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# Tropical residual soil data compilation as guidance for laboratory tests and EPB excavation process simulation

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ABSTRACT: The current trend of intense urban growth around the world has brought an increase in the demand for underground infrastructures including urban tunnels. In many cities, tropical residual soils are the main ground type in which tunnels are driven. Therefore, a thorough understanding of the residual soil engineering behaviour is crucial for planning and design. Considering the large increase in the use of tunnel boring machines, such as the Earth Pressure Balance (EPB), the need for more studies related to this type of construction method when applied to tropical residual soils is undeniable. To characterize the variability of tropical residual soil properties, a database of worldwide published data on laboratory and in-situ testing has been elaborated. This paper presents the results of this compilation together with statistical analyses of its content.

## 1 INTRODUCTION

Historically, the development of large cities took place mainly along sedimentary basins due to watercourse proximity and flatter geomorphology. Consequently, geotechnical studies have been concentrated in Quaternary, Neogenic and Paleogenic sediments, in areas with more economic prominence and major construction works. Nowadays, after the urban centre expansion, the geotechnical information on tropical residual soils from the outer city has become more and more important.

Although tropical residual soils have been previously investigated leading to a substantial amount of laboratory and *in-situ* testing data, the knowledge of their engineering behaviour is not as extensive when compared to that available for transported sedimentary soils.

The purpose of this work is to gather the worldwide available data on the behaviour of tropical residual soils. There is no intent to establish behaviour rules and standards, but only to introduce an overall perspective for the up-to-date information on this type of soil.

## 2 BACKGROUND

In the early 80's, the need for improving renewable energy sources and infrastructure development of several countries resulted in an extensive campaign to investigate and understand the characteristics and behaviour of natural materials used for engineering purposes. During this period, in tropical countries, several dams and roads were constructed and the field of Geotechnical Engineering gained its full strength. In Brazil, for instance, a high amount of research has taken place within the hydro power plant projects and provided a valuable source of support for re-search groups to investigate the tropical residual soils. Prof. Milton Vargas, from the University of São Paulo, a pioneer in Soil Mechanics studies in Brazil, brought to light the distinguishing characteristics and behaviour of tropical soils, sharing his knowledge to the world, later followed by his students.

According to Futai *et al.* (2012), Vargas introduced the tropical soils to Prof. Karl Terzaghi, known as the father of Soil Mechanics, and commented about his impression: "When, during the classes, I was talking about the differences of such soils, Terzaghi showed interest, but when he touched our soil his face excused any additional comment. Yes, he was surprised. Yes, we had a different soil. They were quite accustomed to the Boston sedimentary clay, but had never seen tropical soils".

Nowadays, the interaction of infrastructure engineering projects with this vast and variegated assortment of tropical residual soils still presents challenges. Those challenges become even more tangible when this kind of material is excavated by

TBM's, as mentioned recently by Oliveira and Diederichs (2016) and was called the "Pandora's box" of mechanized tunnelling.

As described by those authors, EPB machines encountered several issues while excavating the typical mixed transitional ground, where a tropical residual soil gradates to a weathered rock, also called as Intermediate Geomaterials (IGM) or as Hard Soil/Soft Rock (HSSR) by Viana da Fonseca and Topa Gomes (2010).

The more heterogeneous the original rock, the more irregular the soil/rock transition. The more irregular the transitional boundary, the more difficult its delimitation prior to the excavation, even with proper site investigations. Therefore, most of the upper mentioned EPB excavation issues lie on the mixed transitional ground.

In order to introduce the reader to the wide heterogeneity of the tropical residual soils, a database was elaborated with the main characteristics of such soils, as published by several researchers.

Furthermore, this database is expected to serve as a guidance for future laboratorial testing and EPB excavation process simulation.

The database is presented in the form of graphs, diagrams and tables, the data information has a detailed description of residual soils originated from gneiss, migmatite and granite. Additionally, it presents a brief idea of the use of this data for guiding future research work on mechanized tunnelling with frontal chamber.

## 3 DATABASE

The database encompasses 519 samples, elaborated with compiled data from 118 publications, including scientific papers, academic thesis and technical reports, starting from 1951 up to contributions recently published in 2017. Its complete version is available as a spreadsheet file that can be consulted online at: *https://www.researchgate.net/publication/309564759_ResidualSoilCompilation_Final.*

All the publications used for this database are listed at the References section. Figure 1 presents the publication year of each contribution. An increase of publications can be observed during the 80's and 90's, reaching the highest amount at the 2000's.

