas with soft or very soft consistency. Near Guanabara Bay, the salinity of mangrove soils poses corrosion risks to reinforced concrete structures. Due to mangroves' environmental significance, public authorities should protect these areas.

Soils with clay and silt-dominated parent materials **(I, III, and IV)** or soils with a textural gradient between horizons A and B **(II)** have poor natural drainage due to their low permeability. These materials, developed under hydromorphic conditions, which are conditions influenced by water, are found in valley bottoms and fluvial and marine floodplains. Their hydraulic and textural properties, along with their location, indicate flood-prone areas. Closer to Guanabara Bay **(IV)**, tides impede drainage during heavy and high rainfall. Intensive urban development in these areas should be avoided due to natural flood susceptibility and the high costs of large-scale landfills and complex drainage systems. These areas are better suited for non-population-dense economic activities like aquaculture and agriculture using floodplain cultivation systems, like rice farming.

Unit II offers the best conditions for urban development in Guapimirim's lowland areas, especially in higher parts where Planosols transition to Latosols. These areas have better conditions for occupation, with soils having greater bearing capacity and less flood susceptibility. However, occupation requires careful technical planning. Areas closer to the lower parts of Planosols can face flooding issues. When this unit contacts geotechnical units with more undulating or mountainous terrain, rapid surface water runoff (high erosion potential) causes flash floods and erosion processes. Therefore, occupying these areas will require robust drainage system projects tailored to local conditions. Exposing the surface soil in this unit is also not recommended to prevent severe erosion processes. The highest portions of this geotechnical unit, where latosols predominate, are the most suitable for occupation as they are not susceptible to flooding and intense erosion processes and have a good support capacity.

Subunits V-A and V-B stand out as the most suitable for sustainable urban development, especially V-A, which has less rugged terrain and requires less extensive earthworks. These subunits offer a promising opportunity for urban development, with soils boasting good bearing capacity, high strength, and better permeability compared to lowland units. However, it's important to note that exposing the C horizons or saprolitic soil can trigger erosion, particularly in silt-rich materials. Field observations show that erosion in C horizons leads to instability in surface soils, causing soil collapse due to a lack of support. Occupation of these units must consider the erodibility of C horizons, dependent on the local geological unit. Projects and excavations must always protect these horizons from surface runoff. Urban development should include drainage systems to manage surface flow in these geotechnical units.

Unit V-C, while possessing suitable geotechnical characteristics for urban occupation (except for erosion issues), presents a challenging terrain, requiring extensive excavation. These terrains transition to mountainous relief, where rocks, Neossolos Litólicos, and Cambisols dominate. Thus, this area disperses typical mountainous processes such as rockfalls, shallow and translational landslides at the soil-rock interface, and flow processes in the valleys. It's crucial to approach future urbanization in this unit with utmost caution, ensuring that it is sparse and supported by engineering structures to contain or minimize gravitational mass movements. Given its scenic beauty, geotourism could aid in its preservation and generate local employment and income.

Table 10 Recommended use for each geotechnical unit. Recommended with technical precautions (green), recommended with restrictions and strict observance of technical measures to minimize impacts (yellow) and not recommended (red).

Unit / Subunit	Urbanization	Rural Activity	Geotourism	Environmental Preservation
I	Red	Green	Red	Red
II	Yellow	Yellow	Yellow	Red
III	Red	Green	Red	Red
IV	Red	Red	Yellow	Green
V-A	Green	Yellow	Yellow	Red
V-B	Yellow	Yellow	Yellow	Yellow
V-C	Red	Yellow	Green	Green
VI	Red	Red	Yellow	Green

The mountainous areas of Serra dos Órgãos, with their native forests and challenging occupation conditions due to the relief and thin soil horizons (**Unit VI**), demand our immediate attention. This area should be designated for environmental preservation, a crucial step in ensuring the conservation of its unique ecosystem. Table 10 summarizes the recommended uses for each geotechnical unit. It is important to note that even recommended uses require the precautions discussed in this section.

4 Conclusion

The geotechnical mapping was conducted in the area of Guapimirim-RJ, Brazil, using the proposed methodology for generating the pedogeotechnical map with its discriminated units as one of the bases for obtaining the final geotechnical map at a scale of 1:50,000. Regarding the definition of geotechnical units, it is relevant to add interpretations of laboratory physical analysis data and use CI and empirical correlations, which are essential for geotechnical mapping.

