Deriving geotechnical properties for Porto granite from the compilation and interpretation of tests and results in the last years

António Topa Gomes[1],

1 CONSTRUCT, Faculdade de Engenharia, Universidade do Porto, Porto, Portugal

Abstract: Porto is located in Northwest Portugal and most of the city and surrounding areas are founded on the Porto granite, a light grey, two mica, medium-grained granite. The geotechnical Portuguese community had put relevant efforts on its geotechnical and physical properties, especially since the beginning of the construction of Porto Light Rail Metro, which comprised several underground structures and tunnels. Since that period, several works related with deep excavations and underground constructions have occurred, with relevant geological geotechnical characterization.

In this paper it is intended to collect the published information regarding geotechnical characterization of Porto granite and, from these results, derive new geotechnical properties, namely characterizing its variability for the most relevant geotechnical groups. This work was produced in the first phase of Porto Light Rail Metro (2000) but, since then, have bot been updated.

The paper will focus also on the derivation of geotechnical parameters for design, particularly having into account the typical depths where the excavations occur, and reflecting this property in the design parameters

Keywords: Granite; Geomechanical properties, variability, residual soils, hydrogeology

1. Introduction

In the last three decades, underground construction had a large increment in the city of Porto, mainly due to the extension of Porto Light Rail Metro, but also due to the fact that building's basements are going deeper. These options imply an investment in the geotechnical characterization of these materials which is, unfortunately, planned individually, missing therefore the agglutination of all the information.

This paper tries to collect the published information regarding the characterization and behaviour of Porto Granite, with different weathering degrees, and bring new reflexions for the modelling possibilities of these type of materials.

Porto is located in Northwest Portugal and most of the city and surrounding areas are founded on the Porto granite, a light grey, two mica, medium-grained, granite, with the location of the outcrops represented in Fig. 1

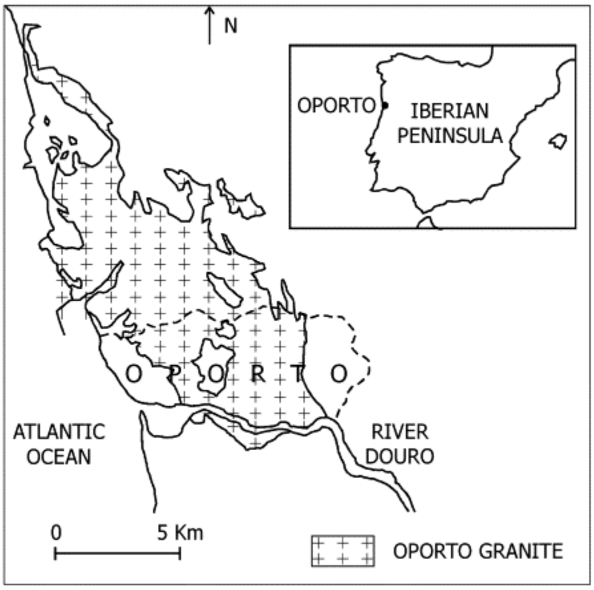

Fig. 1. Location of the outcrops of Porto granite, in Northwest Portugal

2. Major contributions – Design Parameters

Several researchers from the University of Porto have brought major contributions to the characterization of these rock in different weathering degrees. Among these authors (Begonha & Sequeira Braga, 2002) presented a paper that describes Porto granite in terms of its mineralogical, chemical, geotechnical and physical properties. The main results obtained by these authors are summarized at Table 1, where N_T represents the total porosity, N_{48} is the free porosity, d is the dry bulk density, v is the ultrasonic velocity, σ_c is the uniaxial compressive strength, E is the Young modulus and ε is the typical strain at failure.

Table 1 - Variation of some physical properties and parameters with the degree of weathering (Begonha & Sequeira Braga, 2002).

Property	Units	W1	W2	W3	W4
N_T	%	0.72-1.14	1.59-2.07	2.41-3.94	
N_{48}	%	0.72-1.14	1.59-2.07	2.41-3.94	7.79-10.77
S_{48}	%	68-99	78-93	78-91	
d		2.62-2.65	2.60-2.62	2.40-2.60	2.34-2.41
v	$m\ s^{-1}$	5370-6420	3670-5450	1600-4740	1300-1880
σ_c	MPa	130.6-157.0	96.6-132.7	60.0-135.2	20.2-29.4
E	GPa	14.67-22.90	9.96-12.45	5.03-12.89	1.04-1.74
ε	$x10^{-3}$	11.2-12.0	11.5-13.0	9.9-14.8	13.-9-17.1

Apart from these properties, (Begonha & Sequeira Braga, 2002) also presented a set of correlations between physical properties, which could be an important contribution when the intention is to derive certain properties of the rock mass.

