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COMPARATIVE ANALYSIS OF GEOMECHANICAL VERIFICATION THE SLOPE STABILITY IN THE ZONE OF PREVENTIVE MAINTENANCE HALL OF THE COAL MINE PLJEVLJA**

Abstract

During the geomechanical verification the stability of mining facilities, it is necessary to correctly select the calculated values of the rock material properties from an engineering point of view. In order to complete the previous steps, the starting point is data collection from the open pit. This characterizes the demanding work that is put before the engineers, all with the aim of forming a quality database within which the various characteristics of rock mass, covered by the open pit, are collected and analyzed. Based on this, it is possible to adopt the calculation values of the rock material properties, all with the aim of obtaining the relevant data for the slope stability analysis using different groups of methods. This paper presents a comprehensive analysis of determination the safety factors in a part of the Hall for preventive mechanical and electrical maintenance at the Potrlica open pit. Considering the state of working slope in the position of the Hall for preventive mechanical and electrical maintenance, the system of cracks, as well as the presumed faults that occur in the mentioned zone, it is necessary to include in the analysis different groups of methods for verification the safety factor of analyzed working slope. The application of different analysis methods creates an opportunity for a comparative analysis of the obtained safety factors, which is a direct indicator of the state of analyzed working slope.

Keywords: *geomechanical stability check, Pljevlja coal mine, finite element method, limit equilibrium methods*

1 INTRODUCTION

Bringing the slope to a stability state with an appropriate safety factor is a complex technical-technological and geomechanical undertaking that is put before the engineers. An important aspect in understanding the complexity of mechanical behavior of rocks is knowledge of the influencing factors and processes that lead to the slope instability. For the purposes of defining the value of geomechanical properties, it is necessary to include a number of parameters that directly and indirectly affect the slope condition [1]. On the basis of the performed laboratory and field research, the set of processed and obtained data provides the necessary conditions providing the input parameters for formation the geomechanical model [1].

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Based on the research results, the calculation values of the rock material properties will be selected for geomechanical verification the slope stability [1].

On an example of the open pit Potrlica of the coal mine Pljevlja (Figure 1), specifically for the area in the western part, in the area of the Hall for preventive mechanical and electrical maintenance (Figure 2), both the influence of established geomechanical parameters and tectonics present on that area can be analyzed on the stability of formed slopes. The slope state in the part of the Hall for preventive maintenance is characterized by the crack systems and fault zones, a complex structure of engineering-geological units, and the entire area can be characterized as a complex from a geomechanical point of view. Due to the occurrence of cracks, which indicate the existence of processes that lead to the slope instability, it is necessary to perform a geomechanical stability verification on the basis of which the state of analyzed slope will be monitored.

Figure 1 *Open pit Potrlica of the coal mine Pljevlja (October 2022)*

Figure 2 *Slope of the system of open pit working levels in the area of the Hall for preventive maintenance*

2 GEOMECHANICAL CONDITIONS IN THE HALL ZONE

Defining the geomechanical conditions of the slope in the zone of the Hall for preventive maintenance is a key factor in preparing the stability analysis calculation. Defining the influencing factors on the analyzed slope, all the necessary conditions for defining data are acquired related to:

