Engineering Geological Mapping in the Basaltic Cuestas, São Paulo State, Brazil

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Abstract. Some difficulties of performing an engineering geological mapping task in sites where residual and transported sandy soils are widespread are discussed in this paper. The study area is located in the municipality of Analândia in the southeast of Brazil. In this region landscape evolution is dominated by scarp retreat and relief inversion processes. As transported and residual soils have very similar grain size distributions, the results of geotechnical tests performed on both kinds of soils are very similar. Understanding the regional landscape evolution was essential for performing the mapping task. The method used combined aspects of engineering geological mapping based on synthetic and analytical approaches and it is strongly supported by field observations. The expected engineering behaviors of the mapped units are presented. Some of the units correspond to colluviums that occupy hilltops, a geomorphological position were they would not be expected. Moreover, the "stone lines" are common features in the area and their identification clearly defines the unconsolidated material as allochtonous. However, they are not always located at the bottom of the colluvial deposits, and sometimes they are not present at all or show lateral discontinuity. Some other characteristics are distinctive of these widespread deposits.

Keywords: residual and transported sandy soils, "stone line", relief inversion, "Basaltic Cuestas".

1. Introduction

The purpose of engineering geology is to provide basic information for the planning of land-use and for the design, construction and maintenance of civil engineering works. A map provides the best impression of a geological environment, including the character and variety of engineering geological conditions, their individual components and their interrelationships (UNESCO, 1976).

Maps are primarily instruments for arranging, storing, transmitting and analyzing information about the spatial distribution of attributes. Spatial extrapolation or the assertion that place B has the same set of attributes known at place A, even though not all the attributes were measured or observed at B, is one of the transformations to be made by the specialist, when constructing a map (Varnes, 1974). Interpreting the units genetically is essential to allow reliable extrapolation of data.

This paper outlines the engineering geology of an area in the "Basaltic Cuestas", a typical landscape in São Paulo State, in the southeast of Brazil, and it presents the expected geotechnical behavior of each mapped unit.

Emphasis is placed on the experiences and specific difficulties of performing an engineering geological mapping task of the residual and transported sandy soils in a subtropical area where several different sandstone formations outcrop and which is affected by cliff retreat and relief inversion processes.

The experience gained in this research should prove useful in other areas with similar engineering geological conditions and weathering profiles of the "Basaltic Cuestas" geomorphologic province, which occurs in three different countries in South America (Paraguay, Uruguay and Brazil).

Mapping the area also aimed at gathering information about the physical environment to support land use planning. The use of the engineering geological data gathered in this case study for land use planning is discussed in Abreu & Augusto Filho (2012).

2. Study Area

The study area is located in the southeast region of Brazil, in São Paulo state (Fig. 1) and comprises the municipality of Analândia with a total area of 327 km^2. It is situated in a phanerozoic sedimentary basin called Paraná Basin. The Pirambóia, Serra Geral, Botucatu and Itaqueri geological formations outcrop in the area (Table 1).

Most of the study area is located in the geomorphological province called "Basaltic Cuestas", with altitudes ranging from 760 to 1020 m a.s.l. Only the south and central areas along the Corumbatai river are located in the "Peripheral Depression", with altitudes ranging from 560 to 760 m a.s.l. (Fig. 2).

The Basaltic Cuestas are an erosive feature of the Paraná basin border and are considered to have been formed in the Tertiary in the São Paulo state area (Fulfaro,

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Figure 1 - Location of the study area.

1975). In Analândia, this geomorphological province corresponds to two cliff systems, sometimes separated from one another: the lowest one is supported by the diabases of the Serra Geral Formation and ranges from 760 to 800 m. The upper one is supported by the Botucatu sandstone, with altitudes ranging from 800 to 900 m.

Melo *et al.* (1998, apud Melo & Cuchierato, 2004) recognized five planation surfaces having regional extent in the region, which can be interpreted as pediplains formed during Paleogene, Neogene and Quaternary in arid or semi-arid climates. Only three of them occur in the study area. Planation surfaces “A” and “I” were formed during the Paleogene and are located in the Basaltic Cuestas geomorphological province. Their altitudes range from 800 to 880 m (surface “I”) and above 1,000 m (surface “A”). Planation surface “B” was formed during Neogene and is situated in the Peripheral Depression geomorphological province. Its altitude ranges from 700 to 780 m.

According to the Koeppen classification, the predominant climate is type Cwa (humid mesotermic subtropical), with hot and rainy summers, as well as mild dry winters. The average precipitation is 1,350 mm/yr. Most of the study area was assigned as a protected area in 1983 due to its scenic beauty, as well as the remnants of local flora and fauna.

3. Method

The method used in this research combined characteristics of different existing methods of engineering geological mapping and it was presented in details by Abreu & Augusto Filho (2009). Basically, this method joined aspects of the synthetic approach, which is used by several researchers, such as Culshaw *et al.* (1990), Schalkwyk & Price (1990) and Nakazawa (1995), and aspects of the analytical approach, used by UNESCO (1976), Zuquette *et al.* (2004, 2009) and others. A Geographical Information System – GIS (Arcview) was used to combine information on surface and subsurface investigations and laboratory tests.