One of the main drawbacks of Table 1 is that there is no reference to the tensile strength of the Porto granite, and it is known the importance of this parameter, both, to calibrate de Hoek & Brown failure criteria and to model complex geotechnical structures.

The weathering of the granite may produce saprolitic soils which are extremely important for the most geotechnical works at the city of Porto, since they tend to be superficial. When it comes to the geotechnical behaviour of the residual soils, Viana da Fonseca developed an extensive and notable work, constituting the main reference for the Porto residual soils (Viana da Fonseca, 1996, Viana da Fonseca 2003). Table 2 presents the main properties of Porto granite residual soils as identified by (Viana da Fonseca, 1996), where γ_s is the unith weight of the solid particles, w_L is the Liquidity Index, I_p is the Plasticity index, e the void ratio and γ the typical unit weight of the ground. Fig. 2 presents typical granulometric curves for Porto granite residual soils, as presented by (Viana da Fonseca, 1996).

Table 2 – main physical properties of Porto granite residual soils by (Viana da Fonseca, 1996).

γ_s (kN/m^3)	w_L (%)	I_p (%)	e	γ (kN/m^3)
25.4-27.7	26-32	<11	0.40-0.85	17.0-22.0

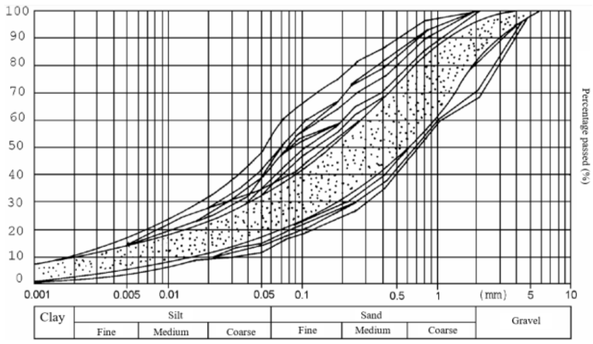

Fig. 2 – Typical granulometric curves of Porto granite residual soils (Viana da Fonseca, 1996)

(Topa Gomes, 2009) presented also a summary of several results regarding strength for the residual soils from Porto Granite, summarized at Table 3.

Table 3 – Typical strength parameters for Porto Granite Residual Soils

N_{SPT}	c'(kPa)	ϕ'(º)
7-60	0-55	27-47

A notable contribution resulted from the first phase of the construction of Porto Light Rail Project, a remarkable project with 70 km of lines, with 7 km underground, corresponding to two TBM tunnels and one by the Sequential Excavarion Method, and 11 underground stations. The number of papers decribing these works is extensive, either focused on the geological/geotechnical charatcterization, either focused on the description of the solutions (Viana da Fonseca & Topa Gomes, 2010; Topa Gomes, et al., 2004; Russo, et al., 2001; Babendererde, et al., s.d.). But the most extensive geological/geotechnical characterizations was completed by the designer of the tunnels and underground stations, which were also in charge of developing the geotechnical model. Besides an internal report from Normetro, the contractor, the paper by (Russo, et al., 2001) summarizes the main results of this study. The authors developed a procedure for geotechnical characterization, which is presented at Fig. 3.

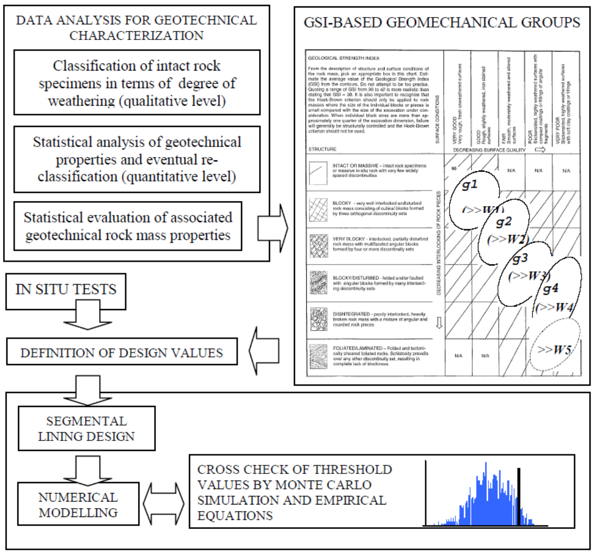

Fig. 3 - Conceptual procedure for geotechnical characterization and design (Russo, et al., 2001)

