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METHODOLOGY FOR EXTRAPOLATION OF ROCK MASS DEFORMABILITY PARAMETERS IN TUNNELING

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Abstract. *This article proposes one approach for extrapolation of necessary parameters for numerical analyses in tunnelling. The approach is named as an empirical – statical – dynamical method for extrapolation. The proposed methodology is based on combination of empirical classification rock mass methods, geophysical measurements and direct dilatometer deformability testing on a field. The analyses are prepared for purposes of investigation and design for several tunnels in Republic of Macedonia. One example for dividing of tunnel length in quasi-homogenous zones, as a basis for forming of geotechnical and numerical model that can be a basis for interaction analyses of rock – structures system and stress-strain behaviour of rock massif, is also given.*
The several original regressive models between rock mass quality, deformability and velocity of longitudinal seismic waves are shown.

Key words: *geotechnical model, rock complexes, physical model, classification, extrapolation.*

1. INTRODUCTION

The problem for extrapolation in geotechnics is one of the key problems and basis for successful geotechnical and numerical modelling in the past few decades. The main goal of this problem is how to extrapolate the parameter from the zone of testing to the whole area (volume) that is of interest for interaction analyses of the system rock mass-structure.

The extrapolation methods are mainly developed for design problems at large dams by Kujundžić, 1973 and 1977. This problem is constantly expanded over time, and in this context it is pertinent to mention the works Kujundžić and Petrović, 1980; Lokin and Čolić 1980, 1990 and 1996; Lokin, Lapčević, Petričević, 1989; Čolić, Manojlović, 1983; Jovanovski, Gapkovski, Petrevski, 1996; Jovanovski and Gapkovski, 1995, 1998; Jovanovski et al., 2000; Jovanovski, Gapkovski, Ilijovski, 2002, 2003, 2004; Ilijovski, Jovanovski, Velevski, 2004; Ilijovski, 2005 etc.

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By the scale effect, the size of the observed area and relation effect were considered by Müller, 1969; Kujundžić, 1977, 1983; Herget, 1988; Charrua-Graca, 1990; Rocha, 1974, Martin et al, 1990; A. P. Cunha, 1990; Rac, M. V., 1968; Lapčević, 1996, 2005, etc.

Site testing methods of deformation of rock massif and shear strength were developed and perfected by Kujundžić and his colleagues from the Institute "Jaroslav Černi", Belgrade, 1965, 1966, 1974, 1977, 1983.

Contribution to defining deformability and shear strength of rock massif through empirical failure criteria is given by Hoek and Brown, 1980, 1983, 1988. Application of this method to rocks of poor quality demanded further changes (Hoek, Wood and Shah, 1992) and even the development of a new classification based on the application of so-called Geological Strength Index (Hoek, Kaiser and Bawden, 1995, Hoek, 1995, Hoek and Brown, 1997, Hoek, Marinos and Benissi, 1998; Marinos and Hoek, 2000, 2001, Hoek, Carranza-Torres, Corkum, 2002; Marinos, V., Marinos, P. and Hoek, 2005, Hoek, Marinos, P. and Marinos, V., 2005; Marinos, P., Hoek, E. and Marinos, V., 2006, Hoek and Diederichs, 2006; etc.). The contributions of Barton and Chobeau, 1994 and Bieniawski, 1993 should also mentined.

Classification systems developed in the field of rock mechanics that need to be highlighted are Geomechanical Classification – Rock Mass Rating system (Bieniawski, 1970, 1973, 1974, 1975, 1976, 1979, 1989); RSR - Rock Structure Rating (Wickham, Tiedemam and Skinner, 1972, 1974); Q system - Rock Mass Quality (Barton, Lien and Lunde, 1974); multiparameter classification system, called ERMR (Excavation Rock Mass Rating), which can be used for main type of excavation problems, studied by Jovanovski, 2001 etc.

Computers development in recent decades has contributed to the development of numerical calculation method in rock mechanics which enabled new and wider possibilities of stress and deformation calculation. This had significantly stimulated the development of rock mechanics as scientific and technical discipline as well as the wider application of research results into practice.

So, this article describes a methodology that shows how it is possible to integrate all these approaches in a problem for extrapolation of the parameters in tunnelling. The proposed methodology is based on combination of empirical classification rock mass methods, geophysical measurements and direct dilatometer deformability testing directly on a field. The analyses are given based on the results from investigations on several tunnels in the Republic of Macedonia.