Table 1 - Simplified stratigraphic column of the study area

Formation	Age	Lithology
Itaqueri	Tertiary	Siltstone, sandstone, claystone
Serra Geral	Jurassic-Cretaceous	Basalt and diabase
Botucatu	Jurassic-Cretaceous	Sandstone
Pirambóia	Triassic	Sandstone

The mapping task was done on two different scales: a regional scale (1:50,000), covering the whole municipality, and a local scale (1:10,000), covering the urban area where geological hazards proved to be more intense. This progressive elaboration and zooming in of the mapping task was performed by other authors, such as Cerri *et al.* (1996) and the ZERMOS program by the French Laboratoire de Ponts et Chausse’s, Paris (Antoine, 1977).

The engineering geological mapping was carried out in three stages: the first stage comprised desk work and aimed at gathering the information already available for the area (government agencies, private consulting firms and research institutes), interpreting the aerial photographs and producing the digital elevation model. Field activities were undertaken, aiming at understanding the most significant geological processes occurring in the area (synthetic approach). This first stage determined the relevant attributes for the engineering geological mapping.

The second stage consisted of field activities and desk work needed to map these attributes (bedrock, unconsolidated materials and slope), as well as drawing the preliminary engineering geological map (analytical approach). Special attention was drawn in this stage to defining the typical weathering profile for each engineering geological unit and to deciding which soil samples could be regarded as representative of the respective profile.

The third stage comprised sampling and testing the materials representative of each typical weathering profile. Transfering geological data into geotechnical behavior involved an analysis of the test results and of the geological processes observed in the area, and relied on previous experience of the mapping team. This stage led to reviewing the unit division proposed on the second stage and drawing the final engineering geological map of the area (regional scale).

At this point, the urban area had already been identified as an area where unit detailing was necessary and the second and third stage activities were undertaken for mapping the urban area on a local scale. Data processing and final map preparation were carried out digitally using GIS tools.

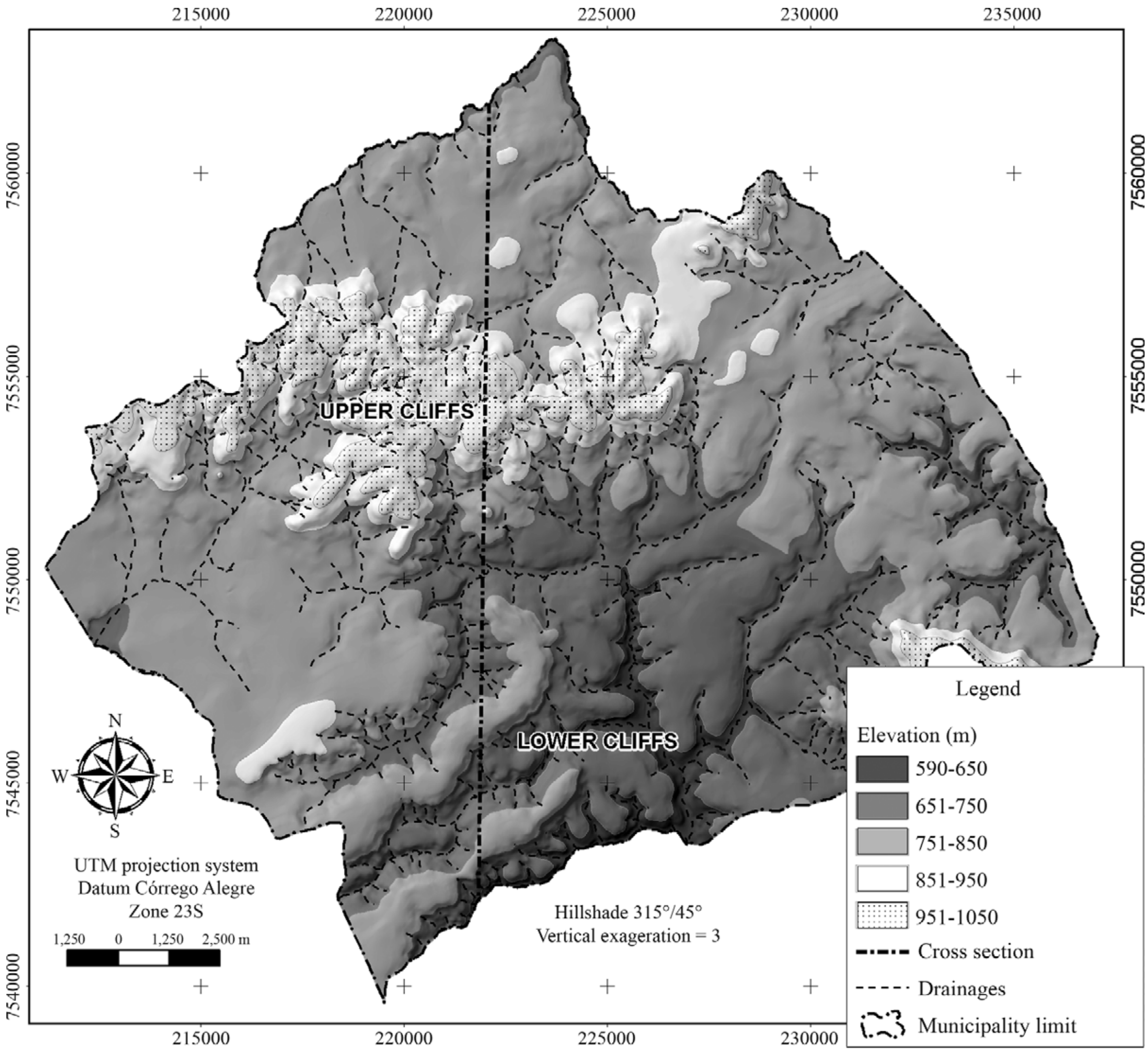

Figure 2 - Regional relief of the study area.