In the same work, the authors, based on the results of 156 uniaxial compressive tests, presented a graph that correlated the variation of the uniaxial compressive strength with the weathering degrees of the Porto granite, as shown at Fig. 4. The graph presents the range of variation as well as an more strict interpretation, base on a statistical analysis.

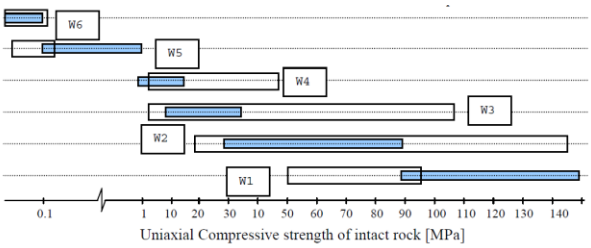

Fig. 4 - Weathering classes over the uniaxial compressive strength range (clear bars indicate classification based only on qualitative evaluation, shaded bars indicate re-classification after statistical analysis and consequent "cut-off"). (Russo, et al., 2001)

Based in the same tests, the authors also presented a correlation between the uniaxial compressive strength and the *Young* modulus, as shown by equation (1):

$$E = 29.43\sigma_c^{1.47} \quad (1)$$

The relation presented at Equation 1 shows a very good correlation ($R^2 = 0.93$). Based on the results of Fig. 4 and the relation proposed by Equation (1), the average, minimum and maximum values for the uniaxial compressive strength and *Young* modulus were derived and presented at Table 4. Note that the values were read from the Fig. 4 for the shaded bars.

Table 4 – Uniaxial compressive strength and *Young* modulus according to the weathering degree

Property	Units	W1	W2	W3	W4
$\sigma_c^{average}$	MPa	120	60	20	2
σ_c^{min}	MPa	90	30	5	6
$\sigma_c^{máx}$	MPa	150	90	35	12
$E^{average}$	GPa	33.51	12.10	2.41	0.08
E^{min}	GPa	21.95	4.37	0.31	0.41
$E^{máx}$	GPa	46.52	21.95	5.48	1.13

Based on the several boreholes collected, (Russo, et al., 2001) performed Monte Carlo simulations to evaluate the distribution and proposed 7 geotechnical units for the region of Porto, to be used during the first phase of the construction of Porto Light Rail Metro, which are presented at Table 5.

Table 5 – Geomechanical groups and associated conditions

Geomechanical Group	Weathering Degree	Fracturing Degree	Correlation W-f [%]	Discontinuity Condition	GSI
g1	W1	f1-f2	80-85	d1-d2	65-85
g2	W2	f2-f3	80-85	d2-d3	45-65
g3	W3	f3-f4	70-75	d3-d4	30-45
g4	W4	f4-f5	65-70	d4-d5	15-30
g5	W5	(f5)	90-95	(d5)	(<20)
g6	W6	n.a.	-	n.a.	n.a.
g7	n.a.	n.a.	-	n.a.	n.a.

The weathering degree is as for intact rock, the fracturing degree is based on ISRM (1981), with the following discontinuity ranges, in *cm*, as follows: f1: >200, f2: 60-200, f3: 20-60, f4: 6-20, f5: <6, the classes of surface conditions as defined for "GSI-Based geomechanical Groups" (Hoek & Brown, 1998), and the term "n.a." indicates that the index is not applicable. Note also that the group "g7" does not refer to granite or soils resulting from granite weathering, but groups "man-made" material and all alluvial soils in the region.

From the geomechanical groups presented at Table 5, the design values were derived for the rock mass groups, assuming for the rock like materials a generalized Hoek & Brown failure envelope, and for the soil like materials the Mohr-Coulomb failure criteria. Table 6 presents for the four geomechanical groups associated to rock like materials the proposed design parameters (Russo, et al., 2001). Similarly, Table 7 presents the design parameters for the soil like geomechanical groups, assuming as failure criteria de Mohr-Coulomb envelope.