2. Basic Theoretical Setup on a Problem of Extrapolation

It is well known, that the process of investigation in rock masses as a media for interaction with tunnel structure is extremely difficult. This comes from the fact that the total tunnel length cannot be completely covered with detailed geological and geotechnical investigations and tests. So it is necessary to find an appropriate way to extrapolate the defined parameters from smaller volume of testing zone to the whole volume of the rock mass along the tunnel length.

It should be mentioned that the problem of extrapolation is mostly developed for large dams, combining statical and dynamical tests and preparation of appropriate Engineering Geological Sections and Models (EGS and EGM). To illustrate the methodology, one ex-

ample is given in Figure 1 where so called Engineering Geological Model (EGM) per deformability parameter for the profile of arch dam "Sveta Petka" on the river Treska in R. Macedonia is shown (Jovanovski et all, 2004). This EGM is constructed by models per parameter of velocities of longitudinal elastic waves (*Vp)* and models and sections per discontinuity parameters, considering all results of geological, geophysical and geotechnical investigations.

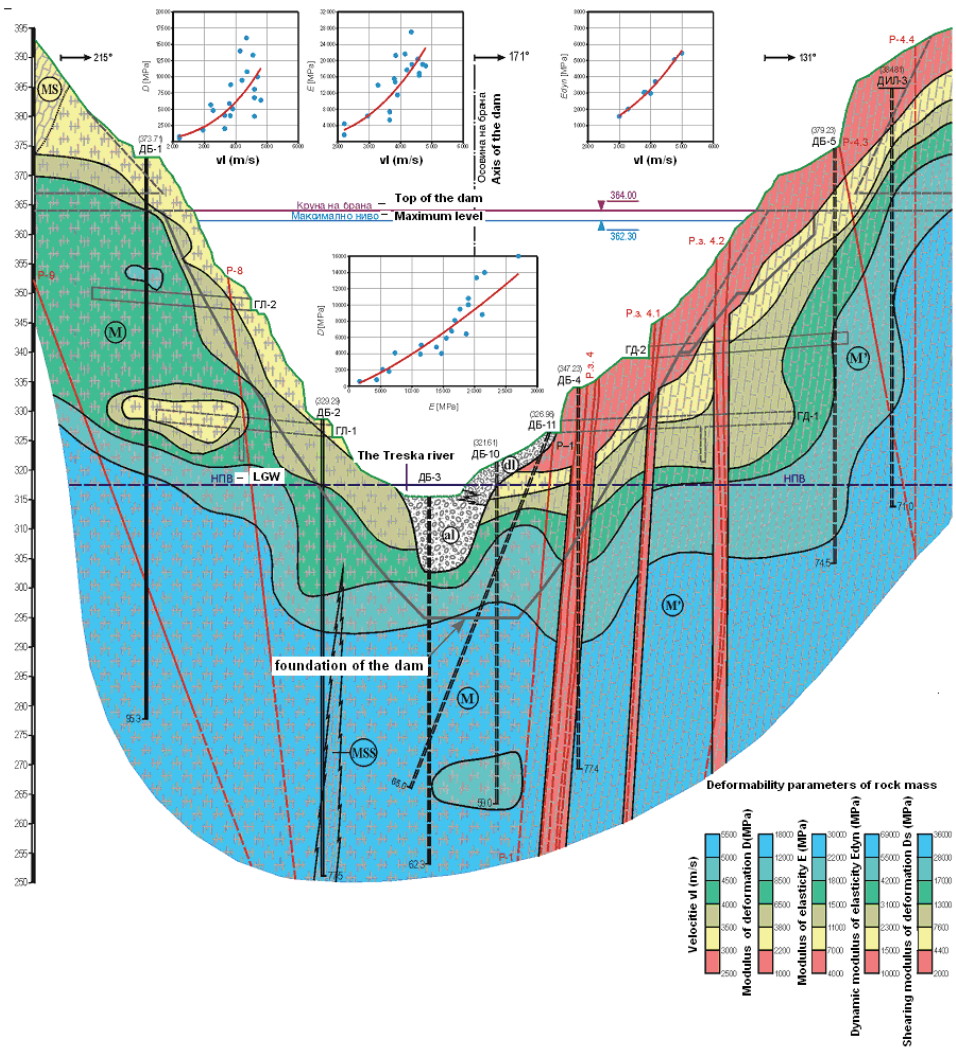

Fig. 1. Engineering-geological model per deformability parameter for profile of arch dam Sveta Petka" on a Treska river, (Jovanovski et al, 2004)

Gradation of parameters is based on defined interval of velocities of longitudinal elastic waves v_l, for main zones, for which correlations between v_l, and the values of

static compression modulus of deformations and elasticity (D and E) and static shearing modulus of deformations (D_s) have been established.