Regarding the scale used in this study (1:50,000), it must be acknowledged that it will not be suitable for more specific purposes, such as application to urban subdivision. Using this scale will also present significant challenges for its application in densely populated regions, where public actions are focused on identifying susceptibilities or risks to geological-geotechnical processes. The scales of most fundamental maps available in Brazil are not suitable for geotechnical applications, which generally require much larger scales. However, in the case of geotechnical mapping for territorial planning, while this issue is relevant, it is less critical depending on the map's intended use. This is particularly true for municipalities with large areas available for expansion.

In this work, the differential compared to other mentioned studies is the creation of the pedogeotechnical map with its established units, later supplemented by physical analyses at strategic points, based on the pedogeotechnical map, resulting in the elaboration of the geotechnical map with its units.

It is understood that pedological interpretations and the creation of the pedogeotechnical map with its units, combined with physical analyses, allow for the delineation of homologous terrain units regarding general geotechnical behaviour, as well as susceptibility to mass movements, floods, and other geodynamic processes. This workflow leads to identifying of aptitudes and constraints for urban expansion in these units.

Therefore, the proposed use of the presented work as an auxiliary methodological tool for developing geotechnical maps and charts is suggested. This methodology is proposed because it is relatively simple to execute in areas where soil maps exist, as geotechnical units can largely be derived from pedogeotechnical interpretations combined with other indices.

The various geotechnical units have been established, and suggestions for potential use have been expressed in this article. However, it is important to highlight that for the implementation of specific projects, it is essential to support decisions with geotechnical studies appropriate to the structure to be installed.

5 Acknowledgments

The authors would like to thank to Serviço Geológico do Brasil for all the support given during the field campaign and making the Digital Elevation Model available.

6 References

ABNT 2016, *Solo - Determinação do limite de plasticidade - NBR7180*, Rio de Janeiro.

ABNT 2017a, *Solo - Determinação do limite de liquidez - NBR 6459*, Rio de Janeiro.

ABNT 2017b, *Solos - Grãos de pedregulho retidos na peneira de abertura 4,8 mm - Determinação da massa específica, da massa específica aparente e da absorção de água - NBR 6458*, Rio de Janeiro.

ABNT 2018, *Solo - Análise granulométrica - NBR 7181*, Rio de Janeiro.

ABNT 2024, *Solos - Preparação de amostras para ensaios de compactação, caracterização e determinação do teor de umidade - NBR 6457*, Rio de Janeiro.

Al-Ghorayeb, A., Al-Shaar, W., Elkordi, A., Faour, G., Al-Shaar, M. & Attalah, Y. 2023, 'Land Suitability Analysis for Sustainable Urban Development: A Case of Nabatiyeh Region in Lebanon', *J — Multidisciplinary Scientific Journal*, vol. 6, no. 2, pp. 267-85.

Aguiar, R.L. 1989, 'Mapeamento geotécnico da área de expansão urbana de São Carlos - SP: contribuição ao planejamento urbano', MSc dissertation, Universidade de São Paulo (EESC/USP).

Amaral, C.P. 1988, 'Mapeamento geológico-geotécnico da baixada de Sepetiba e maciços circunvizinhos da parte sul da folha Santa Cruz (M.E. 1:50.000)', MSc dissertation, Universidade Federal do Rio de Janeiro.

Anon 1972, 'The preparation of maps and plans in terms of engineering geology: Report by the Geological Society Engineering Group Working Party', *Quarterly Journal of Engineering Geology and Hydrogeology*, vol. 5, no. 4, pp. 293-382.

Antunes, F.S., Campos, T.M.P., Polivanov, H., Calderano, S. & Andrade, A. 2013, 'Desenvolvimento de classes e unidades geo-pedológicas a partir da interação entre a pedologia e a geotecnia', *Geotecnia*, no. 127, pp. 61-79.

Antunes, F.S., Barroso, J.A., Pedroto, A. & Polivanov, H. 1987, 'A importância da utilização de levantamentos pedológicos para a elaboração de mapas geotécnicos', *Anais do Simpósio de Geologia Regional RJ-ES*, pp. 227-35.

Barroso, J.A. 1986, 'Pedological maps interpretation for soil planning in the west zone of Rio de Janeiro', *Proceedings of International Association of Engineering Geology Congress*, pp. 1725-30.