Table 6 – Design values of geotechnical parameters for rock like geomechanical groups (Russo, et al., 2001)

Geomechanical Group	Unit weight (kN/m^3)	m_b	s	E (GPa)
g1	25-27	7,45	6,90E-02	35.0
g2	25-27	3,2	7,50E-03	10.7
g3	23-25	0,98	7,50E-04	1
g4	22-24	0,67	0,00E+00	0.4

Table 7 – Design values of geotechnical parameters for soil like geomechanical groups (Russo, et al., 2001)

Geomechanical Group	Unit weight (kN/m^3)	c' (kPa)	ϕ' (^{0})	E (MPa)
g5	19-21	10-50	32-36	50-200
g6	18-20	0-20	30-34	20-70
g7	18-20	0	27-29	<50

For the several geomechanical groups, except g1, Fig. 5 presents the failure envelope in the space$\sigma_n - \tau$, as proposed by (Russo, et al., 2001). Naturally, the failure envelopes using the Hoek & Brown failure envelopes are curve, while the failure envelope for geomechanical groups adopting the Mohr-Coulomb is linear.

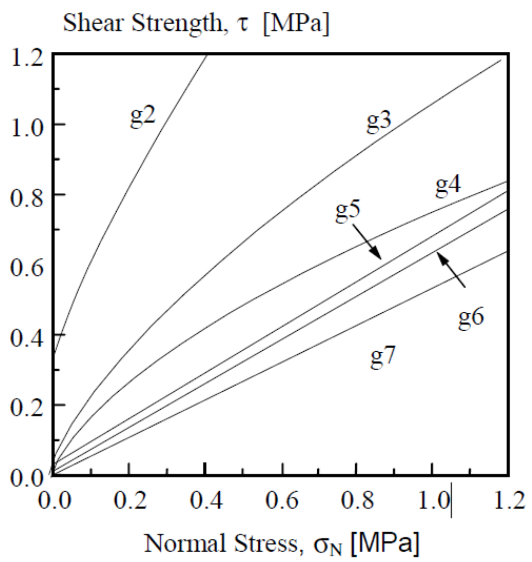

Fig. 5 - Shear strength envelopes for the different geotechnical groups (Russo, et al., 2001)

The study conducted for the first phase of Metro do Porto was the base for the choice of design parameters regarding Porto Granite. Several geotechnical publications related to Metro do Porto, in subsequent years, adopted and described the same parametrization (Topa Gomes, et al., 2004; Miranda, et al., 2005; Viana da Fonseca & Topa Gomes, 2010). Even recently, and after several phases of expansion of Porto Light Rail Metro, in the European Conference of Geotechnical Engineering (XVIII ECSMGE 2024), two papers were presented about the same topic, but again based in the same geotechnical parametrization (Nascimento, et al., 2024; Pereira, et al., 2024).

From the description presented in the present paper it is clear the importance of the geotechnical works and characterization completed during the first phase of Porto Light Rail Metro but, since then, several other works were completed. Nevertheless, the synthesis and agglutination of all these new results had never been completed, which is a topic of the most importance for future developments. This aspect becomes even more relevant since its known local variability is a key issue when dealing with Porto granite.

3. Variability of the main parameters

Porto granite presents an intense variability and rapid change in its characteristics and properties which turn very difficult, if not even impossible, to create reliable geological/geotechnical models. As stated by (Babendererde, et al., s.d.) the spatial development of the weathered rock is completely irregular and erratic. This strain should be motivation for additional research and studies and never the case for lowering arms and assume always the worst-case scenario.

Fig. 6 presents a typical excavation profile with highly weathered material and boulders of nearly sound rock, demonstrating the rapid change in the properties as well as a high variability. Equally, Fig. 7 represents the recovered core of a borehole a University of Porto, showing along 25 m different degrees of weathering.

Fig. 6 – Typical profile of highly weathered to sound granitic masses

Fig. 7 – Different degrees of weathering in granite in a core recovered from a borehole at Porto

The previous pictures demonstrate the intense variability and changes in the geotechnical profiles and, therefore, all the geotechnical models tend do demonstrate this characteristic. Fig. 8 exhibits the predicted geology for the Heroísmo mined station, where heterogeneity in weathering and its erratic geometry is evident. Fig. 9 illustrates the geological-geotechnical profile at Aliados station (Viana da Fonseca & Topa Gomes, 2010) with similar characteristics.