As visualized in Figure 2, the contributions came from 18 countries. Most of the authors whose data contributed to this research are Brazilians working on tunnelling projects. Hence, there is a natural bias to the acquired information. It is imperative to emphasize that such compilation does not represent the actual global scenario of contributions to the subject, but only the geographical distribution of the acquired data. The intention is to continue the compilation work, thus any new collaboration from other researchers are more than welcome.

It is important to mention the valuable contributions from Profs. Viana da Fonseca and Topa Gomes, from University of Porto (Portugal), with publications about the Porto Metro, one of the first to conceive excavations with EPB machines in mixed transitional ground.

Prof. Harianto Rahardjo, from Nanyang Technological University (Singapore), has published works on slope stability.

Also, worth mentioning are the works from University of São Paulo (Brazil), by Prof. Carlos S. Pinto on the mechanical behaviour of residual soils observed with the CamKometer pressuremeter and Prof. Marcos M. Futai about tunnelling in residual soils and their peculiar behaviour, such as yielding envelopes and unsaturated properties. Prof. Willy Lacerda, from University of Rio de Janeiro (Brazil) has also studied residual soils on natural slopes.

Figure 3 provides an over-view of locations with the presence of residual soils (black areas) and some mechanized tunnelling projects excavated along soil/rock transitional boundary (grey stars).

Figure 4 shows the parent rock for each residual soil gathered. Granitic rock is the predominant one, followed by gneiss/migmatite. These rock types add up 77% of all contributions. Therefore, only the residual soils weathered from gneissic,

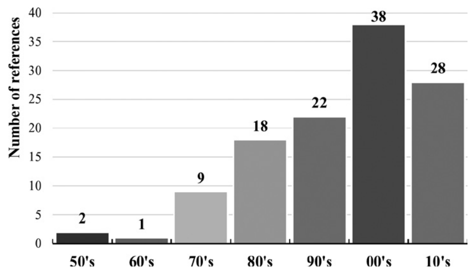


Figure 1. Number of references per decade.

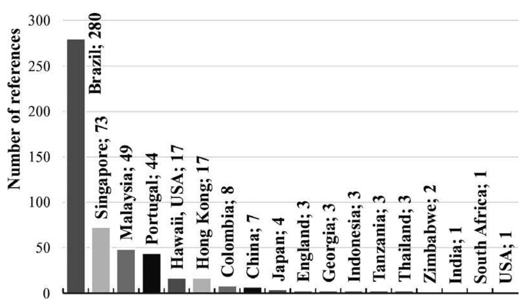


Figure 2. Number of data per country.

Figure 3. World map showing areas affected by extensive tropical weathering (black) and tunnels excavated with TBM's along residual soil with soil/rock boundaries (grey stars), modified from Shirlaw *et al.* (2000).

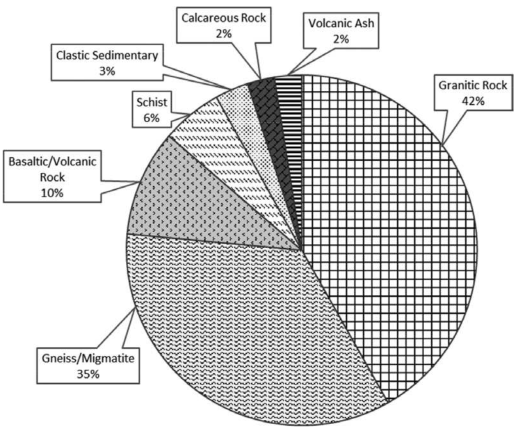


Figure 4. Parent rock of the residual soil references.

migmatitic and granitic rocks will be analysed in detail, as presented next.

Moreover, it is mentioned that such details as preparation of samples, specific methods applied, or any other information that might be missing, must be consulted directly in the primary reference source.

## 4 MAIN ASPECTS AND PROPERTIES

Heterogeneity and anisotropy are some of the prominent characteristics of residual soils, mainly because such soils are a by-product of weathering with no transportation, keeping the features from the original rock. Consequently, the parent rock has a great influence on the resulting material. Furthermore, the diverse chemical and mechanical weathering conditions also contribute by providing a wide range of resulting products.

Many studies have been carried out to further highlight the particularities of tropical residual soils and it is not the main scope of this paper to do so. For further elucidations on this distinguished type of soil, several titles are pointed out in the references section.

