Prediction of geomechanical parameters using a KBS system. Application to two case studies of underground structures.

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ABSTRACT
In this paper the knowledge based system called GEOPAT is presented. The system calculates geomechanical parameters for modelling underground structures in rock, soil and heterogeneous formations. Specialists knowledge in this field was congregated and organized in causal nets. GEOPAT is still under development and aims to be an important tool for decision support. Nevertheless GEOPAT was already applied to some underground structures with success. In this work two of these applications are presented. The first is a large underground station of Metro of Porto and the last is the powerhouse complex composed by two caverns of the Venda Nova II hydroelectric scheme. Both structures were built in a granite rock mass. The geomechanical parameters were obtained using GEOPAT based on some information gathered in the field. Numerical models were developed and the results were compared with the monitored values. They showed in general a good agreement however it is still necessary to improve and increase the knowledge inside the system.

Keywords: artificial intelligence, knowledge based systems, numerical modelling

1 INTRODUCTION

Experience and empirical knowledge play a very important role in every step of geotechnical design due to the difficulties in gathering enough geological-geotechnical information to evaluate the correct behaviour of the ground. The advantages of congregating the experience and knowledge of one or several specialists in this field are indubitable. Artificial Intelligence techniques like the Knowledge Based Systems (KBS) can play an important role in reaching this goal.

A KBS is a computer software which uses explicitly represented and organized knowledge to solve problems (Russel and Norvig, 1995). This kind of system manipulates knowledge in an intelligent way intending to simulate the processes of human reasoning to achieve solutions or recommendations for a given problem. They are often developed for decision support in a very restrict and specialized field. Nevertheless decision making always requires human intervention.

A KBS for the prediction of geomechanical parameters in rock, soils and heterogeneous rock masses called GEOPAT is presented (Figure 1). This system was developed based on systematized and organized knowledge obtained by specialists in tunnelling and geomechanical characterization. To organize this knowledge causal nets have been established. The parameters calculated by this system can be used in modelling underground structures. GEOPAT aims to be an important tool for decision support (Miranda, 2003).

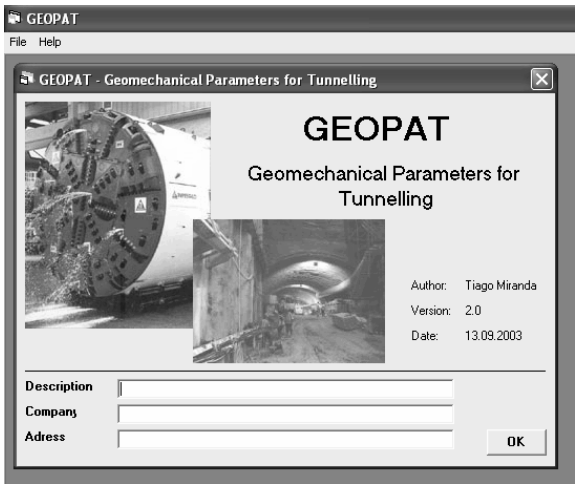

Figure 1. Initial window of GEOPAT

GEOPAT was applied to two different underground structures located in granite rock masses

considering the different construction stages. The first case study presented is a large and shallow underground station in urban environment of Metro of Porto (Sarra Pistone et al., 2004). The second is deep powerhouse complex composed by two caverns. Numerical models were developed and the results compared with monitored values.

2 THE KBS GEOPAT

2.1 *General*

One of the main issues in the development of a KBS is the acquisition of knowledge and their organization. This phase was carried out by an extensive bibliographic research, interviews with specialists and detailed studies of the several expressions and hypotheses to use. The information was then organized in causal nets. In the next sections the establishment of the knowledge base and the architecture of the system for the different types of formation will be presented.

2.2 *Rock formations*

The evaluation of deformability modulus for the rock formations was carried out on basis of a comparative study of several expressions found in literature (Miranda, 2003). This leads with ponderation of experience of some specialists, to the selection of a group of expressions, some of them with imposed limitations. Table 1 summarizes the adopted expressions.