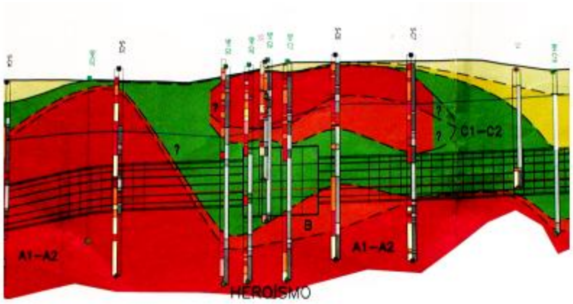

Fig. 8 – Predicted geology for the Heroísmo mined station (Assessment by Transmetro, documents of Metro do Porto).

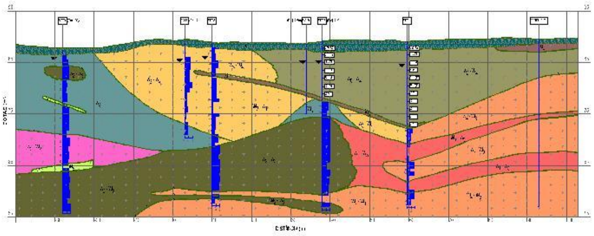

Fig. 9 – Geological-geotechnical profiles at Aliados station (Viana da Fonseca & Topa Gomes, 2010)

It is clear that change in geology is of great importance and, on the top of that, there is the natural variability of each geomechanical group, this means, the intrinsic variability of a material with, for example, a given weathering degree. In particular, when considering six geomechanical groups, that vary from sound granite to totally weathered residual soils, the variation of the parameters is too large and, within each geotechnical group, a relevant variation occurs, making difficult to consider average parameters.

In any case, apart from the mean values, there have been an effort to characterize the variability of geotechnical properties, namely trying to characterize the standard deviation of the main parameters. (Russo, et al., 2001) presented the standard deviation for the rock like materials in the first phase of Porto light rail metro, as shown at Table 8.

Table 8 – Standard Deviation of the design parameters for the rock like materials (Russo, et al., 2001)

Geomechanical Group	Unit weight (kN/m^3)	m_b		s		E (GPa)	
		mean	SD	mean	SD	mean	SD
g1	25-27	7,45	1,15	6,90E-02	3,20E-02	35.0	10
g2	25-27	3,2	0,5	7,50E-03	3,40E-03	10.7	3
g3	23-25	0,98	0,07	7,50E-04	1,70E-04	1	0,5
g4	22-24	0,67	0,12	0,00E+00	-	0.4	0,2

The previous table gives for m_b coefficients of variation varying from 7.1% to 17.9%, for s CV varying from 22.7% to 46.4% and for E CV varying from 25.0% to 50.0 %.

In what regards to the soil like materials, (Russo, et al., 2001) do not present any values for the coefficient of variation. In any cases several authors have characterized this type of soils and obtained a detailed characterization of their variability. Particularly, (Pinheiro Branco, et al., 2014) conducted a relevant number of tests in more than 40 samples of a residual soil, collected in a very restrict area (1,15×1,15 m^2), as shown in Fig. 10, which allowed the determination of the mean parameters of this material, but also a first estimation of the properties defining its variability. In what regards to the index properties, Table 9 presents the coefficient of variation of the index properties of a residual soils collected near Salgueiros Station, at Porto.

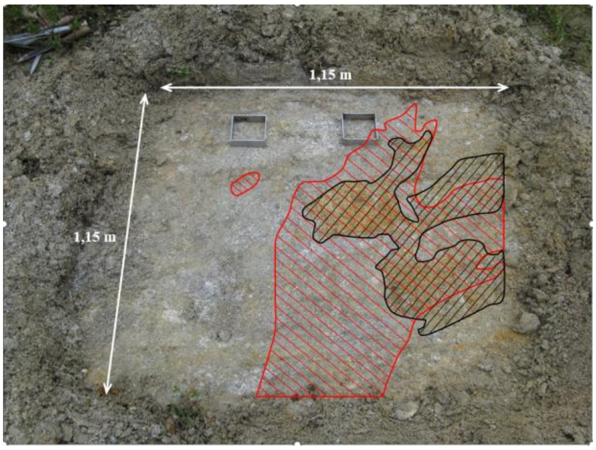

Fig. 10 – Detail of study area for characterization of the intrinsic variability of a residual soil (Pinheiro Branco, et al., 2014):