The approach proposed by Vaz (1996) was used to describe the weathering profiles. It comprises tropical soils and is based on a life-long experience in dealing with engineering geology in building and repairing dams, roads and tunnels in all kinds of rocks. This classification is based on the origin of the materials and encompasses transported and residual soils. In the study area, the transported soils consisted of alluviums, colluviums and talus.

For the *in situ* materials, the weathering profiles were divided into two significant horizons: residual soil, which corresponds to diggable material, and rock, which corresponds to rippable and blastable materials. The residual soil was subdivided into eluvial soil, which is homogeneous and shows no more traces of the original rock, and saprolite, which is heterogeneous and shows properties inherited from the parent rock.

The rock horizon was subdivided into weak weathered rock (WWR), hard weathered rock (HWR) and fresh rock (FR). WWR corresponds to a rippable, considerably weakened material, in which discoloration is penetrative. HWR and FR correspond to blastable material. FR is the material unchanged from the original state and HWR is the material that shows slight discoloration and weakening, especially along fractures. A description of a weathering profile does not necessarily include all these five subdivisions. Weak rocks typically show only the more weathered horizons, while hard rocks usually develop a complete weathering profile.

A total of 151 outcrops were described. Twenty disturbed and 20 undisturbed samples were collected. Samples were taken from slide planes, excavations, quarries and road cuts. Bearing in mind that it is crucial to transfer geological data into mechanical parameters, and to work with a minimum budget at the same time, few samples were taken for each unit, after considering which outcrops could be regarded as representative of the weathering profile for each unit.

The Atterberg limits, grain size distribution, unit weight, specific gravity and void ratio were determined in accordance with ASTM standards. The "activity" of the soils, as defined by Skempton (1953), was calculated.

The results of 115 m of boreholes with Standard Penetration Tests (SPT) performed in the urban area and 122 m performed in a nearby quarry were also considered for the characterization of the units.

4. Mapped Engineering Geological Units

Twelve individual engineering geological units were defined in the study area based on their origin, composition and expected geotechnical behavior. As expected for a subtropical climate, most of these units correspond to unconsolidated materials. Only two of them are characterized as fresh rock domains. The main characteristics of these engineering geological units are described as follows:

4.1. Unit 1- Recent alluvium

This includes loose soil deposits which occupy the river floodplains. They consist of clayey sands with light to dark grayish colors, sandy dark gray organic clays and brownish clayey gravels. These layers tend to be discontinuous and saturated. The engineering difficulties expected for this unit are low bearing capacity and differential settlements, as well as flooding prone areas.

4.2. Unit 2 - Recent talus

These deposits occupy the cliff footslopes in the present landscape. They consist of sandstone blocks, basalt-core gravels and a sandy or clayey sandy matrix, in variable proportions. The watertable forms at the bottom of the deposits. The geological processes associated with this unit are rotational landslides, especially in the rainy season, and creep.

4.3. Unit 3 - Sandy colluvium

These are terrestrial deposits, 5 to 15 m thick. They are composed of non plastic brownish or orange sands, with massive porous fabric, classified as SP-SM or SW-SM in the Unified Soil Classification System (USC).

They occur at the hilltops and slopes of broad hills with slopes ranging from 0 to 20% and elevations ranging from 680 to 880 m (Fig. 2). Melo & Cuchierato (2004) wrote about the origin and characterization of these deposits, which are regarded as quaternary colluvial-eluvial covers, and assigned them to the Santa Rita do Passa Quatro Formation.

"Stone lines" can usually be identified in these deposits. They should indeed be called "stone layers", as proposed by Morrás *et al.* (2009), because they are a three-dimensional body. In the study area these "stone lines" are flat or undulating sub-horizontal surfaces, which parallel the slope surface only when the slope is gentle. The gravel in the "stone lines" is formed of basalt, silica cemented sandstone, iron oxides cemented sandstone, ferricrete angular fragments and rounded quartz cobbles. The matrix is sandy, showing the same characteristic of the layers above and underneath the "stone line". Its thickness varies from 0.1 to 0.6 m and it can either show large lateral continuity (over a hundred meters) or it can be discontinuous. It may appear at the bottom of the deposit, but it is also often observed in the middle of it (Fig. 3) and sometimes there are various "stone line" levels in the same deposit.

These deposits have low bearing capacities and high compressibility, as stated by the SPT N values, which range from 0 to 9. They are prone to linear erosion and shallow translational slides. They are mined for the foundry and construction industries. Moreover, circular slides are common in road cuts.