This extrapolation method is mainly based on the following assumptions given by Kujundžić (1977):

1. Parallel statical and dynamical testing directly on a field with flat jacks and geophysical methods, as a basis to obtain sets of values for deformability and values of longitudinal seismic waves.
2. Determination of values for longitudinal seismic waves for the interaction area with the engineering structure.
3. Forming direct and indirect analytical regression models between modulus of deformation and elasticity (D and E) with values of longitudinal waves (Vp) and dynamic elasticity modulus (Edyn).
4. Extrapolation of the parameters using the formed regression curves from the area of testing to the whole rock mass volume involved in system rock mass-structure interaction.

In general, the methodology can be defined as a static-dynamic method of testing and extrapolation of the results.

3. Proposed Methodology for Extrapolation in Tunneling

The proposed methodology can shortly be defined as empirical–static-dynamic methodology of extrapolation. This means that all known methods for defining of deformability and shear strength of rock masses can be used and combined for extrapolation of parameters for the whole area and length of structures. The prerequisite for using this methodology is following:

1. To have enough data for reliable rock mass classification.
2. To have enough testing data for deformability with static tests.
3. Whole structural zone (in this case tunnel) to be covered with geophysical seismic tests.

Such testing must be performed in a manner that will ensure reliable data for geotechnical modeling of the natural geological environment of the whole area along the tunnel. Having in mind that too many properties are needed to characterise certain rock mass completely, it is easy to conclude that the claim for uniformity of all or most of the properties cannot be achieved.

So, before some areas are selected, we choose one or few properties for which the uniformity of one area is demanded. We call these areas quasi-homogenous zones and they represent the basic and constitutive elements of geological model.

Inside such zone some conditions or properties are the same in every point, and very different outside it. Each and every zone is determined by space limits and consists, in some way, properties which are important for the study.

It shall be noted, that the process of extrapolation is strictly connected and interrelated to the process of geotechnical modelling of the terrain. The complex geotechnical model is consisted of three basic models (Pavlović, 1995, 1996):

- model of natural geological environment;
- model of engineering activity - geotechnical model in narrow sense (GM);
- model of interaction - model of stress-strain behavior.

One way to show phases during defining model of interaction is given in Figure 2 where it can be seen that the model of engineering activity and the model of interaction are final phases of geotechnical modelling.

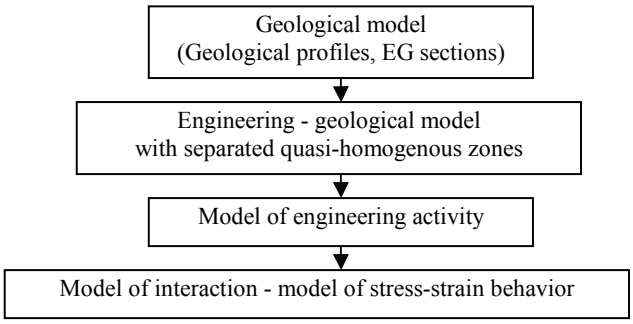

Fig. 2. Phases in defining model of interaction

Named geotechnical model could be divided additionally on physical and mathematical (Figure 3). Physical models in principal present certain simplified reproduction of real conditions in terrain. Mathematical models have one goal in defining certain properties and terrain conditions with analytic relations or models of stress-strain behavior. In any case, physical models are base for any mathematical model.

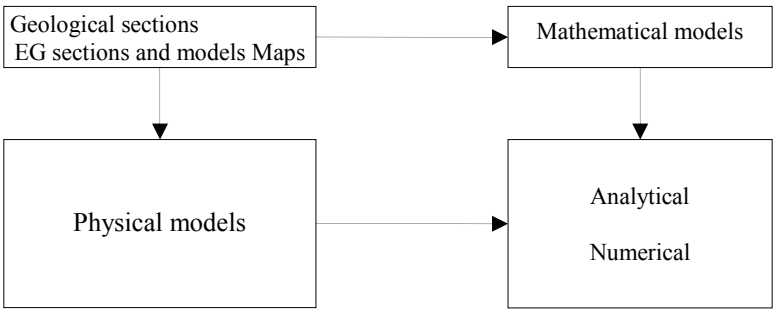

Fig. 3. Geotehnical models divided on physical and mathematical model

While we respect every advantages and possibilities, it must not be forgotten that the validity of numerical methods depends on reliability and details' degree of engineer-geological model, as well as that these methods are not the only ones neither they are always expectable and optimal.