Table 9 – Coefficient of variation of the index properties for a saprolite soil from Porto granite (Pinheiro Branco, et al., 2014)

γ_d	γ_{sat}	e
3,50%	1,80%	9,60%

Referring to the strength parameters, (Pinheiro Branco, et al., 2014) grouped the 44 test samples in groups of 4, varying the confining stress between 25 kPa and 150 kPa. The stresses were intentionally kept low, since the samples were collected at a depth of 5 m ($\sigma'_v \sim 100\ kPa$), and therefore the structure and cementation of the samples was not destroyed. The results for the coefficient of variation of the Mohr-Coulomb envelope is presented at Table 10.

Table 10 – Coefficient of variation of the Mohr-Coulomb strength parameters for a saprolite soil from Porto granite (Pinheiro Branco, et al., 2014)

ϕ'_p(º)	c'	ϕ'_{cv}(º)
7.9 %	68.0 %	3.4 %

It must be referred that the coefficient of variation of the cohesion is high, but in accordance with the typical values referred in the literature (Kulhawy & Phoon, 1999). Regarding the friction angles, both values, the peak friction angle and constant volume friction angle present values within the typical range of variation of these parameters.

Another aspect relevant to mention is that, while for the friction angle, both, the peak value and the constant value, the normal distribution fits well to the obtained valued, for the cohesion, due to the cut-off at zero, an exponential distribution had to be used.

Regarding the deformation parameters, there are no references to its coefficient of variation measured for Porto granite residual soils. Nevertheless (Kulhawy & Phoon, 1999) present a typical coefficient of variation for sands between 20% and 70%, which is somehow in accordance with the values measured for the granite rock like materials: 25-50%.

One last aspect is related to the horizontal scale of fluctuation of residual soils. (Pinheiro Branco, et al., 2014) performed some measures of this parameter, in the horizontal direction, and arrived to values of 0.42 m, which are very small and, therefore, traducing a rapid variability.

4. Range of variation of the parameters within geomechanical groups

When it was produced the main geotechnical characterization for Porto Light Rail Metro, the main idea was to produce a general orientation for the geomechanical groups to be considered in the geotechnical design. Nevertheless, due to the extent and detail of the work, particularly the number of samples analysed and incorporated in the classification, the initial work by (Russo, et al., 2001) served as reference until our days. The initial idea was, in any case, that any specific site should be object of additional characterization and specific design parameters should be adopted. Particularly, the site results should conduce to specific design parameters, with variation ranges much narrower than the originally given.

As for example, Fig. 11 presents the failure envelopes of the geotechnical groups $g2, g3$ and $g4$, within the variation of the mean value plus/minus two standard deviations.

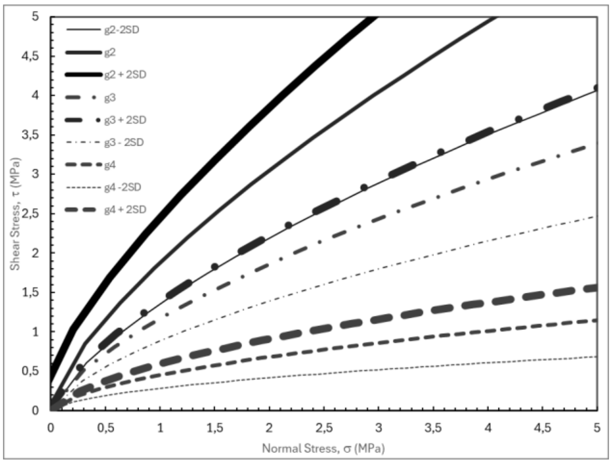

Fig. 11 - Shear strength envelopes for the different geotechnical groups assuming a variation of plus or minus two standard deviations

Within the interval $mean\ value \pm 2SD$ should be included 95% of the samples of each geotechnical group. It is clear from Fig. 11 that the above-mentioned interval does not produce overlap in any geotechnical group, although the maximum of $g3$ properties touches the minimum of $g2$. This clearly states that the variation assumed for each geomechanical group is very high. Therefore, the variation expected in the design will be very significant and, consequently if the parameters of each group are not detailed, the design has to be either unsafe or too costly.