### 4.1 *The residual soil horizons*

Soil mechanics was conceived based on sedimentary soil information from temperate climate countries, in particular from Europe and North America. In tropical countries, however, the residual soil occurrence is more pronounced.

In tropical areas, the high temperature and precipitation are responsible for a more intensive physical-chemical-biological weathering than in colder and drier areas, with residual soils at greater depths.

It is important to note that not all tropical soils are residual, designations sometimes mistakenly used interchangeably.

For design purposes, it is of interest to divide the weathering profile in layers and assign to them different properties. Some attempts to standardize such subdivisions were made for example by Deere and Patton (1971), which was the basis for the horizons initially presented by Vargas (1980) and reiterated by Pastore and Fontes (1988). Although such standards exist, it is usual to find variations in the terminology describing the weathering horizons.

Such classifying standard is extremely important to make data correlations and comparisons between authors and places. More importantly, however, is the consensus between property differences of each horizon.

The horizons should be subdivided, at least, depending on the soil texture and particle size distribution. For the current practice, such subdivision is oriented by grouping the $N_{SPT}$ values.

The present work does not dictate which terms should be used. However, with the purpose of clarifying the weathering profile subdivision considered for this study, a description of the three horizons considered is presented, according to Futai *et al.* (2012).

- mature residual soil, which does not present remaining textures from the parent rock, is more homogeneous and has higher clay content;
- young residual soil, or saprolitic soil, presenting lower pedologic evolution, has lower clay content and preserves remaining features from the parent rock (structure, foliation, discontinuities); and
- saprolite, or transitional soil, with higher sand content, presents boulders and rock fragments, usually detected only with rotary drilling

prospecting with low recovery and not by percussion drilling.

A predominance of silt is normally observed in residual soil profiles. The change between horizons is gradual and their division is difficult to determine, sometimes varying according to the appraiser. These three layers do not necessarily occur simultaneously at the same site.

The saprolite layer is the “Hard Soil/Soft Rock” or “Intermediate Geomaterials” mentioned by Viana da Fonseca and Topa Gomes. This layer is usually a great challenge for TBM excavations, and could be classified as a Mixed Transitional Ground (MTG), as explained in Oliveira and Diederichs (2016).

Regarding the database, some of the samples have been classified in terms of mature and young residual soils, still, the majority has not been distinguished, consequently, when the term residual soil is applied in a general manner, it refers to the total of samples, including mature, young and saprolite, whenever sampling was feasible for this last layer. Consequently, the sum of mature and young residual samples are not equal to the total amount of samples.

### 4.2 *Residual soils weathered from granite*

Figure 5 presents the percentages of grain size contents for granitic residual soils and Table 1 the respective mean values (μ) and standard-deviations (σ). It is clear in terms of grain size distribution that most of the entries consist of practically all grain sizes.

It is possible to notice the differences between the layers of mature and young granitic residual soils in Table 2. The mature soil has typically higher percentages of clay and a lower portion of sand particles.

Figure 6 presents the plasticity chart for the granitic residual soils with a predominance of fine particles. As expected, there is considerable data scattering due soil origin and the natural soil heterogeneity. Moreover, it is possible to observe that much of the entries falls under Line A, indicating a predominant silty behaviour.

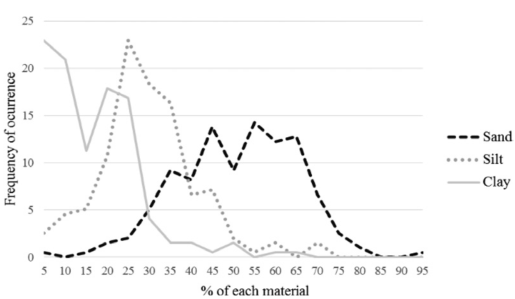


Figure 5. Percentages of grain size content for residual soils from granite (196 entries).