Table 1. Expressions for the calculation of the deformability modulus in rock masses

E_M		Limitations
$E_M = 10^{(RMR-10)/40}$	(1)	RMR ≤ 80
$E_M = 2RMR - 100$	(2)	RMR >50 and σ_c>100MPa
$\frac{E_M}{E_R} = \left(0{,}0028RMR^2 + 0{,}9e^{(RMR/22{,}82)}\right)$	(3)	-
$E_M = \left(1 - \frac{D}{2}\right)\sqrt{\frac{\sigma_c}{100}}10^{(GSI-10)/40}$	(4)	σ_c ≤ 100MPa
$E_M = \left(1 - \frac{D}{2}\right)10^{(GSI-10)/40}$	(5)	σ_c > 100MPa
$E_M = 10Q^{1/3}$	(6)	-
$E_M = 1{,}5Q^{0,6}E_R^{0,14}$	(7)	$E_M \le E_R$ and Q ≤ 500

E_M – deformability modulus of the rock mass; σ_c – uniaxial compressive strength of the intact rock; E_R – deformability modulus of the intact rock; D – disturbance factor to account stress relaxation and blast damage.

For the calculation of strength parameters of the rock masses Hoek-Brown failure criterion (Hoek et al., 2002) was used.

The geomechanical information can be introduced in this system by two different ways. In the first, RMR and Q systems are applied and eventually the values of the interaction matrix, as formulated by Hudson (1992). In the second, data is inserted in a more expedite way considering the direct introduction of GSI. Figure 2 show the window related to the RMR system.

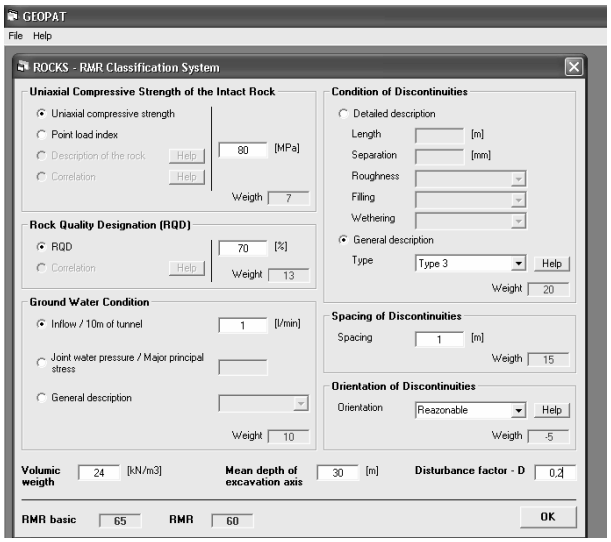

Figure 2. Window related to the RMR system

As the information is being inserted the values of the several weights, RMR_{basic} (RMR without the orientation of discontinuities correction) and the value of RMR are calculated and presented to the user. This interactive form of data input allows the user to analyze the sensibility of the values of RMR to any changes of the initial data. For the application of the Q system a similar methodology was followed. After inserting this information the value of GSI is calculated through correlations with the RMR (corrected value) or Q' which is a modified form of the Q parameter (Hoek, 2000).

The values of the deformability modulus and the strength parameters (Hoek-Brown m_i, m_b, *s* and *a* and Mohr-Coulomb c' and ϕ' parameters) are then calculated using the correspondent expressions. A methodology was defined for obtaining one final value taking into consideration the mean and variance values (Miranda, 2003). It is possible to calculate RMR_{weigth} and Q_{weigth} which correspond to the RMR and Q considering the values of the interactions between the parameters involved in the classification following the prin-

ciple of interaction matrix developed by Hudson (1992). Figure 3 shows an example of the results given by GEOPAT using the RMR and Q systems.

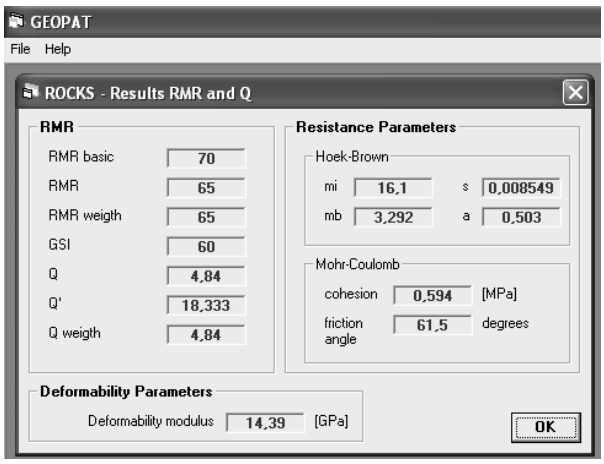

Fig. 3. Example of results using the RMR and Q systems.

2.3 *Soil formations*

In the case of soil formations GEOPAT calculates strength and deformability parameters from a wide range of laboratory and *in situ* tests distinguishing the cases of residual and transported soils. The expressions used in the system where found in the work of several authors. In this paper only the expressions used for transported soils are presented.