Barroso, J.A. 1989, 'Experiências em mapeamento geológico-geotécnicos do Rio de Janeiro: escalas, detalhes a considerar e resultados', *Anais do II Colóquio de Solos Tropicais e Subtropicais e suas Aplicações em Engenharia Civil*, pp. 218-27.

Barroso, J.A. & Barroso, E.V. 1996, 'O meio físico como fator indispensável ao planejamento da expansão das cidades: o caso de Niterói – RJ', *Revista Brasileira de Geotecnia*, vol. 19, no. 1, pp. 63-77.

Barroso, J.A., Barroso, E.V. & Cabral, S. 1998, 'Evolução e análise da metodologia de mapeamento geotécnico no Rio de Janeiro', *Anais do III Simpósio Brasileiro de Cartografia Geotécnica*.

Barroso, J.A., Cabral, S., Pedroto, A.E. & Lino, G.L.S. 1986, 'Geological Geotechnical mapping of Rio de Janeiro's metropolitan region', *Proceedings of the 5th International Association for Engineering Geology and the Environment Congress*, pp. 1715-24.

Barroso, J.A., Cabral, S. & Fernandes, C.E.M. 1987, 'Problemas de mapeamento geológico-geotécnico em encosta com favela de alta densidade populacional', *Anais do V Congresso Brasileiro de Geologia de Engenharia*, pp. 267-78.

Barroso, J.A. & Lino, G.L.S. 1984, 'Subsídios geológico-geotécnicos para ordenação da ocupação do município de Petrópolis-RJ', *Anais do IV Congresso Brasileiro de Geologia de Engenharia*, pp. 279-90.

Barroso, J.A. & Pedroto, A.S. 1984. 'Mapeamento geológico-geotécnico em áreas dos municípios de Saquarema e Maricá', *Anais do IV Congresso Brasileiro de Geologia de Engenharia*, pp. 267-78.

Barroso, J.A., Polivanov, H., Antunes, F.S. & Cabral, S. 1981, 'Correlações de caracteristicas genética de solos e suas propriedades geotécnicas', *Anais do Simpósio dos Solos Tropicais em Engenharia*, pp. 187-98.

Bitar, O.Y., Campos, S.J.A.M., Monteiro, A.C.M.C., Argentin, P.M., Corsi, A.C. & Paulon, N. 2021, 'Mapeamento de áreas suscetíveis a movimentos gravitacionais de massa e inundações na região da macrometrópole Paulista', *Revista Brasileira de Geologia de Engenharia e Ambiental*, vol. 11, pp. 29-49.

Burmister, D.M. 1949, 'Principles and techniques of soil identification', *Proceedings of Annual Highway Research Board Meeting*, vol. 29, pp. 402-34.

Cabral, S. 1979, 'Mapeamento geológico-geotécnico da baixada de Jacarepaguá e maciços circunvizinhos', MSc dissertation, Universidade Federal do Rio de Janeiro.

Cabral, S. 1983, 'Mapeamento geológico-geotécnico da Baixada de Jacarepaguá e maciços circunvizinhos', *Solos e Rochas*, vol. 6, no.2, pp. 21-40.

Calderano Filho, B., Polivanov, H., Calderano, S.B., Barroso, E.V., Chagas, C.S., Guerra, A.J.T., Carvalho Junior, W. & Donagemma, G.K. 2013, 'Interpretação pedogeotécnica em paisagens montanhosas do médio alto curso do Rio Grande, região serrana do Estado do Rio de Janeiro, RJ', *Boletim de Pesquisa e Desenvolvimento - EMBRAPA Solos*, vol. 227, 55.

Calitz, F. & Hattingh, J.M. 2007, 'The value of Land Type information with regard to Initial Geotechnical Assessments in South Africa', *Proceedings of African Regional Conference for Soil Mechanics and Geotechnical Engineering*, pp. 31-6.

Caputo, H.P. 2015, *Mecânica dos Solos e suas Aplicações - Fundamentos*, 7th edn, LTC, Rio de Janeiro.

Carvalho, T.R.R. & Sobreira, F.G. 2016, 'Suscetibilidade a processos geodinâmicos e aptidão à urbanização na bacia do Rio Maracujá, Ouro Preto, MG', *Revista Brasileira de Cartografia*, vol. 68, n. 2, pp. p. 373-89.

Costa, A.N., Polivanov, H., Alves, M.G. & Ramos, D.P. 2011. 'Multicriterial analysis in the indication of favorable areas for edifications with shallow and deep foundations in the municipality of Campos dos Goytacazes - Rio de Janeiro, Brazil', *Engineering Geology*, vol. 123, no. 3, pp. 149-65.