Also, numerical methods should be economical, and their technical information exact enough, which can be checked only if we compare them with results obtained from real situations. The final result should be their verification, especially in a phase of construction.

It is obvious that the models must satisfy two, on the first hand, contradictory demands: to simulate real terrain conditions the best as they can, but to be as simple as possible.

4. PRACTICAL EXAMPLE

According to previously defined issues and with clear objectives in mind, the following example is completed for collected data from several tunnels designed along highway E-75, section from Demir Kapija to Smokvica in the Republic of Macedonia. The following methodology of investigations is used:

1. Collection of data for rock massif test results, particularly laboratory and field test results of strength, deformation, discontinuities and other parameters.
2. Specific laboratory and field testing for a specific purposes.
3. Statistical analysis and comparison of data collected from the literature and data collected through research and tests performed for purposes of this article.

In the first phase, the collected data was used for preparation of geological models. To illustrate the methodology, simplified engineering geological section is presented in Figure 4.

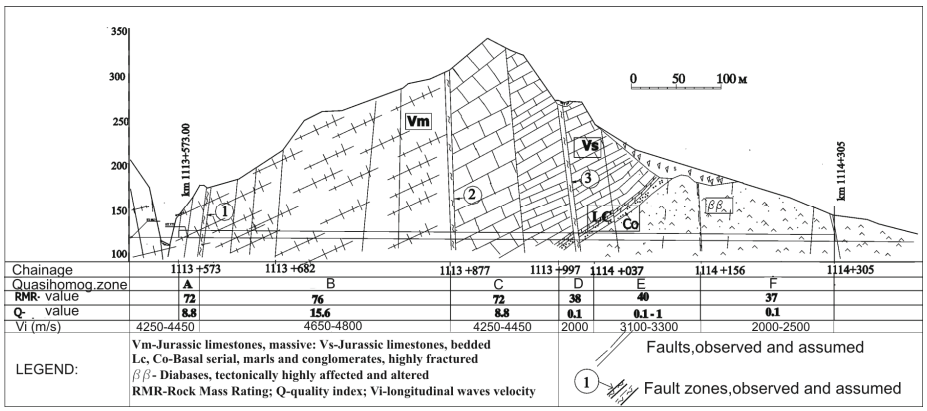

Fig. 4. Simplified engineering geological section of tunnel 1

After that, all of the results from geological, geotechnical and geophysical investigations were used for establishing physical model through the RMR, Q and GSI classification.

Various physical models defined by GSI values using Hoek, Carranza-Torres and Corkum, 2002 and Hoek and Diederichs's, 2006 methods were used for analytical models and prediction of shear strength and deformability parameters of rock massif.

Correlations between the quality of rock massif (RMR, GSI and Q indexes), dynamic (Vp and E_{dyn}) and static properties (D and E) of rock masses are expressed using results of the detailed classification of the rock massif around the measuring point with dilatometer testing.

Some typical values for main lithological types along analysed section in a term of GSI value are given in Figure 5.

Typical deformability diagrams from dilatometer tests for some lithological types are given in Figure 6. On the diagrams, some sets of RMR and Vp values are also presented in order to see the type of deformation process related with some rock mass values.

Based on detail analyses, a numerous regression models are obtained in order to fulfill the necessary criteria for extrapolation. For example, regression models between static modulus of deformation (D) and elasticity modulus (E), as well as radial deformations around dilatometer testing zones are shown on Figure 7.