- Geology of the narrower area, characterized by a contact of marl and clay, clay and coal, marl and coal, marl and limestone and coal and limestone. In addition, there are also different types of marl, limestone and clay where the deposit conditions have changed and where the structure has been disturbed in relation to the condition that existed during the formation of deposit itself. Although the area in question was explored with a fairly dense network of drillholes that were made in order to define the structural structure of the deposit layers and geomechanical characteristics, due to its complexity, it cannot be studied at a sufficient level because it implies an irrationally dense network of exploratory drillholes and a large volume of field and laboratory testing and research. The initial assumption is that the weakened contact zones between different engineering-geological structures can be represented by the presence of those materials that show the lowest values of strength parameters.
- Tectonics, characterized by the presence of crack systems. Tectonic processes in the deposit after its creation led to the destruction of original structure. During exploitation, by unloading and creating the free surfaces in places that are predisposed to the tectonic processes, the open cracks appeared and phenomena that indicate processes that lead to the instability of formed individual working slopes and systems of working slopes. Prospecting, exploration works and geological mapping determined the primary directions and inclinations of cracks and fault zones.
- Engineering geological environments are characterized by the presence of a large number of geological and engineering - geological structures (units). The geomechanical characteristics of these units were determined in different periods of exploration and exploitation of the deposit, and the determined values of the geomechanical parameters are mostly the result of laboratory tests and are in a wide range. The engineering-geological characteristics of the environment of the rock masses of the Potrlica deposit are of the primary importance within the framework of the analysis that will be carried out. [2] As such, the following engineering-geological units were exposed in the open pit area: quaternary, marl, interlayered clays, coal, podine clays and limestone.
- Geomechanical parameters of the working environment are characterized by the values that move within wide limits, irregularly spatially distributed sampling points on the surface and depth of the deposit, and insufficient reliability for this phase of the open pit mining.

- Adopted values for the calculation. On the basis of an insight into the available documentation of the Coal Mine Pljevlja and presented data, obtained by the exploration works and certain laboratory test, the values on the basis of which the statistical processing of data was performed were taken. The statistical processing of data on the available set of values determined the relevant parameter values, which were adopted for the geomechanical stability check on the basis of reliability.

3 GEOMECHANICAL VERIFICATION OF THE SLOPE STABILITY IN THE ZONE OF THE HALL FOR PREVENTIVE MAINTENANCE

The analysis of safety factor calculations was performed on 8 characteristic profiles (Figure 3). The emphasis of the F_s value verification was only in the area of the Hall for preventive maintenance. The reason for the geomechanical stability verification in the mentioned zone is the appearance of cracks on the ground surface, foundations of the Hall and on the open level profiles. The presence of cracks indicates processes that can lead to the instability of the mentioned part of slope.

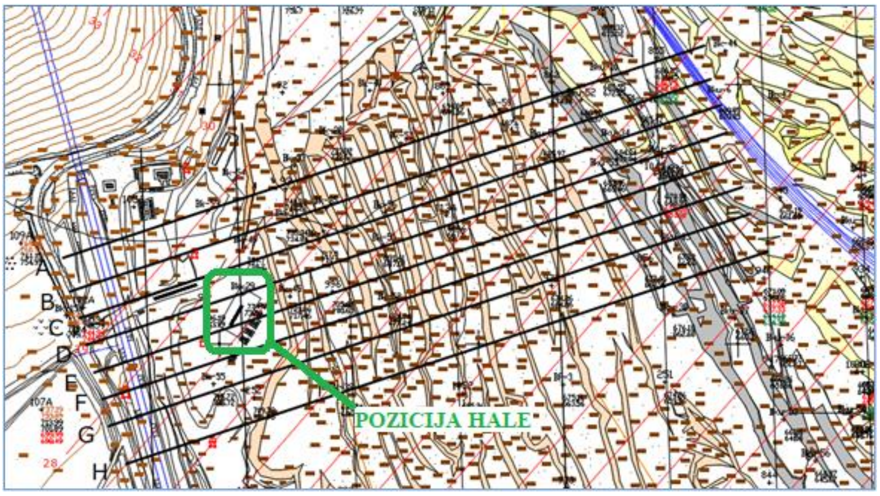

Figure 3 *Position of the cross section for verification the slope safety factor in the Hall area*

Positioning of the cross-sections was done so that, to the greatest extent possible, they were perpendicular to the direction of the system of working levelz, to include the completed works on the coal exploitation in the foothill and position of the regulated bed of the Ćehotina river.

The initial analyzes of the working slope stability in a part of the Hall were carried out using the limit equilibrium methods, based on the use of lamellas, for circular failure and predisposed (plane) failure of the slope. For the needs of more precise results in the disturbed zone of the rock mass such as in the Pljevlja basin, the application of the finite element method (FEM) will present an approach to the analysis of the working slope stability that is more appropriate to the nature of the prevailing rock mass, marl.