CPRM 2001, *Geologia do Estado do Rio de Janeiro: texto explicativo do mapa geológico do Estado do Rio de Janeiro*, CPRM - Companhia de Pesquisa de Recursos, Brasília.

CPRM 2015, *Carta de suscetibilidade a movimentos gravitacionais de massa e inundação: município de Guapimirim – RJ,* CPRM - Companhia de Pesquisa de Recursos, Brasília.

Cratchley, C.R. & Denness, B. 1972, 'Engineering geology in urban planning with an example from the new city of Milton Keynes', *Proceedings of International Geological Congress*, pp. 13-22.

Da Silva, A.F., Talamini, A.A. & Zuquette, L.V. 2021, 'Engineering geological mapping procedures in data-scarce hillsides for shallow landslide assessments: applications in southeastern Brazil', *Journal of South American Earth Sciences*, vol. 111, 103489.

Dantas, M.E., Renk, J.F.C., Shinzato, E., Souza, L.V., Calderano, S.B., Fidalgo, E.C.C. & Aranda, C.C.C. 2012, 'Geomorfologia das bacias dos rios Guapi-Macacu e Caceribu - recôncavo da Baía de Guanabara - Estado do Rio de Janeiro', *Boletim de Pesquisa e Desenvolvimento - EMBRAPA Solos*, vol. 215, p. 59.

Dearman, W.R. & Fookes, P.G. 1974, 'Engineering geological mapping for civil engineering practice in the United Kingdom', *Quarterly Journal of Engineering Geology*, vol. 7, no. 3, pp. 223-56.

Dias, R.D. 1995, 'Proposta de metodologia de definição de carta geotécnica básica em regiões tropicais e subtropicais', *Revista do Instituto Geológico*, vol. 16, pp. 51-5.

Dias, R.D. & Gehling, Y.Y.W. 1982, 'Resistência ao cisalhamento e compressibilidade da crosta de um depósito de argila (Glei húmico) da Grande Porto Alegre', *Anais 8° Congresso Brasileiro de Mecânica dos Solos e Engenharia de Fundações*, pp. 107-20.

Dias, R.D. & Gehling, Y.Y.W. 1985, 'Influence of the microstructure originated from pedologic process on the mechanical behaviour of lateritic porous soil in south Brazil', *Proceedings of International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils*, pp. 255-68.

DRM 1972, *Projeto carta geológica do Estado do Rio de Janeiro*, folha SF-23-Z-B-IV, Escala 1:50.000, Petrópolis.

DRM 1980, *Projeto carta geológica do Estado do Rio de Janeiro*, folha SF-23-Z-B-II-3, Escala 1:50.000, Teresópolis.

DRM 1981, *Projeto carta geológica do Estado do Rio de Janeiro*. folha SF-23-Z-B-V-1. Escala 1:50.000, Itaboraí.

DRM 1984, *Projeto carta geológica do Estado do Rio de Janeiro*. folha SF-23-Z-B-I-4. Escala 1:50.000, Itaipava.

Eckel, E.B. 1952, 'Interpreting Geologic Maps for Engineers', in Committee D-18 (ed.), *Symposium on Surface and Subsurface Reconnaissance*, ASTM International, West Conshohocken, pp. 5-15.

Failache, M., Pons, N., Pejon, O.J. & Zuquette, L.V. 2022, 'Suitability zoning for sustainable drainage systems (SuDSs): Application in a basin in southern Brazil', *Sustainability*, vol. 14, no. 5, 2577.

Fanourakis, C.G. 2022, 'Utilising Land Type data for geotechnical investigations', *Journal of the South African Institution of Civil Engineering*, vol. 64, no. 1, pp. 12-24.

Fanourakis, G.C. 2012, 'Estimating soil plasticity properties from pedological data', *Journal of the South African Institution of Civil Engineering*, vol. 54, no. 2, pp. 117-25.

Fookes, P.G. 1967, 'Planning and stages of site investigation', *Engineering Geology*, vol. 2, no. 2, pp. 81-106.

Grossi Sad, J.H., Pinto, C.P., Serra, J.C., Barros-Dutra, J.E., Hettich, M. & Andrade, M.T. 1980, Projeto carta geológica do Estado do Rio de Janeiro - Folhas Anta, Duas Barras, Teresópolis e Nova Friburgo. Escala 1: 50.000, DRM-RJ/ GEOSOL, Rio de Janeiro.