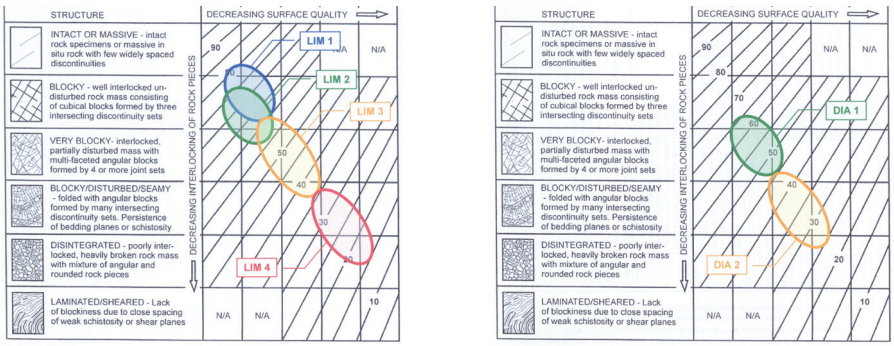

Fig. 5. Range of GSI values for different zones of limestones (LIM) and diabase (DIA) for the analysed sections

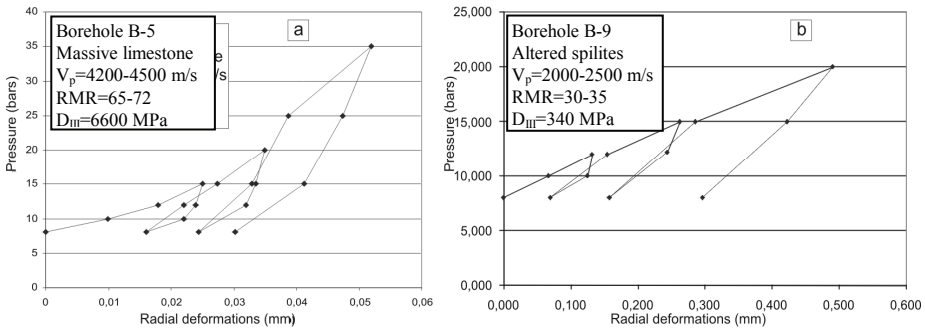

Fig. 6. Typical diagrams from dilatometer tests

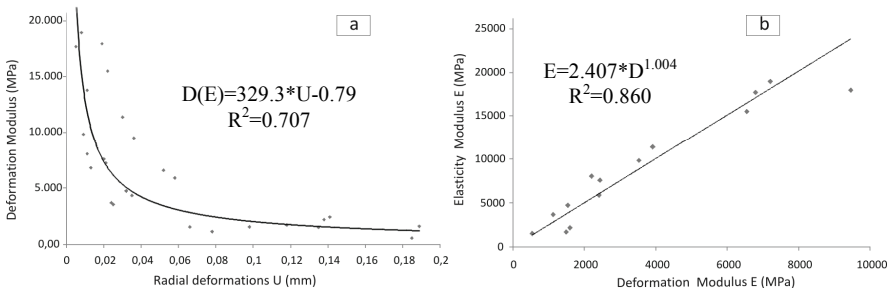

Fig. 7. Correlations between (a) deformation modulus (D) and radial deformations (U) and (b) deformation modulus (D) and elasticity modulus (E) for analysed tunnels

Regression models between velocities of longitudinal elastic waves v_l with quality of rock mass by *RMR* and *Q* system are shown on Figures 8 and on Figure 9. Finally, some regression models between static and dynamic deformation parameters are given on Figure 10.

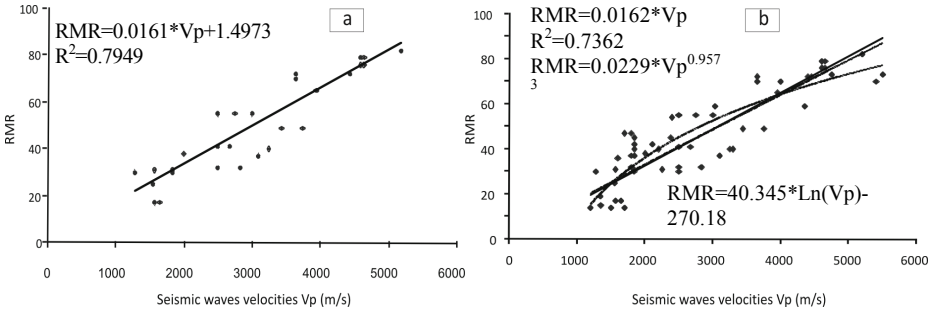

Fig. 8. Correlations between rock mass rating (RMR) and longitudinal seismic wave velicities for (a) tunnels along section from Demir Kapija to Smokvica and (b) other tunnels in RM