The finite element method represents a group of methods from the set of numerical modeling. The advantages of the FEM application are primarily in accuracy, versatility and requiring much smaller prior assumptions, especially regarding the fracture mechanism that can occur. The challenge for engineers is the system complexity in a part of the working slope near Hall, and based on the complexity of the state, the rock massif represents a type of problem that should ideally be studied using the finite element method.

On the basis of such study, the conditions were created to break the current balance applying the FEM to the moment for monitoring the development of fracture, including the fracture itself caused by shearing. The factor of safety in the FEM slope stability analysis is determined from the ratio of shear strength of material and shear strength required to achieve the equilibrium. The presented F_s is characterized in exactly the same way as with the traditional methods of limit equilibrium, and the obtained safety factor can still be defined as the ratio of maximum and realized moments. The basic methodology for determining the FEM safety factor implies the application of the shear strength reduction technique. The failure criterion is the Mohr-Coulomb.

The application of the Shear Strength Reduction (SSR) technique in the slope stability analysis using the finite element method is a simple way to systematically study and determine the Strength Reduction Factor (SRF) or the value of safety factor (F_s) by which the slope leads to the limit state of failure [3].

The physical problem of the slope model is numerically modeled in such a way that the entire analyzed area is divided into elements. The suitability of application the finite element method is reflected in its adaptability to solve the problem of geomechanical stability in conditions of pronounced tectonics and non-linear material properties such as occur in the Pljevlja basin.

Calculation of the safety factor on the formed geomechanical models of slopes on the characteristic cross sections and for the adopted parameters of the working environment was carried out using the software packages "Slide" and "Phase2" from the company Rocscience Inc.

The Rocscience Inc. "Slide" is an in-plane slope stability analysis software. It can be used for the design or analysis of natural and artificially formed slopes (slopes of embankments, levels of open pits, dumps and landfills, slopes of ditches and embankments and free or additionally stabilized walls). The program enables analyzing the stability by self-generated or user-defined sliding surfaces. Sliding surfaces can be circular, flat or a combination of these surfaces. The Slide program package within its graphic editor enables modeling of the tested objects as well as different ways of displaying the calculation results and interpretation of individual calculation elements [4].

The Slide program package also enables the positioning of an arbitrary or determining the position of sliding surface with the minimum value of safety factor. The Rocscience Inc "Phase2" is a software adapted to verify the behavior of elasto-plastic media based on their stress state using the finite element method. It is used both for the analysis of voltage conditions of the working environment in the existence conditions of the underground exploitation facilities as well as open pits. It serves to solve a number of engineering problems, such as the construction of stable slopes at the open pits, stable underground exploitation rooms, in construction for foundations and construction the retaining walls and other ways of stabilizing the base and slopes, etc. [5]. One of the advantages of this software is a relatively simple user interface and numerous ways of visualizing the results, which enables their easier interpretation.

Geomechanical verification the slope stability of the system of working levels was performed for all 8 shown profiles, and in this work, Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 show a characteristic view of calculations on profile D. All calculations were done for circular, predisposed sliding planes and planes under the maximum shear stress. The adopted coefficient of seismicity in both horizontal and vertical directions is 0.015.