4.4 Unit 4 - Clayey-sandy colluvium

These are tertiary-quaternary terrestrial deposits, which are over 7 m thick. They are composed of red brownish clayey sands, with massive porous fabric, classified as SC or SC-SM in the USC. They often present a "stone line", with the same characteristics of the "stone lines" described

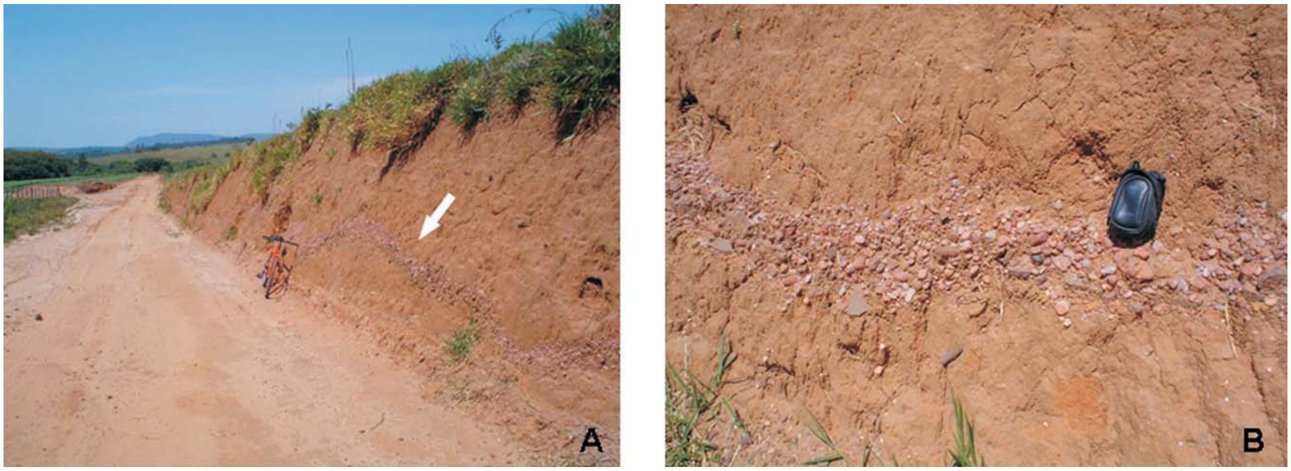

Figure 3 - Stone line in the middle of the sandy colluvium. A: Outcrop general aspect. B: Close view.

for the sandy colluviums (unit 3), except that the matrix is of clayey-sandy material.

This unit occupies the hilltops at the southwest of the study area, with elevations ranging from 780 to 870 m a.s.l. (Fig. 2). A colluvial origin is not expected for this geomorphological position, but the presence of the "stone lines" suggests an allochthonous origin for these covers.

These deposits are expected to have low bearing capacities and to behave as collapsible soils. They show little tendency to linear erosion and shallow translational slides are common in road cuts. This material is very adequate for fills, especially when impermeability is desirable.

4.5. Unit 5 - Sandy-gravelly colluvium

This unit comprises various layers of transported soils with different grain sizes and thicknesses (0.05 to 3 m) that are interpreted as remnants of old talus or alluvial fan deposits, formed at the footslope of ancient (eroded) cliffs. The most common layers are sands, gravelly sands, sandy gravels or clayey sandy gravels, with gravels composed of basalt, silica cemented sandstone, iron oxides cemented sandstone and ferricrete angular fragments and rounded quartz cobbles. Coal grains are also common and sandstone blocks occur rarely.

Where the gravel layers are thick, this material is extracted to be used for dirt road conservation, and the exposed layers are now prone to accelerated erosion. It is not always possible to determine the lateral extent of these deposits, unless large excavations are made, and this was not the aim of the present study. Nonetheless, site specific investigations in correlated areas must be aware of the possibility of its occurrence.

Engineering difficulties expected when handling these deposits are heterogeneities for excavation and for foundations (rock blocks immersed in a clayey-sandy matrix).

4.6. Unit 6 - Duricrusts of the Itaqueri Formation

The duricrusts correspond to tertiary nodular ferricretes that occupy the highest elevations of the study area, at the top of angular narrow hills. They comprise a 3 m thick layer formed in a more arid climate which is now being weathered under present climatic conditions. The ferricrete is a rippable material and it has been used by local farmers for dirty road conservation. The residual soil developed over this layer is eluvial homogenous brown silty clayey sand (SM) only 0.5 m thick. Coal grains are common in this soil. This unit is expected to have a high bearing capacity for shallow foundations and very low susceptibility to linear erosion.

4.7. Unit 7 - Residual soils of the Itaqueri Formation (non duricrusts)

This unit occupies the moderate to very steep slopes of the angular narrow hills, which occur in the study area in altitudes ranging from 940 to 1050 m. It corresponds to the weathering profiles developed over the conglomerates and conglomerate sandstones of the Itaqueri Formation. These profiles are uniformly weathered, and can be over 4 m deep in moderate and moderately steep slopes and only 2 m deep in steep to very steep slopes. In fact, no fresh rock has been identified in the outcrops. Only eluvial soils and saprolites were described.