The soil's peak friction angle (φ'_P) can be calculated from the results of the cone penetration test (CPT) and Marchetti dilatometer test (DMT). The expressions used for the calculation of this parameter are presented in Table 2 (Robertson and Campanela, 1983; Mayne, 2001).

Table 2. Expressions for the calculation ϕ'_P

$\phi'_p = \arctan\left[0{,}1 + 0{,}38 \cdot \log\left(q_c / \sigma'_{v0}\right)\right]$	(8)
$\phi'_P = 20° + \dfrac{1}{0{,}04 + 0{,}06 / k_D}$	(9)

ϕ'_P - peak angle of shearing resistance; q_c - tip resistance of the CPT test; σ'_{v0} - initial vertical effective stress; k_D - horizontal stress index obtained with the results of the DMT test.

Dilatance angle (α) is calculated using the empirical strength-dilatancy relationship proposed by (Bolton, 1986):

$$\alpha = \phi'_p - \phi'_{cv} = m\left\{D_R\left|Q - \ln\left(\sigma'_{mf}\right)\right|\right\} - R \qquad \phi'_P \geq \phi'_{cv} \tag{10}$$

where: ϕ'_{cv} is the residual state friction angle, *m* is a coefficient respectively equal to 3 and 5 for axisymetric and plane strain conditions; D_r is the relative density index; R≈1 for sands; Q is a logarithmic function of grains compressive strength (quartz sands≈10 and calcareous sands≈8); σ'_{mf} the mean effective stress at failure (in the system this value is considered equal to σ'_{v0}). The value of D_r can be obtained from correlations with the standard penetration test (SPT) and CPT tests (Jamiolkowski et al., 2003).

The calculation of the secant modulus for deformation levels which interest the underground works is done based in the small strain Young's modulus (E_0). Some tests provide this value directly while others are better related with the shear modulus (G_0), based on which it is possible to obtain E_0. For the calculation of G_0 the considered tests are the following: SPT, CPT and CH. The expressions which relate the parameters obtained by these tests and G_0 are presented in Table 3 (Gomes Correia, et al., 2004).

Table 3. Expressions for the calculation of G_0

G_0	
$\dfrac{G_0}{q_c} = 290.57\left[\dfrac{q_c}{\left(\sigma'_{vo}\, p_a\right)^{0.5}}\right]^{-0.75}$	(11)
$\dfrac{G_0}{q_c} = 144.04\left[\dfrac{q_c}{\left(\sigma'_{vo}\, p_a\right)^{0.5}}\right]^{-0.631}$	(12)
$V_S = 69 \cdot N_{60}^{0,17} \cdot Z^{0,2} \cdot F_A \cdot F_G$	(13)
$G_0 = \rho \cdot V_s^2$	(14)
$\dfrac{G_0(\text{MPa})}{F(e)} = [3.16 \text{ to } 5.72] \cdot \left[p'_0(\text{MPa}) \cdot 10^3\right]^{0.4}$	(15)
where: $F(e) = \dfrac{(2.17 - e)^2}{1 + e}$	(16)

p_a – reference stress (100kPa); V_s - wave velocity (m/s); N_{60} - number of blow/feet for a energy ratio of 60%; Z - depth (m); F_G - geological factor (clays=1; sands=1.086); F_A - age factor (Holocene=1; Pleistocene=1.303); ρ - total mass density; e – void ratio; p'_0 – mean effective stress.

The value of E_0 can be obtained from the modulus determined by the DMT test (M_{DMT}) using the approximate relation (Gomes Correia, et al., 2004):

$$E_0 \approx 0.8 M_{DMT} \tag{17}$$

As there are several expressions to obtain the geomechanical parameters the calculation of the final values of the parameters is done through the

same methodology already described for the rock masses.

The deformability modulus of geotechnical materials is highly strain dependent and the value to use in design should be adapted for the expected level of strains according the serviceability limit state of the structure. For this purpose the system proceeds to a correction of E_0 (mean value obtained by the described methodology) multiplying it by a corrective factor (F). Considering several proposals found in literature is assumed reasonable values of 0.05% and 0.3% for strain levels, in the case of bored and SEM/NATM tunnels, respectively (Miranda, 2003).