Table 1. Percentages of grain size content for residual soils from granite (196 entries).

| | Clay | Silt | Sand | Gravel |
|---|---|---|---|---|
| μ | 14.5 | 27.6 | 49.1 | 14.2 |
| σ | 10.9 | 11.7 | 14.2 | 13.9 |
| min | 0.0 | 3.0 | 3.0 | 0.0 |
| max | 65.0 | 69.0 | 95.0 | 55.0 |

Table 2. Percentages of grain size content for residual soils from granite, considering their weathering level: mature (49 entries) and young (36 entries).

| | | Clay | Silt | Sand | Gravel |
|---|---|---|---|---|---|
| Mature | μ | 9.9 | 29.8 | 48.3 | 12.7 |
| | σ | 10.7 | 15.5 | 13.6 | 15.0 |
| | min | 0.0 | 3.0 | 22.0 | 0.0 |
| | max | 56.5 | 69.0 | 69.5 | 55.0 |
| Young | μ | 6.6 | 22.7 | 54.0 | 17.7 |
| | σ | 4.0 | 9.5 | 12.0 | 13.0 |
| | min | 0.0 | 5.0 | 32.0 | 1.8 |
| | max | 18.8 | 44.3 | 77.0 | 55.0 |

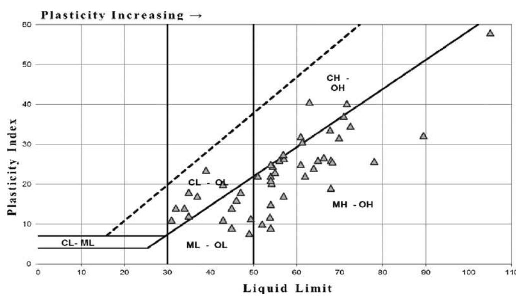


Figure 6. Plasticity chart for residual soils from granite.

Table 3 presents the main indexes and parameters for the granitic residual soils: natural and dry specific weights ($\gamma_n$ and $\gamma_d$), density of solids (G), void ratio (e), saturation (S), water content (w), liquid limit ($w_L$), plasticity index (PI), activity index (AI), effective cohesion and friction angle (c’ and $\varphi'$), and conductivity coefficient (k).

In the online spreadsheet file, some conclusions can be made regarding the differences between countries.

The highest percentages of fines (clay + silt particles) were found in Brazil and Singapore (more than 70%). The entries with highest natural densities and lowest void ratios are from Singapore and Thailand. Conversely, the lowest natural densi-

Table 3. Main indexes and parameters for residual soils from granite.

| | $\gamma_n$ (kN/m³) | $\gamma_d$ (kN/m³) | G | e | S (%) | w (%) | $w_L$ (%) | PI (%) | AI | c′ (kPa) | φ′ (deg.) | k (cm/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| entries | 161 | 161 | 205 | 162 | 171 | 157 | 154 | 154 | 142 | 74 | 74 | 69 |
| μ | 18.7 | 15.1 | 2.642 | 0.805 | 75.8 | 25.8 | 48.3 | 17.9 | 1.54 | 13.7 | 33.1 | $6.6 \times 10^{-5}$ |
| σ | 2.6 | 2.4 | 0.097 | 0.327 | 12.4 | 10.2 | 17.0 | 12.6 | 1.51 | 12.0 | 8.4 | $4.2 \times 10^{-4}$ |
| min | 13.9 | 9.2 | 1.850 | 0.000 | 33.0 | 10.0 | 18.5 | 2.0 | 0.38 | 0.0 | 4.0 | $4.0 \times 10^{-9}$ |
| max | 27.5 | 25.0 | 3.220 | 1.920 | 97.8 | 57.0 | 116.0 | 68.0 | 8.75 | 81.0 | 46.0 | $3.5 \times 10^{-3}$ |

ties and highest void ratios are from Portugal and Japan. Regarding the plasticity index, Portugal has the lowest and Singapore the highest values. This shows that more evolved soils originate from tropical climates rather than by the temperate climates.

The clay activity index also indicates this climate influence. From 142 entries, 59 soils are active (above 1.25), while the highest activity indexes (above 3.00) are from Singapore, Hong Kong and Malaysia. Such clay activity is related to the clogging potential in EPB machines and must be further investigated.

Lastly, another important index for mechanized tunnelling is the soil conductivity, since it influences the excavation method choice. For the granitic residual soils, the mean value for the conductivity coefficient is around $10^{-5}$ and $10^{-6}$ cm/s. Some higher values from Brazilian residual soils (around $10^{-3}$ and $10^{-4}$ cm/s) does call the attention, which could be an influence of structures remaining from the parent rock, such as discontinuities.

### 4.3 *Residual soils weathered from gneiss/migmatite*

As presented in Figure 7 and Table 4, in terms of grain size distribution, the majority of the entries also counts with the presence of practically all grain sizes, similarly to the granitic soils.