The saprolite developed over the conglomerates shows inherited fabric: the matrix corresponds to a white and red silty sand (SM – sampled material), where the weathered gravel of the original conglomerate can be clearly identified. This horizon shows higher activity than all the other soils in the area and swells with moisture variations. The eluvial soil developed from the conglomerates is red clayey silty sand (SC-SM – sampled material).

The conglomerate sandstones showed no eluvial soil, and the saprolite showed clear inherited interbedded layers: sandy clays (CL-ML – sampled material) and sandy-gravels.

These soils can be excavated, but there are cobbles of ferricrete and quartz on the surface, so mechanized agriculture has to be done carefully. They are moderately prone to linear erosion. Swelling in the silty sands of the saprolite horizons and creep in the steep and very steep slopes have been observed in this unit. These soils are expected to have low bearing capacity and moderate compressibility. Pearched watertables occur.

4.8. Unit 8 - Residual soils of the Botucatu sandstones

They are composed of brownish non plastic sands, with massive fabric, classified as SP-SM. The weathering profile can be up to 20 m deep and is very permeable and homogenous. These soils occupy the tops and slopes of broad hills, with slope angles ranging from 0 to 20% and elevations ranging from 840 to 890 m a.s.l. They are expected to have low bearing capacities and high compressibility. They are prone to linear erosion and shallow translational slides are common in road cuts.

4.9. Unit 9 - Botucatu sandstone cliffs

This unit corresponds to the outcrops of silica cemented sandstone in the cliffs that surround the hills in the study area. They correspond to the upper cliff described previously. Residual soil up to 1 m thick may be present and corresponds to clean sand. Slab and block failures are common geological processes. The fresh Botucatu sandstone is used in neighboring areas as dimension stone.

4.10. Unit 10 - Residual soils of basalts and diabases (Serra Geral Formation)

The basalts and diabases which occur in moderate to moderately steep slopes in the area (angles ranging from 6 to 20%) show thin weathering profiles (2 to 5 m deep). The rock mass is typically corestone weathered and the eluvial soil is clayey, classified as MH, with a high void ratio. This material is used to maintain dirt roads. Linear erosion and creep are the most frequent processes in this unit.

4.11. Unit 11 - Diabase cliffs and steep slopes (Serra Geral Formation)

The diabases hold the lower scarp and neighboring steep slopes in the study area. The weathering profiles are corestone, usually less than 1 m deep, or the fresh rock is covered by recent colluvial soil. Slab and block failures and shallow translational slides are typical.

4.12. Unit 12 - Residual soils of the Pirambóia Formation

This unit is mainly composed of non plastic sands (classified as SM-SW soils), gravelly sands and clayey sands. These soils occupy the tops and the slopes of broad hills in altitudes ranging from 560 to 840 m.

The unit can be subdivided into three subunits, according to slope angles and corresponding erosion susceptibility (0%-12% - low tendency to erosion; 12%-20% - moderate tendency to erosion and 20%-40% - high tendency to erosion). This subdivision was based on a statistical analysis of the distribution of the existing linear erosions lengths in the various slope angle ranges.

The weathering profile can be over 30 m deep, showing only eluvial soil, saprolite and WWR horizons up to this depth. WWR is of interest as raw material for the glass industry. Saprolite and eluvial soil are of interest for the foundry industry. Eluvial soils give SPT N values of 3 to 9 and are up to 6 m thick. Saprolites give SPT N values of 7 to 13 in the first three meters and 28 to impenetrable to the SPT for another 3 to 4 meters, where they reach the WWR layer.

These soils are moderately permeable and develop pearched watertables over the clayey layers. Piping is a common process. They are diggable materials expected to have low bearing capacity for shallow foundations and to show high compressibility. Natural slopes with positive breaks show rotational landslides.

Table 2 presents the area distribution of the engineering geological units in the study area and summarizes their expected geotechnical behavior. Tables 3 and 4 present the results of the laboratory tests for the soils considered to stand for units 3, 4, 6, 7, 8, 10 and 12.

Units 1, 2 and 5 were not sampled, because they correspond to naturally discontinuous and heterogeneous materials and a few samples would not be representative of their variability. Units 9 and 11 were not sampled either, because no tests were performed on fresh rocks. Units 7 and 12 show significant variability in terms of grain size and only the most significant (or widespread) layers have been sampled.

Figure 4 illustrates the spatial relationships between the engineering geological units mapped using a south to north cross section of the study area.

Unit 3, which corresponds to sandy colluviums, stands out for covering over 50% of the land area. Residual soils of the Pirambóia Formation (Unit 12) also cover a significant municipal land area.