If the same exercise is performed for the soil-like geomechanical groups, as shown in Fig. 12, it clear that the pattern is significantly different, as a total overlap between the groups occur.

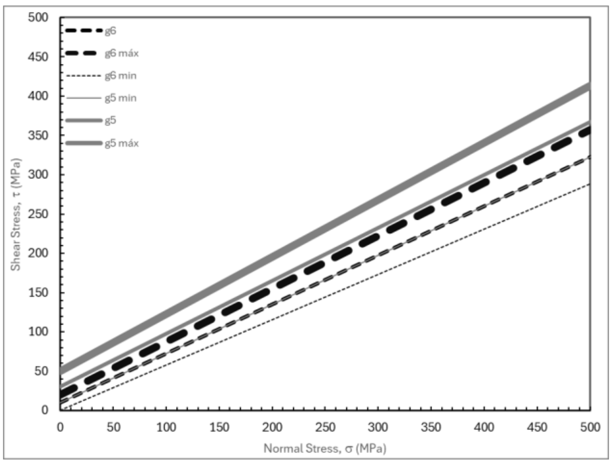

Fig. 12 - Shear strength envelopes for the different soil-like geotechnical groups assuming the variation between extremes limits

This means that clearly the option for the design was to consider narrower intervals, for the soil-like materials which is wise since the tunnels and stations in Porto Metro are typically superficial works, and, therefore, subjected to low confining stresses.

In any case the variability of the parameters considered, although relatively reduced is extremely relevant in the behaviour of surface works, since low cohesion would conduce to significant yielding in excavations. In this case apparently more relevant than the variation in the parameters can be the model itself and, particularly, the ability to capture shear strength for very low normal stresses and, also, deformation, for small strains.

5. Hydrogeology and Permeability

The permeability of the rock mass is dependent upon the weathering grade and the associated fractures. In the less weathered rock, the flow is related primarily to the fracture system while, in the more heavily weathered material, the ground behaves more like a porous medium.

The overall permeability is rather low, of the order of 10^{-6} m/s, or lower. However higher permeabilities were measured in pumping tests, which result from preferential drainage paths existent within the granite mass. The very weathered material, having little or no cohesion may be erodible under high hydraulic gradients.

In the first phase of Porto Light Rail Metro several Lefranc (for the soil-like geomechanical groups) and Lugeon tests (for the rock-like geomechanical groups) were completed which allowed a preliminary definition of the permeabilities for different geomechanical units, as shown at Table 11.

Table 11 – Permeability coefficient for several geomechanical units (Topa Gomes, et al., 2004)

Geomechanical Unit	k (m/s)
g3	1×10-7 a 1×10-8
g4	1×10-7 a 1×10-8
g5	1×10-6 a 1×10-7
g6	1×10-5 a 1×10-7
g7	1×10-5 a 1×10-7

This average permeabilities obtained through in situ tests clearly showed that the overall permeability was underestimated. In fact, water inflow measurements during the excavation of shafts or cut & cover stations conducted to volumes typically 10 to 20 times bigger than those resulting from the estimations using the above permeabilities.

This aspect that was of decisive importance in the choice of the solutions, clearly demonstrates that, on one hand, the global permeabilities tend to be higher than the local measurements, and, on the other hand, the models used do not reflect properly the behaviour of Porto granite materials.

This is clearly one topic that requires additional studies, regarding local and global measurement of permeabilities, but also in research for obtaining adequate models for the type of geology in Porto. Additionally, the development of a local/regional hydrogeological model is of paramount importance for the region, now that the geoenvironmental concerns become more and more present.

In what regards, to the water level, it was defined on each borehole of the several campaigns, being always detected close to surface. According to (Viana da Fonseca & Topa Gomes, 2010), the water level variation during the year is low (2 m in average) and can be explained by the high-water recharge due to the presence of regional aquifers. In any case, for design purposes, it is necessary to constitute a base with water table measurements during longer cycles – one decade as minimum – also because the water table oscillation may explain the higher or lower deformability associated with water table lowering during construction.

6. Conclusion

During the present paper a discussion on the geological and geotechnical characterization of Porto granite was completed, collecting the most relevant results on these materials on the last 3 decades. Since the construction of Porto Light Rail Metro was the most relevant work in the region during this period, the reference to the characterization obtained on it was the main base for discussion and conclusion.