Harmse, H.J.M. 1977, 'Die interpretasie van pedologiese data vir ingenieursdoeleindes', *Proceedings of 7th Conference of the Soil Science Association of South Africa*.

IAEG 1976, *Engineering Geological maps: A guide to their preparation*, UNESCO, Paris.

IBGE 2020, *Cidades e Estados*, viewed 12 February 2024, <https://www.ibge.gov.br/cidades-e-estados/rj/guapimirim.html>.

ICMBio 2012, *Plano de Manejo da Estação Ecológica da Guanabara*, viewed 13 February 2024, <https://uc.socioambiental.org/pt-br/noticia/111076>.

Kim, H.S. & Ji, Y. 2022, 'Three-dimensional geotechnical-layer mapping in Seoul using borehole database and deep neural network-based model', *Engineering Geology*, vol. 297, 106489.

Köppen, W. 1948, *Climatología: con un estudio de los climas de la tierra*, Fondo de Cultura Econômica, Mexico.

Lee, E.M. & Griffiths, J.S. 1987, 'The importance of pedological soil survey in land use planning, resource assessment and site investigation', *Engineering Geology Special Publications,* vol. 4, no. 1, pp. 453-66.

Lollo, J.A., Santos, F.M. & Curti, J.S. 2013, 'Avaliação do terreno em cartografia geotécnica expedita para planejamento urbano: exemplo de Ilha Solteira (Brasil)', *Revista de Geología Aplicada a la Ingeniería y al Ambiente*, vol. 31, pp. 29-38.

Luz, T.E., Lima, E.B.N.R., Salomão, F.X.T. & Lima, Z.M. 2015, 'Morphopedological approach applied to construction in the urban perimeter of Várzea Grande watershed, MT', *Ambiente e Água – An Interdisciplinary Journal of Applied Science*, vol. 10, no. 3, pp. 646-59.

Matula, M. 1979, 'Regional engineering geological evaluation for planning purposes', Bulletin of the International Association of Engineering Geology – *Bulletin de l'Association Internationale de Géologie de l'Ingénieur*, vol. 19, no. 1, pp. 18-24.

Mendonça-Santos, M.L., Antunes, F.S., Calderano, S.B., Santos, H.G., Polivanov, H., Campos, T.M.P., Zaroni, M.J., Donagemma, G.K. & Amaral, C.P. 2009, 'Correlação pedológico-geotécnica do Município do Rio de Janeiro', *Boletim de pesquisa e desenvolvimento - EMBRAPA Solos*, vol. 117, 46.

Moisa, M.B., Babu, A. & Getahun, K. 2023, 'Integration of geospatial technologies with RUSLE model for analysis of soil erosion in response to land use/land cover dynamics: A case of Jere watershed, Western Ethiopia', *Sustainable Water Resources Management*, vol. 9, no. 1, 13.

Moura, R.B. & Canil, K. 2018, 'Utilização das cartas de suscetibilidade e de aptidão à urbanização como forma de compreensão dos limites de ocupação do território no município de Angra dos Reis, RJ', *Anais do 16º Congresso Brasileiro de Geologia de Engenharia e Ambiental*.

Nogueira, F.R., Vasconcelos, V.V., Motta, M.R. & Varallo, L.S.S. 2019, 'Carta geotécnica de aptidão à urbanização: instrumento de planejamento para prevenção de desastres naturais no município de Itapecerica da Serra, SP', *Revista Brasileira de Geologia de Engenharia e Ambiental*, vol. 9, no. 01/02, pp. 26-35.

Nola, I.Á.S. & Zuquette, L.V. 2021, 'Procedures of engineering geological mapping applied to urban planning in a data-scarce area: Application in southern Brazil', *Journal of South American Earth Sciences*, v. 107, 103141.

Oliveira, C.M.G., Rodrigues, R.A. & Lollo, J.A. 2007, 'Carta de risco de colapso de solos para a área urbana de Ilha Solteira (SP), na escala 1:10.000', *Geotecnia*, vol. 110, pp. 183-98.

Oliveira, T.A., Riedel, P.S., Vedovello, R., Souza, C.R.G. & Brollo, M.J. 2007, 'Utilização de técnicas de fotointerpretação na compartimentação fisiográfica do município de Cananéia, SP - apoio ao planejamento territorial e urbano', *Geociências*, vol. 26, pp. 55-65.