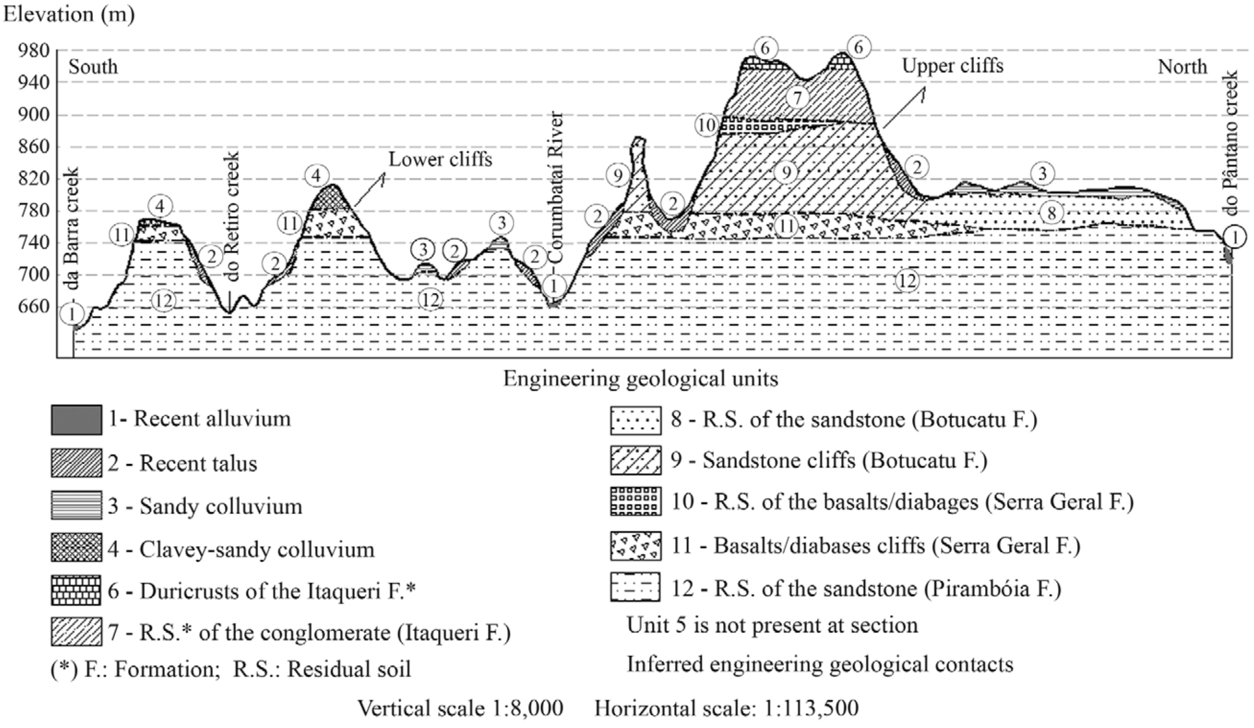

Figure 4 - Cross section of the study area with the mapped engineering geological units.

Table 2 - Engineering geological units and their expected geotechnical behavior.

Engineering geological units	Expected geotechnical behavior	Municipal land area (%)
1-Recent alluvium	Low bearing capacity for shallow foundations and differential settlements. Diggable material. Areas subjected to annual flooding.	2.3
2-Recent talus	Rotational landslides, especially in the rainy season, and creep. Heterogeneities for excavation and for foundations.	1.9
3-Sandy colluviums	Low bearing capacity for shallow foundations and high compressibility. Diggable material. High tendency to linear erosion. Shallow translational slides and circular slides in road cuts.	50.5
4-Clayey-sandy colluviums	Low bearing capacity for shallow foundations and collapse. Shallow translational slides in road cuts. Material is diggable and very adequate for fills, especially when impermeability is desirable.	5.6
5-Sandy-gravelly colluviums	Heterogeneities for excavation and for foundations. This material is exploited for dirt road conservation. Accelerated linear and laminar erosion takes place in exposed areas.	0.2
6-Duricrusts of the Itaqueri Formation	Rippable material, which has been used for dirt road conservation. High bearing capacity for shallow foundations and low susceptibility to linear erosion.	1.5
7-Residual soils of the Itaqueri Formation	Swelling in the silty sands of the saprolite horizons. Creep in the steep and very steep slopes. Low bearing capacity for shallow foundations and moderate compressibility. Perched water tables occur. Moderately prone to linear erosion. Diggable material, but there are cobbles of ferricrete and quartz on the surface, so mechanized agriculture must be done carefully.	7.4
8-Residual soils of the Botucatu Formation	Low bearing capacity for shallow foundations and high compressibility. Prone to linear erosion. Shallow translational slides in road cuts.	2.0
9-Botucatu Formation cliffs	Slab and block failures. Fresh Botucatu sandstone is quarried as dimension stone.	5.0
10-Residual soils of basalts and diabases (Serra Geral Formation)	Linear erosion and creep are the most frequent processes in this unit. Heterogeneities for excavation and for foundations. Typically corestone weathered material used to maintain dirt tracks.	1.8
11-Diabase cliffs and steep slopes (Serra Geral Formation)	Slab and block failures. Shallow translational slides.	2.6
12-Residual soils of the Pirambóia Formation	Perched water tables over the clayey layers are common. Piping is expected. Diggable material. Low bearing capacity for shallow foundations and high compressibility. Natural and man-made slopes show rotational landslides. Erosion susceptibility varies from low to high, depending on slope angle. Weak weathered rock horizons are of interest for the glass industry. Eluvial soils and saprolites are of interest for the foundry industry.	19.2

Table 3 - Engineering geological units, grain size distribution and Unified Soil Classification (USC).