One first aspect to be referred is related with the relevant geological/geotechnical characterization performed during the first phase of the construction, which came up with a geotechnical model and 7 different geomechanigal groups that, despite the additional number of new studies, remains valid in the most recent designs. This aspect clearly results as a delusion, since exhibits an impossibility to integrate all the information in a unique database, producing more complete, reliable and relevant knowledge. This aspect is not only a challenge to the academy, contractors, designers and public owners, but also a commitment if we pursuit better geotechnical engineering.

Regarding the characterization of the intact rock in the laboratory, although the high number of tests performed, there are no measurements of the tensile strength neither of typical strength and deformability of the discontinuities. This information has to be collected which is easy since the Geotechnical Laboratory at FEUP is equipped with the apparatus necessary to complete this type of tests.

Most probably the harshest topic to deal with Porto granite is the variability in space and its intrinsic variability. Despite some efforts have been done to, mainly, characterize the intrinsic variability of the material, the adopted models to not deal adequately with this difficulty. This is the most challenging aspect for the designers and with the advent of random theories there is here a space for relevant research and developments. Certainly, the behaviour of weathered material intercalated with sound material is much better than a homogeneous residual soil, regarding, both, strength and deformability.

One final conclusion is related with the hydrogeology of the region and permeability measurement. Since the beginning of the Project of Porto Light Rail Metro this topic has been cause of dispute, and still there are no adequate models to predict the hydrogeological behaviour of the most relevant works in the city. There is a clear lack of local determinations of the permeability, a regional model and, therefore, this is a topic that requires additional research.

7 References

Babendererde, S., Hoek, E., Marinos, P. & Silva Cardoso, A., n.d. s.l., s.n.

Begonha, A. & Sequeira Braga, M. A., 2002. Weathering of the Porto granite: geotechnical and physical properties. *Catena,* 49(1-2), pp. 57-76.

Hoek, E. & Brown, E. T., 1998. Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences,* 34(8), pp. 1165-1186.

Kulhawy, F. & Phoon, K. K., 1999. Characterization of geotechnical variability. *Canadian Geotechnical Journal,* 36(4), pp. 612-624.

Miranda, T., Gomes Correia, A. & Sousa, L., 2005. *Determination of geomechanical parameters using a KBS system and application to an underground station.* Moscow, ISRM, pp. 218-225.

Nascimento, V., Mateus, S. & Coelho, I., 2024. *Brief report on the construction of the Liberdade/São Bento.* Lisbon, Taylor and Francis, pp. 2507-2510.

Pereira, A., Azeredo, T., Carvalheira, A. & Coelho, I., 2024. *The description of underground works evolution in Hospital Santo António station (Porto Metro).* Lisbon, s.n., pp. 2534-2537.

Pinheiro Branco, L., Topa Gomes, A. & Silva Cardoso, A., 2014. Natural Variability of Shear Strength in a Granite Residual Soil from Porto. *Geotechnical and Geological Engineering,* 32(4), pp. 911-922.

Russo, G., Kalamaras, G., Origlia, L. & Grasso, P., 2001. *A probabilistic approach for characterizing the complex geologic environment for the design of Metro do Porto.* Milan, ITA - Aites.

Topa Gomes, A., 2009. *Poços Elíticos pelo Método de Escavação Sequencial. O Caso do Metro do Porto.* PhD Thesis ed. Porto: FEUP.

Topa Gomes, A., Gaspar, A., Monteiro, J. & Malato, P., 2004. *Obras Subterrâneas do Metro do Porto - Aspetos geotécnicos.* Lisbon, SPG, pp. 2217-2234.

Viana da Fonseca, A., 1996. *PhD Thesis - Geomechanics of the residual soils of the Porto Granite. Design criteria for shallow foundations.* Porto: University of Porto.

Viana da Fonseca, A., 2003. *Characterising and deriving engineering properties of a saprolitic soil from granite, in Porto.* Lisse, Taylor and Francis, pp. 1341-1378.

Viana da Fonseca, A. & Topa Gomes, A., 2010. Project and Construction of Underground Stations and Tunnels (TBM and NATM) in Heterogeneous Masses for Metro do Porto. In: *Excavations and tunnels in granite.* Barcelona: Universidad Politècnica de Catalunya, Dep. D'Enginyeria del Terreno, Cartogràfica i Geofísica, pp. 133-172.