Table 5 presents the differences between the layers of mature and young gneissic/migmatitic residual soils. As expected, the samples behave similarly as granitic ones, with a higher content of clay for mature soils and a lower for young ones. Likewise, the gravel content is higher in young soils.

Worth mentioning is the significant presence of biotite particles in these soils, both in clay and silt sizes. The soil features remaining from the parent rock are also important, which must be considered for further research in terms of interaction and behaviour during excavation by EPB machines.

Figure 8 presents the plasticity chart for the gneissic/migmatitic residual soils with predominance of fine particles. It is possible to perceive that the data are less scattered, when compared to the granitic residual soils chart. This is probably because most of the samples come from a similar location and, consequently, from a similar climate.

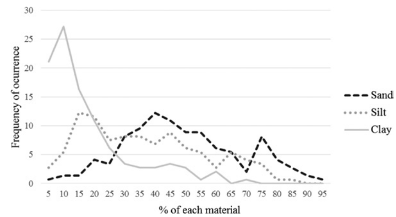


Figure 7. Percentages of grain size content for residual soils from gneiss and migmatite (147 entries).

Table 4. Percentages of grain size content for residual soils from gneiss and migmatite (147 entries).

| | Clay | Silt | Sand | Gravel |
|---|---|---|---|---|
| μ | 15.8 | 34.7 | 47.1 | 2.7 |
| σ | 13.7 | 19.4 | 19.0 | 5.2 |
| min | 0.0 | 3.0 | 0.0 | 0.0 |
| max | 66.0 | 83.0 | 91.0 | 36.0 |

Table 5. Percentages of grain size content for residual soils from gneiss and migmatite, considering their weathering level: mature (32 entries) and young (33 entries).

| | | Clay | Silt | Sand | Gravel |
|---|---|---|---|---|---|
| Mature | μ | 24.3 | 32.5 | 41.8 | 1.3 |
| | σ | 18.3 | 14.8 | 13.3 | 1.9 |
| | min | 0.0 | 14.0 | 14.0 | 0.0 |
| | max | 58.0 | 71.0 | 71.0 | 6.0 |
| Young | μ | 11.2 | 33.5 | 53.5 | 2.6 |
| | σ | 8.8 | 15.2 | 15.2 | 2.5 |
| | min | 0.0 | 9.8 | 20.0 | 0.0 |
| | max | 45.0 | 70.0 | 83.0 | 8.0 |

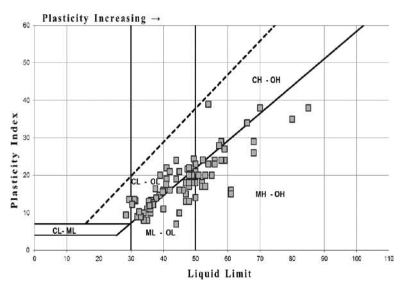


Figure 8. Plasticity chart for residual soils from gneiss and migmatite.

Table 6. Main parameters for residual soils from gneiss and migmatite.

| | $\gamma_n$ (kN/m³) | $\gamma_d$ (kN/m³) | G | e | S (%) | w (%) | $w_L$ (%) | PI (%) | AI | c′ (kPa) | $\varphi'$ (deg.) | k (cm/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| entries | 146 | 143 | 180 | 143 | 164 | 154 | 148 | 152 | 136 | 75 | 75 | 36 |
| μ | 17.8 | 14.4 | 2.719 | 0.898 | 77.2 | 24.5 | 43.9 | 16.5 | 1.46 | 19.2 | 29.0 | $6.2 \times 10^{-4}$ |
| σ | 2.1 | 2.4 | 0.042 | 0.346 | 15.9 | 10.7 | 11.8 | 7.8 | 1.12 | 19.7 | 5.9 | $6.4 \times 10^{-3}$ |
| min | 12.6 | 9.0 | 2.591 | 0.066 | 20.9 | 2.0 | 23.0 | 0.0 | 0.28 | 0.0 | 15.0 | $1.7 \times 10^{-7}$ |
| max | 25.3 | 24.8 | 2.870 | 2.063 | 99.5 | 60.0 | 85.0 | 39.0 | 7.50 | 83.0 | 42.5 | $5.7 \times 10^{-3}$ |

Moreover, it is possible to observe that the entries are located around Line A, indicating an intermediate behaviour between silt and clay.