Engineering geological units	Grain size distribution (%) (according to ASTM D422-63)				USC
	Gravel	Sand	Silt	Clay	
3-Sandy colluviums	0-2	88-90	3	5-9	SP-SM (SW-SM)
4-Clayey sandy colluviums	0-1	67-77	6-8	16-25	SC (SC-SM)
6-Itaqueri Formation – Duricrusts	2	49	20	29	SM
7- RS* Itaqueri Formation	0-9	39-67	10-20	10-44	CL-ML; SC-SM;
8- RS Botucatu Formation	0	65-91	4-20	5-15	SP-SM
10-RS Serra Geral Formation	0	3	24	73	MH
12-RS Pirambóia Formation	0-2	77-90	4-13	4-10	SW-SM

(*)RS = residual soil.

Table 4 - Engineering geological units, field density (ρ_{nat}), field dry density ($\rho_{d\ nat}$), specific gravity (ρ_s), field void ratio (e_{nat}), liquid limit (w_L), plastic limit (w_P) and activity of the clay fraction (A).

Engineering geological units	ρ_{nat} (g/cm^3)	$\rho_{d\ nat}$ (g/cm^3)	ρ_s (g/cm^3)	e_{nat}	w_L (%)	w_P (%)	A
3-Sandy colluviums	1.573-1.675	1.505-1.618	2.791-2.833	0.729-0.854	-	NP	-
4-Clayey sandy colluviums	1.427-1.676	1.322-1.587	2.722-2.849	0.775-1.145	21-32	15-18	0.28-0.67
6-Itaqueri Formation – Duricrusts	1.627	1.445	2.780	0.924	37	29	0.33
7- RS* Itaqueri Formation	1.455-1.775	1.300-1.588	2.848-2.986	0.880-1.191	39-64	25-44	0.36-2.86
8- RS Botucatu Formation	*	2.625	*	*	-	NP	-
10-RS Serra Geral Formation	1.668	1.217	3.156	1.593	98	46	0.80
12-RS Pirambóia Formation	1.636	1.544-2.780	2.786	0.804	-	NP	-

(*)RS = residual soil; * = sample was damaged during transportation.

Some of the units have economic or scenic importance, even though they account for a small land area. For instance, Unit 9 (Botucatu sandstone cliffs) accounts for the scenic beauty of the area and for the income from tourism. Unconsolidated materials of units 5 (sandy-gravelly colluviums), 6 (duricrusts of the Itaqueri Formation) and 10 (residual soils of the Serra Geral Formation) are used for dirt road conservation in the rural areas.

5. Discussion

One of the most challenging aspects of the performed mapping task was to identify the origin of the various sandy unconsolidated materials which occur in the area and to map their continuity. As described previously, units 3, 4, 8 and 12 are composed mainly of sandy materials (over 65% of their grain size distribution).

As weathering profiles developed over sandstones are relatively simple, when compared to those developed over igneous and metamorphic rocks (Price, 1995), one would at first expect that mapping the engineering geological units in the study area would be an easy task.

The fact that the landscape in the area is marked by cliff retreats implies that transported soils are widespread in the study area and mapping their distribution makes the mapping task much more complicated.

Moreover, there are two separated cliff systems in the study area, which are locally joined in one escarpment. This implies that the terrestrial transported unconsolidated materials (talus and colluviums) derived from the retreat of the upper cliff system may occupy the hill tops of the lower cliff system, and that characterizes a process of relief inversion. Figure 5 is an interpretation of how the landscape evolved in the area during Paleogene and Neogene adapted from Vaz (1997).

This is typical of Unit 4 in part of the study area (Fig. 4). Materials classified as Unit 4 can be easily distinguished from the other sandy materials, both in field work and when comparing laboratory test results, because their clay content (minimum 16%) is sufficient to give them plasticity and this alters their geotechnical behavior significantly. Moreover, the material shows a distinctive red brownish color, when compared to the other yellowish sandy materials which characterize units 3, 5, 8 and 12. However, as they occupy hill tops and show this particular color, they have been mapped as residual soils derived from diabases in some of the previous work done in the area. Identifying "stone lines" has proved that they are terrestrial transported soils derived from the weathering of basalts and sandstones in the upper cliff retreat process. As the area is undergoing relief inversion, "stone lines" occupy hilltops nowadays.

Units 3, 8 and 12 are all composed mostly of non-plastic unconsolidated materials classified as SW-SM-SP soils. Figure 6 shows a comparison of their grain size distribution, highlighting the difficulty in distinguishing one from the other, considering the test results only. This situation could even be expected, as the sandy colluviums are basically transported soils formed by sandstone cliff retreats. In other words, Unit 3 is a transported soil derived from materials of Unit 8, which explains their similarities. Unit 12, although not directly related to the origin of Unit 3 (except locally), is composed of sandy soil profiles, which can mistakenly be interpreted as belonging to Unit 3, if their origin is not properly identified.

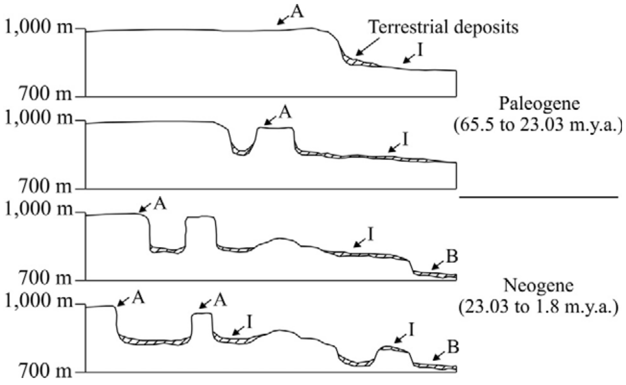

Figure 5 - Schematics of landscape evolution in the study area (m.y.a. = million years ago).