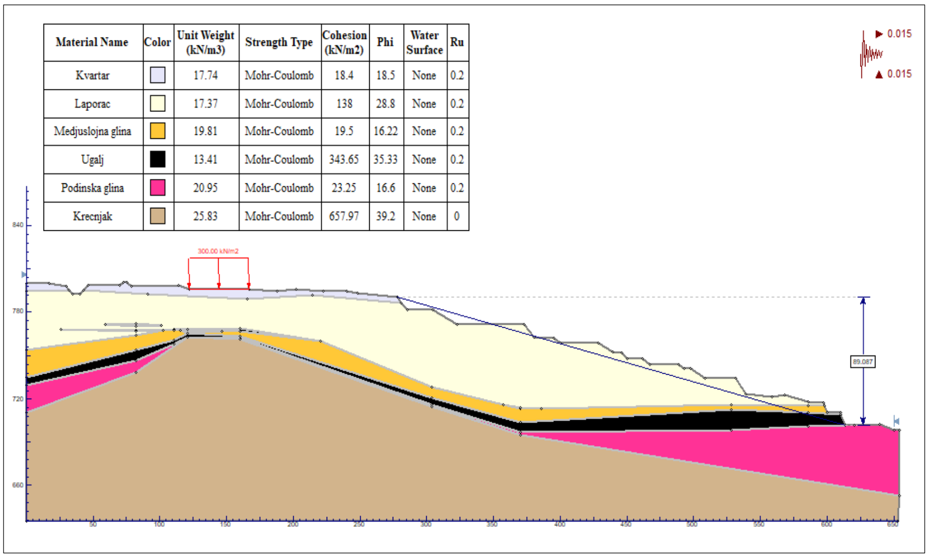

Figure 4 *Geomechanical model of the existing slope on the cross section D-D*

The geomechanical model of the slope was defined on the basis of data from exploration works and laboratory tests on a profile and parameters determined by the valid study [6], [7], [8]. The load of Hall was taken with a value of 300 kN/m^2 and many times exceeds the real load of the Hall. It follows that the impact of the Hall loading is taken with a significant safety margin. The stability analysis of the system of working slopes in the Hall area was carried out using the method of A. W. Bishop and Yanbu, which belong to the group of limit equilibrium calculation methods. For these needs, the program package "Slide" version 6.0 of Rocscience Inc. was used. The aforementioned program package is the property of the Mining and Metallurgy Institute Bor.

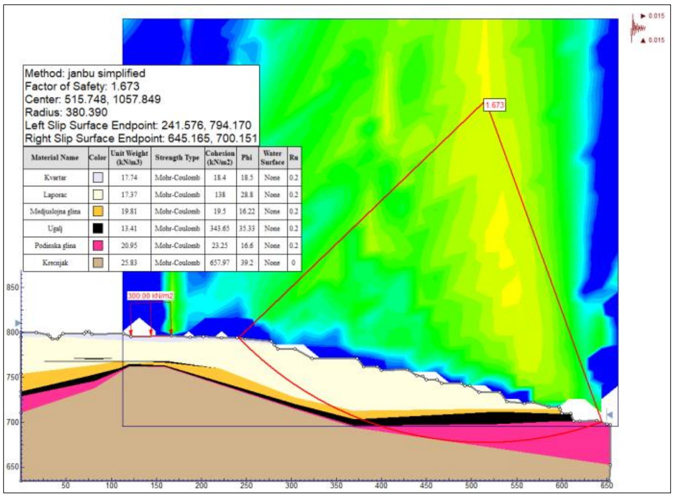

Figure 5 *Minimum safety factor and critical sliding plane for the Mohr-Coulomb failure criterion and limit equilibrium methods for circular sliding plane according to the Yanbu method*

The formed slope model is mainly built by the engineering-geological units of quaternary, marl, clay, coal, interlayered clay and limestone. In order for the stability analysis to include the slope as a whole, it is necessary to position the center of sliding circles, which provides all the prerequisites for interpretation the sliding circles and verification the safety factor of the analyzed slope.

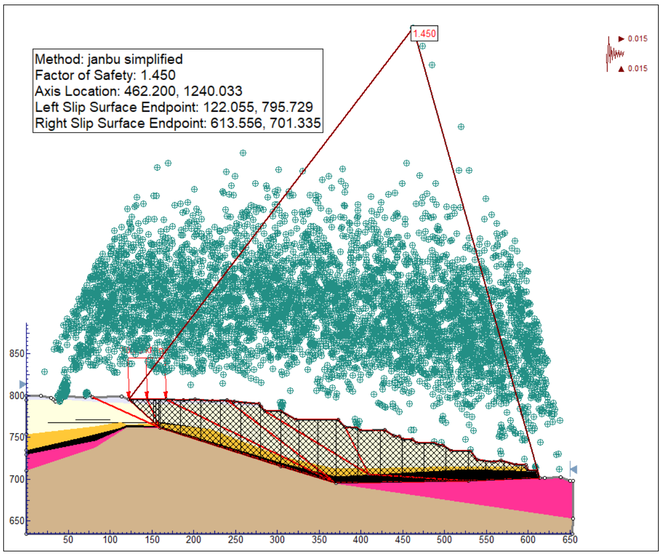

Figure 6 *Minimum safety factor and critical sliding plane for the Mohr-Coulomb failure criterion and limit equilibrium methods for the predisposed sliding plane according to the Yanbu method*