Paranhos, H., Farias, R., Silva, J.M.L., Pereira, P.S., Sousa Júnior, R.P. & Hausser, A.M. 2019, 'Use of the Pedological Map in the Geotechnical Characterization of Aris Mestre D'Armas in Planaltina - DF', *Proceedings of Recent Research on Engineering Geology and Geological Engineering*, pp. 149-60.

Pejon, O.J. 1987, 'Estudos Geológico-Geotécnicos da Região de Araraquara-SP', MSc dissertation, Universidade de São Paulo (EESC/USP).

PNPDEC 2012 – no. 12 608.

Polivanov, H., Antunes, F.S., Barroso, J.A. & Cabral, S. 1984, 'Correlações entre parâmetros químico-mineralógicos e geotécnicos de Latossolos', *Anais 4° Congresso Brasileiro de Geologia de Engenharia*, pp. 391-406.

Popov, I.V., Kats, R.S., Korikovskaia, A.K., & Lazareva, V.P. 1950, *Technique of compiling engineering geological maps*, Ministry of Geology Press, Moscow.

Prandini, F.L.; Nakazawa, V.A. & Campanário, M.A. 1992, 'Cartografia Geotécnica da Grande São Paulo', *Atas do Simpósio Problemas Geológicos e Geotécnicos na Região Metropolitana de São Paulo*, pp. 242-52.

Prefeitura de Guapimirim 2000, 'Boletim Informativo Oficial do Município de Guapimirim', *Diário Oficial Eletrônico,* vol. 20, no. 575.

Rego-Neto, C.B. 1988, 'Morro da Cruz - Florianópolis - SC: condicionantes geológico-geotécnicos ao uso do solo', MSc dissertation, Universidade Federal do Rio de Janeiro.

Ribeiro, R.S. & DIAS, G.P. 2020, 'Carta geotécnica de aptidão à urbanização de Cataguases (MG): levantamento do histórico de ocupação territorial e proposta para a expansão urbana', *Anuário do Instituto de Geociências*, vol. 43, pp. 189-98.

Rozos, D., Apostolidis, E. & Xatzinakos, I. 2004. 'Engineering-geological map of the wider Thessaloniki area, Greece', *Bulletin of Engineering Geology and the Environment*, vol. 63, pp. 103-8.

Ruiz, M.D. 1987, 'A evolução da geologia de engenharia no Brasil e suas perspectivas', *Anais do 5º Congresso Brasileiro de Geologia de Engenharia*, pp. 29-46.

Rutka, A. 1961, 'Correlation of engineering and pedological soil classification in Ontario', in R. Legget (ed.), *Soils in Canada*, University of Toronto Press, Toronto, pp. 183-92.

Salomão, F.X.T. 1984, 'Interpretação geopedológica aplicada a estudos de Geologia de Engenharia', MSc dissertation, Universidade de São Paulo.

Santos, M.T. & Salomão, F.X.T. 1981, 'Utilização da pedologia em um estudo geológico-geotécnico para implantação de projeto de irrigação do distrito agroindustrial do Jaiba', *Anais III Congresso Brasileiro de Geologia de Engenharia*, pp. 401-16.

Secretaria Estadual do Ambiente - RJ 2011, *Estudo de Favorabilidade das Terras do Estado do Rio de Janeiro a Múltiplos Usos na Escala de 1:100.000*, viewed 12 December 2023, <https://www.cbhbig.org.br/plano/produtos/08%20-%20Relato%CC%81rio%20de%20Descric%CC%A7a%CC%83o%20da%20Base%20de%20Dados%20-%20BD.pdf>.

Simpson, B. 1938, 'Some practical examples of geology in civil engineering', *Institute Civil Engineers (South Wales and Monmouthshire Association)*, pp. 1-32.

Skempton, A.W. 1953, 'Colloidal "Activity" of Clays', P*roceedings of International Conference of Soil Mechanics and Foundation Engineering*, pp. 57-61.

Sobreira, F.G. 1989. 'Estudo de encostas ocupadas desordenadamente na cidade do Rio de Janeiro - a favela do Vidigal', MSc dissertation, Universidade Federal do Rio de Janeiro.

Souza, L.A. & Sobreira, F.G. 2013, *Guia para elaboração de cartas geotécnicas de aptidão à urbanização frente aos desastres naturais*, CPRM, Brasília.