2.4 *Heterogeneous formations*

Relatively to the heterogeneous rock formations and due to the great uncertainty in their geomechanical behavior, a probabilistic approach was implemented. A statistical distribution of these geotechnical structures is obtained using the RMR system. The mean and standard deviation of the weights of this classification inputted. Then, assuming a normal distribution, the system generates a thousand random values for each of the weights using the Monte Carlo method. These values are added being obtained the correspondent values of the RMR which are transformed in the GSI parameter. A probabilistic distribution of this parameter is then obtained, which can be visualized through one histogram (Figure 4). Mean and characteristic values of GSI which cover, practically, all possible scenarios, are presented and can be later used for the determination of the strength and deformability parameters.

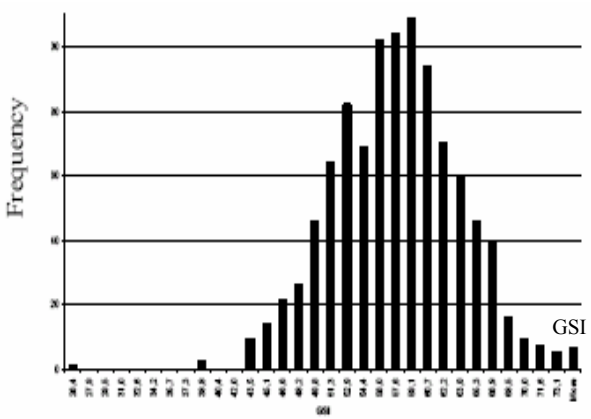

Figure 4. Histogram of the GSI parameter given by GEOPAT

3 APPLICATION TO TWO UNDERGROUND STRUCTURES

3.1 *Bolhão underground station*

The Bolhão underground station, from the Metro of Porto network, is situated in one of the main commercial areas of the city under buildings dating from the beginning of the 20th century and "Capela das Almas" which is town patrimonial heritage (Gaspar et al., 2004).

This station was built at a depth of 12 m and its layout consists in two perpendicular caverns with 70 and 62 m of length and diameters of 18 and 16 m, respectively. This structure is located in a granite formation commonly known as "Granito do Porto" which is characterized by the occurrence of highly heterogeneous weathering profiles and hinders the establishment of a standard geomechanical behaviour. Figure 5 presents a plant of the layout of the cavern as well as the spatial distribution of the geomechanical groups.

The rock mass interesting this structure was composed by three main geomechanical groups. The geomechanical parameters obtained for these groups using GEOPAT are presented in Table 4.

Table 4. Results from the application of GEOPAT

Geo. groups	E (GPa)	Mohr-Coulomb		Hoek-Brown		
		φ' (º)	c' (kPa)	m_b	s	a
G3	3.4	54	126	1.35	5.87E-4	0.51
G4	1.6	44	66	0.84	1.41E-4	0.53
G5	0.84	28	24	0.55	4.03E-5	0.56

Finite element numerical models were developed considering the six stages of the construction sequence and the geomechanical parameters given by the developed system. The considered section for the model was far from the intersection between the caverns to avoid disturbance in the results due to the three-dimensional effect of the geometry. Figure 6 shows the calculated curves of the surface settlements along the construction stages, which are very similar to the theoretical ones. The maximum monitored surface settlement in this section was about 2 mm which agree very well with the computed value which is about 1.8 mm.

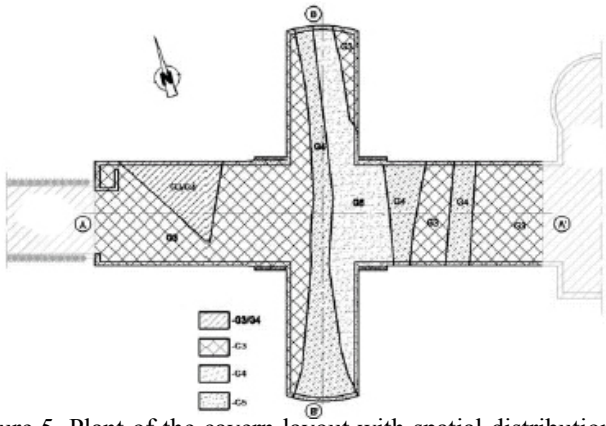

Figure 5. Plant of the cavern layout with spatial distribution of the geomechanical groups

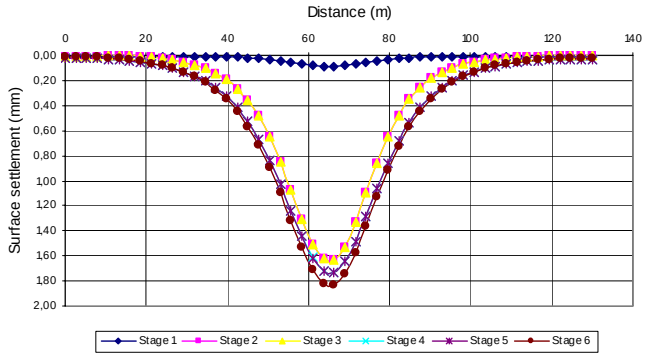

Figure 6. Calculated curves of surface settlements during the construction stages.