In addition to the limit equilibrium method, the analysis of stability in the Hall zone was also carried out by the FEM. For the purposes of calculating F_s according to this method, the software package "Phase2" from Rocscience Inc. was used. The aforementioned program package is the property of the Mining and Metallurgy Institute Bor.

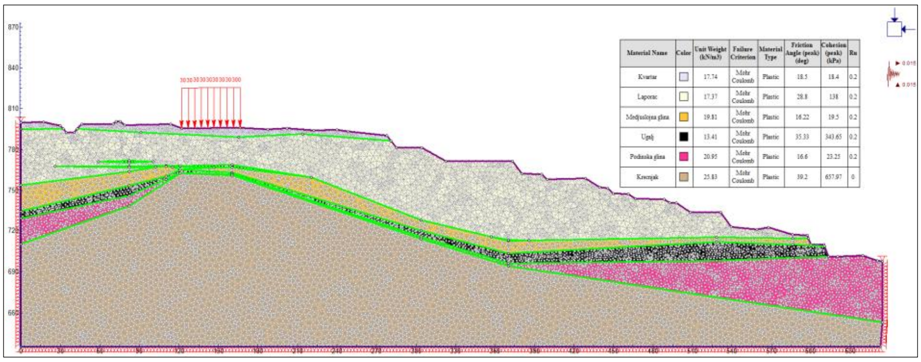

Figure 7 *Geomechanical model of the existing slope on the D-D cross section for calculation using the finite element method*

The boundary conditions of the model according to the FEM should emphasize that the medium is incompressible in the boundary zones of the model. Model boundaries can be defined by different axis constraints. By limiting the model with an engineering approach, the surface is divided into a certain number of elements. Size of an element, i.e., the number of nodes, should be adapted to the smallest dimensions of the engineering-geological environments represented in the model. Interpretation of the FEM calculations can be given in several ways, the most commonly used being the display of horizontal displacements and maximum shear stresses.

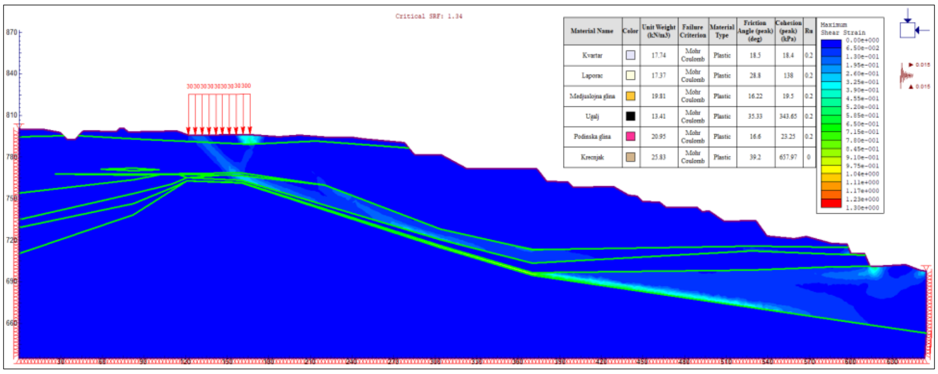

Figure 8 *Minimum factor of safety and critical sliding plane for the Mohr-Coulomb failure criterion and finite element methods*

The analyzed condition of the slope and obtained safety factors using different groups of methods indicate that the slope can be characterized as stable. The reason for geomechanical stability verification using different groups of methods is reflected primarily from the engineering point of view and initial assumptions by visual observation the working slope. The slope stability analysis was performed for different forms of sliding surfaces, which took into account all the possibilities of forming sliding surfaces at the contact of engineering-geological units.