Souza, L.A. & Sobreira, F.G. 2015, ‘Procedimentos para Elaboração de Cartas Geotécnicas no Planejamento Urbano’, *Revista Brasileira de Cartografia*, vol. 67, no.1, pp. 141-56.

Souza, L.A. & Sobreira, F.G. 2017a, ‘Proposta de unidades geomorfológicascomo suporte ao planejamento urbano e ordenamento territorial’, *Revista Brasileira de Geomorfologia*, vol. 18, no. 4, pp. 703-17.

Souza, L.A. & Sobreira, F.G. 2017b, ‘Bacia hidrográfica do Ribeirão do Carmo: atributos morfométricos, equação de chuva intensa e tempo de concentração, e análise da suscetibilidade a inundação’, *Revista Brasileira de Cartografia*, vol. 69, no. 7, pp. 1355-70.

Souza Pinto, C.E. 2016, *Curso básico de Mecânica dos Solos*, 3rd edn, Oficina de Textos, São Paulo.

Taveira, L.S. 1986, ‘Contribuição ao Mapeamento Geotécnico Preliminar do Município de Campinas-SP’, MSc dissertation, Universidade de São Paulo (EESC/USP).

Terzaghi, K. 1944, ‘Ends and Means in Soil Mechanics’, *Engineering Journal*, vol. 27, no. 12, pp. 608-15.

Terzaghi, K. & Peck, R.B. 1968, *Soil Mechanics in Engineering Practice*, 2nd edn, John Wiley & Sons, New York.

UFF/FEC 2010, ‘Planejamento Estratégico da Região Hidrográfica Rios Guapi-Macacu Caceribu-Macacu’, viewed 12 February 2024, <https://www.projetomacacu.uff.br/>.

Varnes, D.J. 1974, *The logic of geological maps, with reference to their interpretation and use for engineering purposes*, viewed 12 December 2023, <https://pubs.usgs.gov/publication/pp837>.

Vedovello, R., Ferreira, C.J., Salim, A., Costa, J. A., Matsuzaki, K., Rossini-Penteado, D. & Ohata, A.T. 2020, ‘Unidades básicas de compartimentação (UBC) do estado de São Paulo e seu uso para avaliações geoambientais e planejamento territorial’, *Revista Brasileira de Geologia de Engenharia e Ambiental*, vol. 10, pp. 73-87.

Wagner, A.A. 1957, ‘The use of the unified soil classification system by the bureau of reclamation’, P*roceedings of International Conference on Soil Mechanics and Foundation Engineering*, pp. 125-34.

Wilson, G. 1973, *Soils of the Morden-Winkler Area, Manitoba Soil Survey*, Manitoba, Canada.

Zuquette, L.V. 1981, ‘Mapeamento geotécnico preliminar da região de São Carlos’, MSc dissertation, Universidade de São Paulo (EESC/USP).

Zuquette, L.V. 1993, ‘Importância do mapeamento geotécnico no uso e ocupação do meio físico: fundamentos e guia para elaboração’, PhD thesis, Universidade de São Paulo (EESC/USP).

Zuquette, L.V. & Gandolfi, N. 2004, *Cartografia geotécnica*, Oficina de Textos, São Paulo.

Author contributions

Helena Polivanov: conceptualization; formal analysis; methodology; project administration; supervision; validation; writing – original draft; writing – review & editing. **Emilio Velloso Barroso:** formal analysis; methodology; writing – original draft; writing – review & editing. **Renan da Silva Ramos:** formal analysis; investigation; writing – original draft. **Victor Augusto Hilquias Silva Alves:** software; writing – original draft. **Felipe Polivanov Ottoni:** software; writing – original draft. **Rian Lucas Porto:** formal analysis; investigation; writing – original draft.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data included in this study are publicly available in the literature or they were obtained directly in the laboratory and explicitly presented in the manuscript tables.

Funding information

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and PIBIC/CNPq that financed the master’s and scientific initiation scholarships granted to the third and fourth author, respectively.

How to cite:

Polivanov, H., Barroso, E.V., Ramos, R.S., Alves, V.H.S., Ottoni, F.P. & Porto, R.L. 2025, ‘Geotechnical Cartography Applied to Territorial Planning: A Pedo-Geotechnical Approach’, *Anuário do Instituto de Geociências,* 48:e63135. https://doi.org/10.11137/1982-3908_2025_48_63135