Table 6 presents the main indexes and parameters for the gneissic/migmatitic residual soils. Practically all the entries analysed are from Brazil, except 3 samples from Colombia and 1 from United States. Therefore, it was not possible to investigate the differences between countries in detail.

Regarding the soil conductivity, the gneissic and migmatitic residual soils present higher mean values ($10^{-3}$ to $10^{-4}$ cm/s) than the granitic ones.

## 5 APPLICATION OF THE DATABASE FOR EPB RESEARCH

To expose the goal for this data compilation, the scenario of interaction between the residual soils and an EPB TBM must be briefly explained.

Firstly, there is the need to bring attention to the evident difference between transported and residual soils. Secondly, most of the charts and diagrams usually have been developed considering the behaviour of a typical sedimentary soil. With that in mind, it is obvious that all the previous studies on sedimentary soils would not necessarily work well for the residual soils.

In the specific case of EPB tunnelling, this difference in material behaviour needs to be promptly and completely addressed, especially concerning the interactive mechanisms of excavation, the soil conditioning, the charts used for clogging and wearing estimates, among others. Only then, we will be able to better understand the challenges and provide the correct mitigation measures.

As discussed by Oliveira and Diederichs (2016), problems with the excavation of tropical residual soils are still happening. The excavations through the mixed transitional ground are especially problematic, where the rock/soil boundary is not easily defined prior to excavation.

Figure 9 presents the diagram used for the evaluation of clogging potential in EPB machines, according to three main parameters: liquid limit, plasticity index and water content. This illustrates how this data compilation could support the understanding of the interaction between the residual soils and the excavation process of the EPB machine.

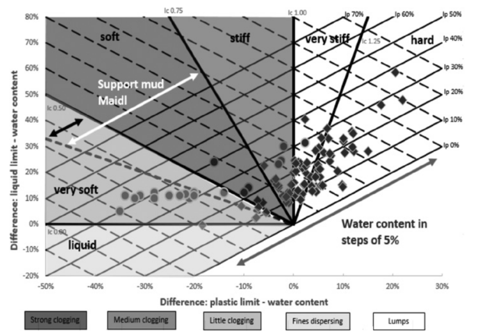


Figure 9. Diagram for the evaluation of clogging potential with entries from São Paulo, Brazil (diamonds) and Singapore (circles), modified from Hollmann and Thewes (2013).

The sample values for São Paulo (diamonds) and Singapore (circles) are included in the diagram; the majority of the São Paulo samples lie in the "very stiff" and "hard" fields, while Singapore sample's lie mainly in the very soft field. For the São Paulo samples, to attain the right consistency for the excavated material and to allow it to function as a support medium for the machine water must be added, this would "displace" the ground towards the lower left side of the diagram, as detailed by Hollman and Thewes (2013).

As the ideal soil consistency is achieved, high clogging potential would also occur, possibly leading to clogging issues. Therefore, the operation of an EPB machine along this mixed transitional ground, especially in terms of finding the optimum soil condition to create an ideal support medium, is probably one of the main issues. An absence of a functional support medium could lead to great soil losses and consequently, settlements and sinkholes on the ground surface.

Therefore, it is of uttermost necessity to further investigate this interaction of the conditioned soil (support medium) with the excavation process. There are several details still to be investigated, as mentioned earlier, such as the clogging potential of the material and the behaviour of the residual soils to reach an ideal consistency, functioning as a plug for the screw conveyor of the machine. To achieve that, it is essential to understand the residual soils and their behaviour during mechanized excavation process.

## 6 FINAL REMARKS

It is crucial to understand the distinguished behaviour of tropical residual soils, considering the issues faced while excavating them with closed frontal chamber TBMs. The first step to achieve this goal is to gather as much knowledge as possible for this type of material.

As shown so far, it is a challenging scenario, called by the first authors as the "Pandora's box" of mechanized tunnelling. It is important to mention that due to the heterogeneity and anisotropy of the tropical residual soils, the task is not an easy one, which might take an effort from several collaborative researchers, as it was previously done in other engineering subjects, such as dam and road projects.

During the 80's and 90's, committees were created to combine efforts, providing a collaborative space to investigate deeper the behaviour of the tropical residual soils, driven by the projects demands. Now we are facing new challenges with the urban growth and the advance of technological solutions for infrastructure projects requiring continued improvement to tunnelling methods.

Therefore, it is expected that with further investigation and research, mechanized tunnelling projects through this type of ground will be done in a more efficient way, with less accidents and higher advance rates.


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