The geomechanical stability verification using the circular shape of sliding surface indicates that the obtained sliding circles do not pass on the contact parts of the engineering-geological environments, characterized as the critical places, and therefore the obtained values of safety factors are slightly higher. For the slope stability analysis for a flat fracture of the sliding surface, the obtained safety factors indicate that the engineering assumptions at the contact of different engineering-geological environments were taken with reliable foundations. The care should be taken here since it cannot be claimed with certainty, based on the engineering assumptions that the critical surfaces were correctly defined. Predisposed sliding planes are constructed so that they include both the entire slope and partial parts of the slope, as well as passing through materials with the lowest strength parameters, where the obtained safety factors for the sliding planes show regularity in the spatial arrangement, and the minimum value is not at the border of that space. For the purposes of this analysis, the given fracture plane on the critical surfaces and obtained safety factors indicate that there is a greater possibility of occurrence the slope sliding at the contact between the layers.

With the complex structure of the rock mass as it was created in the Pljevlja basin, the author's engineering approach has emphasized the geomechanical stability verification according to the FEM due to the possibility of analyzing the parts that have been disturbed by force. Based on such impacts, the rock material has been disturbed, where the disturbed rock material can be characterized as crushed. As a result, cracks and microcracks appeared at the contact of such structured material, and in some areas real faults, lenticular clay and other structural changes occurred. Such a description of the state of the rock massif indicates that the original formations suffered severe tectonic changes, which led to various deformations under the impact of all-round pressures. This is how the formations of artificial contacts between marl and limestone were created, on the basis of which the state of the slope was best analyzed by the FEM.

Applying of this method, according to the general structure of material, the software itself can determine the weakest places within the model (profile), i.e., within the massif itself, and based on that to predict where it can, i.e., where it is expected to break, based on the stress state and characteristics, that is the resistance parameters of the material. After the completed analysis using the FEM, the initial assumptions of engineers have turned out to be good, where the obtained safety factors for the analyzed part of slope are significantly lower than during the analysis using the methods from the limit equilibrium groups. The results of the obtained safety factors of all 8 characteristic cross sections for different shapes of sliding surfaces and analysis by different methods are given in Table 1.

Table 1 *Results of geomechanical stability check using different groups of methods*

Shape of sliding surface	Circular		Predisposed plane		By maximum shear stresses
Method	Bishop	Janbu	Bishop	Janbu	FEM
Cross section A-A	1.637	1.592	1.333	1.29	1.33
Cross section B-B	1.835	1.792	1.504	1.464	1.24
Cross section C-C	2.147	2.022	1.841	1.829	1.26
Cross section D-D	1.747	1.673	1.494	1.45	1.34
Cross section E-E	1.799	1.752	1.553	1.507	1.28
Cross section F-F	1.637	1.592	1.396	1.357	1.23
Cross section G-G	1.835	1.792	1.504	1.464	1.39
Cross section H-H	2.046	1.979	1.557	1.513	1.47

Based on the presented results of stability calculations using the group of limit equilibrium methods and finite element method, the obtained safety factors for analysis the system of working slopes in the Hall area were calculated for the case of maximum expected seismic activity. The stated values of the safety factor indicate that in the event of occurrence the seismic tremors and tremors from blasting, the stability of working slope is not threatened on the basis of the analyzed model.

According to the results for the analyzed slope condition, under the influence of seismic coefficient (ks = 0.015), the safety factor meets the stability criterion, $F_s \geq 1.15$. Based on the previous analysis, it can be concluded that the system of working levels in the area of the Hall for preventive mechanical and electrical maintenance, according to the analyzed models, is stable with a safety factor that is above the minimum prescribed by the Rulebook. The appearance of the comparative safety factor curves is shown in Figure 9.