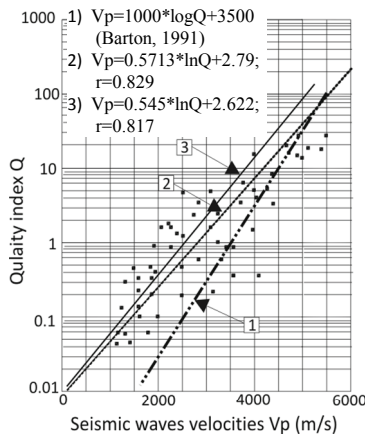

Fig. 9. Correlative dependences between rock mass quality index (Q) and longitudinal seismic wave velocities:
1) Correlation by Barton, 1991:
2) Correlation for tunnels along section from Demir Kapija to Smokvica;
3) Correlation for other tunnels in R. of Macedonia

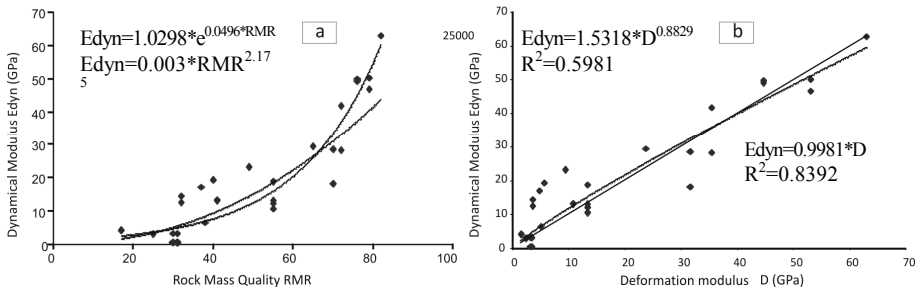

Fig. 10. Correlative dependences between (a) quality of rock mass by RMR and dynamical elasticity modulus (Edyn) and (b) deformation modulus (D) with Edyn

Analyzing all regression models, it is obvious that determination coefficients (r^2) indicate strong connection between examined parameters.

Lower values of *RMR* and v_p are referring to category of poor to poor rock mass (20 – 40 RMR and v_p mostly from 1500-2500 m/s). Class of parameters' value in a range from RMR=40-60 and v_l from 2800 – 4500 m/s fits to fair rock, while higher values for good rock mass rating.

Having such correlations and defined values of seismic waves, for each quasi-homogenous zone along tunnels, it is possible to extrapolate necessary input parameters for numerical analyses.

5. CONCLUSION

The presented empirical–static–dynamic method for data extrapolation can be very useful tool in preparation of geotechnical models for further analyses in tunneling. Because of its verification, the suggested methodology must be critically re-examined meanwhile in terms of possibilities to apply it on other locations and other facilities in different geological media.

However, it will open doors and possibilities for further researches, considering that it is practically impossible to exhaust this scientific theme with only one paper. Analytical models for prognosis of possible intervals of deformation modulus *D* are useful as input data in numerical analysis for relatively shallow tunnels.

Also, the process of modelling must be harmonized with research and design phases. It is common to use simpler approaches in initial phases, which meet current quality and quantity of available data. Results of such kind of initial models for complex facilities can indicate the need for new data and they enable re-interpretation of existing data, what, in the other hand, influences the improvement of models or leads to new ideas for new model types.

Based on the aforementioned, we can conclude that there are many unlimited possibilities for further researches in this area. The purpose is to improve and confirm the methodologies suggested in this article, yet not only when it comes to tunnelling but also for other types of structures.

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METODOLOGIJA ZA EKSTRAPOLACIJU PARAMETARA DEFORMABILNOSTI STENSKIH MASA U TUNELOGRADNJI

Zlatko Zafirovski, Igor Peševski, Jovan Papić

U ovom radu prikazan je jedan pristup za ekstrapolaciju ulaznih parametara za naponsko-deformacijske analize kod tunela. Postupak je nazvan empirijsko–statičko-dinamički metod ekstrapolacije, a zasniva se na paralelnoj primeni empirijskih klasifikacionih metoda stenskih masa, geofizičkih merenja i terenskih ispitivanja deformabilnosti metodom sondažnog dilatometra na nekoliko lokacija u Republici Makedoniji.

Kao primer, prikazano je izdvajanje kvazihomogenih zona koje su osnova za definisanje geotehničkih i numeričkih modela. Oni se, dalje, koriste u analizama interakcije objekta i stenske mase i procene naponsko-deformacijskog stanja stenske mase.

Takođe, u radu je priloženo i nekoliko originalnih regresionih modela.

Ključne reči: *geotehnički model, stenski kompleksi, fizički model, klasifikacija, ekstrapolacija*