3.2 *Venda Nova II powerhouse complex*

The powerhouse complex consists of two caverns interconnected by two galleries. In plant, these caverns are rectangular and have respectively, for the powerhouse and transformer caverns, the following dimensions: 19.0x60.5m and 14.1x39.8m. The distance between their axes is 45.0m. Both caverns have vertical walls and scheme arch roofs. In the case of the arch of the powerhouse cavern, the invert of the ceiling is located 20.0m above the main floor (level 235), whereas in the case of the cavern containing the transforming units, such distance is 10.45m (Figure 7).

The rock mass in which the hydroelectric complex is installed is characterized by medium-size grain granite. The geomechanical parameters obtained for the rock mass by GEOPAT are the following: E = 45GPa,ϕ' = 54º and c' = 4MPa.

Numerical analyses were performed for this underground complex considering the seven construction stages. The predicted results are compared with the corresponding monitored values of displacements measured in extensometers installed in sections along the caverns axis (Figure 8). Analyzing the results it is possible to conclude that the values show in general a good agreement.

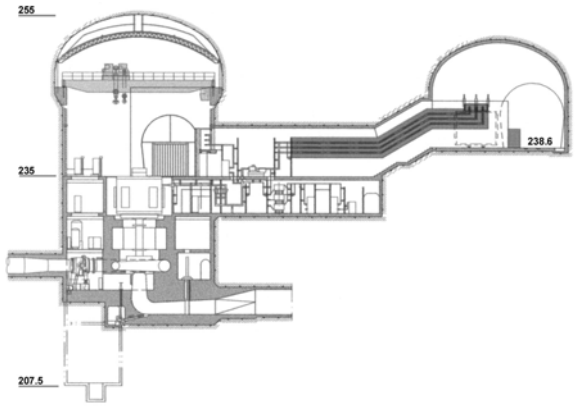

Figure 7. Powerhouse complex

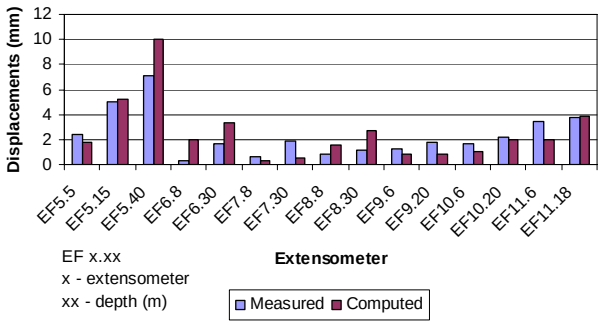

Figure 8. Measured displacements vs computed displacements for the powerhouse complex

4 CONCLUSIONS

A KBS for the calculation of geomechanical parameters for underground structures modelling called GEOPAT was presented. Different methodologies were defined for rock, soils and heterogeneous formations. The knowledge base was developed based on intensive bibliographic research, interviews with specialists and detailed studies. The gathered knowledge was organized in causal nets and a methodology was developed to calculate the final values of the parameters.

In the case of the rock masses, strength parameters are calculated using the Hoek-Brown criterion while for the deformability the calculation is carried out through several expressions, selected after a bibliographic and parametric study.

For the soil masses the values of the geomechanical parameters are calculated based on the results of a great variety of tests. Distinction is made when dealing with transported or residual soils. For the deformability parameters the value of E_0 is calculated and then corrected for deformation levels which interest the underground works. It was considered reasonable to assume a value of 0.05% of strain, on bored tunnels, and 0.3% on SEM/NATM tunnels.

The calculation of the parameters in heterogeneous rock masses is executed through a probabilistic analysis of the value of RMR and GSI.

The developed GEOPAT system was applied to a large underground station in urban environment and to a powerhouse complex. Both structures were excavated in granite formations. Using the geomechanical information obtained from the characterization of the rock formations it was possible, using the developed system, to obtain the geomechanical parameters to use in their modelling.

These parameters were used in structure modelling. The results obtained where compared with the monitored values of displacements. In both cases they show a good agreement. This validate the rules and knowledge of the developed KBS system. Nevertheless it is necessary to permanently update the rules, incorporate new knowledge and apply the system to more case studies in an iterative process of systematic improvement of the system.

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