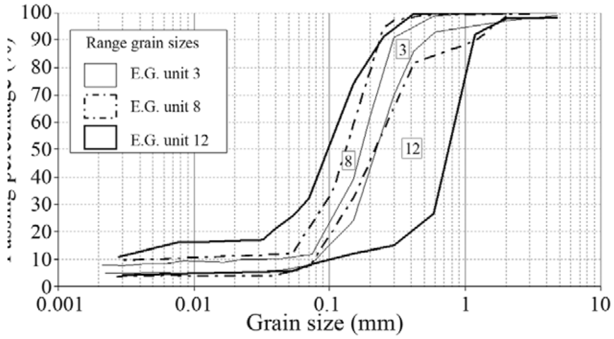

Figure 6 - Range grain sizes of the engineering geological units: sandy colluviums (3); residual soils of Botucatu formation (8) and residual soils of Pirambóia formation (12).

Although their expected geotechnical behavior is similar, especially for units 3 and 8, it is important to map these materials as separate units. Understanding their genesis is essential to defining their spatial distribution and extrapolating expected behaviors for land-use planning and engineering design purposes. Field work is essential to distinguish between these two units. The sandy colluviums (Unit 3) show a distinctive porous massive fabric with scattered quartz pebbles (4-64 mm). In the residual soils of the Botucatu Formation (Unit 8) the fabric is massive, but less porous, and the quartz pebbles are not common.

Identifying a "stone line" is a decisive factor in considering the sandy material as transported, but unfortunately this is not always possible. On one hand, because the "stone line" is not always present in the deposit and on the other hand, because sometimes the outcrop is not high enough to show the "stone line". "Stone lines" covered by 1.5 up to 10 meters of sandy material were identified in the study area.

There is much controversy in the literature about the origin of "stone lines" and results obtained so far suggest that there may exist allochthonous and autochthonous "stone lines" (Braucher *et al.*, 1998; Lichte & Behling, 1999; Brown *et al.*, 2004; Morrás *et al.*, 2009). The characteristics of the "stone lines" in the study area suggest that they are allochthonous, in accordance with Melo & Cuchierato (2004). The cobbles in the "stone lines" are clearly transported material, because they include siliceous and iron cemented sandstone and laterite fragments, similar to those that occur in Unit 6 on hilltops of the upper cliff system (highest elevations of the area).

Moreover, in many outcrops more than one "stone line" was identified, which proves that they are not necessarily located at the bottom of the transported material layer and belies common sense that their identification characterizes the end of the deposit (*e.g.* Landim *et al.*, 1974; Giacheti *et al.*, 1993).

Mapping Unit 12 and separating it from the other sandy materials is relatively easy and clear, because it shows greater variability in grain size distribution (Fig. 6) and has occasionally an interbedded clayey-sandy layer or a sandy-clayey layer, and thus it can be identified in the field and in comparing test results.

6. Conclusion

The method used for this mapping task combines the characteristics of other different methods presented in the technical literature and is able to gather sufficient information about the geological setting of a region, while working with a minimum budget. It combines field and laboratory work, as well as data from superficial and subsurface investigations.

Twelve engineering geological units have been mapped in Analândia. The expected engineering properties of these units, as well as the geotechnical problems which occur in the area were presented. Because the study area is part of a larger, geologically and geomorphologically similar terrain, the anticipated problems here are relevant to other similar areas.

As the area is almost entirely covered by sandy soils, one could first expect that there would be no significant differences in their response to the various engineering tasks. However, this study has shown that, although these soils have similar behavior, they also show distinctive characteristics. Understanding their origin is the only way of reliably extrapolating their characteristics and mapping their lateral continuity and spatial distribution.

In the Analândia municipality, some of these sandy soils are colluviums and occupy geomorphological positions were they would not be expected (hilltops). Their position in the present landscape is explained by the fact that the area is undergoing relief inversion. Understanding the evolution of the regional landscape is essential for mapping these units.

These tertiary-quaternary colluviums are widespread in the border of the Paraná Basin in the southeast of Brazil and play an important role in engineering. On one hand, it has been determined that there are three different kinds of colluviums in the area: sandy colluvium, clayey sandy colluvium and sandy gravelly colluvium. On the other hand, it has been shown that it is impossible to distinguish between residual soils developed over the sandstones and the sandy colluvium, based only on currently used geotechnical tests (grain size distribution and Atterberg limits). Understanding the occurrence of these deposits in the present landscape and observing their undisturbed characteristic in natural or artificial cuts is essential for mapping their spatial distribution.

Moreover, it has become clear that "stone lines" are not always located at the bottom of the colluvial deposits, and sometimes they are not present at all or show lateral discontinuity. Identifying a "stone line" clearly defines the unconsolidated material as allochtonous, but this is not the only distinctive characteristic of these deposits. Their massive porous fabric is also an important characteristic, which must be observed in field work.

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