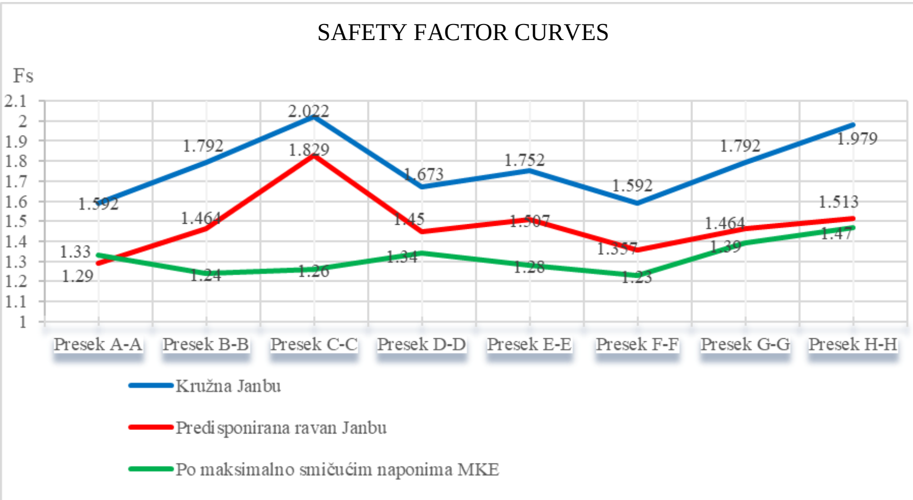

Figure 9 F_s *curve using different methods for geomechanical stability verification*

Based on the interpreted safety factor curves for the analyzed sections, a comparison of the obtained F_s can be performed using different groups of methods. From Figure 9, as a final engineering consideration the advantages of applying the finite element method for the analysis of geomechanical stability verification, it is reflected in the fact that during calculation the finite element method, the software analyzes the maximum shear stresses at the critical contact of engineering geological environments. The obtained safety factors can be taken as the values with greater reliability, which puts the engineering conclusions of the safety side at a higher level.

4 CONCLUDING CONSIDERATIONS

State of the system of working slopes in the area of the Hall for preventive mechanical and electrical maintenance is a consequence of the need for a geomechanical check the stability of slopes due to the appearance of crack systems and assumed fault zones. Complexity of this analysis is reflected in the changed environments in terms of lithology, position of the Hall, as well as appearance of cracks in the zone of the Hall foundation. Through a detailed analysis of application different groups of methods, the safety factor values were obtained, which indicate that the analyzed condition of slope is stable. At the same time, from the group of numerical modeling methods, application of the finite element method (FEM) is an advantage compared to the traditional limit equilibrium methods because during the analysis it is not necessary to make any assumptions in advance regarding the shape and position of the sliding surface, lamellar lateral forces and their directions.

Applying the FEM, the state of stress, deformation and corresponding shear strength in the rock material can be calculated very precisely. Development of the fracture mechanism itself can be very general and does not have to be a simple circular or logarithmic curve. The finite element method can also be applied to the fractures that occur as a result of spalling, rock material that behaves as brittle materials, rock material with variable parameters, which is also the case for analysis the system of working slopes at the open pit "Potrlica" - Pljevlja.

In the further development of works at the open pit "Potrlica" in the analyzed area, it is necessary to relieve the slope and thereby increase safety in the Hall area. The relief of slope can be done increasing the number of levels and reducing the height in the analyzed zone, and in this way all relevant parameters will be satisfied on the basis of which the condition of slope stability will be fulfilled. The reason for this is the multitude of crack systems that are a direct consequence of post-struggle tectonics. In order for the slope to be considered stable, it is necessary to verify the stability by at least 2 methods, where after the analysis, it is necessary that the obtained safety factors meet the minimum values prescribed by the regulations.

Through the control check, it can be concluded that a better knowledge of the working environment is needed, on the basis of which the calculated safety factors will be obtained with a greater reliability. Due to this reason, it is necessary to carry out the regular checks with visual observations of the slope and periodic calculation of safety factors, which will have as an indicator that the condition of analyzed working slope is stable and meets the values of minimum safety factors prescribed by the Rulebook.

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