



RESEARCH ON DETERMINING THE LOAD FACTOR FOR DIFFERENT TYPES OF ROCKS FOUND IN THE JIU VALLEY BASIN IN ORDER TO ACHIEVE ROCK-SUPPORT EQUILIBRIUM IN MINING CONSTRUCTIONS

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Abstract: *The load factor is an important index and the philosophy of construction uses it as a tool to anticipate a potential danger of irreversible deformations of a structure. In order to achieve a classification of the possibility of a structure to yield or collapse, the minimum and maximum criteria call for the determination and evaluation of structures based on the load factor. In this article the proposed method is used to determine the maximum and minimum load factor applied to metal supports used in mining constructions. This leads to the writing of equilibrium state equations specific to the rock-support interaction. The case study consists of using data on the physical-mechanical proprieties of rocks from the Jiu Valley basin in correlation with the parameters of common metal supports. The results offer the option of categorizing, through the load factor, the behavior of a metal structure in correlation with the rocks in which it is mounted. Categorizing the dependence between the load factor and the way a metal structure takes on the load from the surrounding rock pressure can make the difference between switching or not to alternative support solutions without the permanent loss of the profiles through the occurrence of irreversible deformations, respectively reaching the point where their load-bearing capacity has been exceeded because they have entered the plastic range of use.*

Keywords: *mining exploitation, rock pressure, metallic structure, equilibrium equations, loading factor, galleries stability*

1. Introduction

The exploitation of essential mineral resources is crucial to human progress and the development of modern civilization. As surface and shallow-depth mineral reserves have been extracted or depleted, the mining industry has been increasingly moving to deep and ultra-deep operations, facing unprecedented geological and engineering challenges. [1]. At these significant depths, maintaining the structural stability of horizontal underground workings requires an accurate assessment of the stress-strain state around mining excavations. By formulating the equilibrium equation in terms of virtual mechanical work between the metallic support and the surrounding rocks of the Jiu Valley basin, this method bridges the gap between deep mining challenges and practical, on-site stability assessments, providing a clear added value for proactive ground control.

Artisanal and small-scale mining (ASM) plays a critical role in supplying critical minerals essential for clean energy, yet underground rock collapse remains a major safety and sustainability challenge. [2] Deep mining necessitates addressing the inherent and man-caused potential instabilities of the rock mass, which are influenced by rock strength, brittleness, in-situ stress magnitude, dynamic disturbances, excavation sequences, and geological structures. [3] Of particular interest are methods for calculating the stress strain state of the ground environment around mine workings, including at their limit state. [4] Most importantly, the impact of the deformation history and the displacement and energy demands from static and dynamic rock mass failure processes have to be considered. [5] To address these challenges, this research introduces an analytical approach based on the determination of a simplified loading factor. By evaluating the equilibrium state through

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virtual mechanical work, this method provides a direct preview of the interaction between surrounding rock pressure and common metallic supports, establishing a proactive tool for ground control in highly or medium stressed environments.

Over time, research has been conducted both underground and on the surface regarding the optimal assembly of metallic structures with different construction features with the aim of optimizing their service life, to make mining exploitation activity safer and maintain galleries stability. Determining the minimum and maximum load factor leads to categorizing the functioning way a metallic support system have and when and where is in equilibrium state. The loading factor can predict the increasing or decreasing value of the rock pressure and can be use in artisanal, small-scale mining and also for deep mining situations. In this paper, the determination of the load factor was carried out based on writing the equilibrium equation in terms of mechanical work between the metallic support and the surrounding rocks of the type found in the Jiu Valley basin.

The loading factor that results from the equilibrium state equations can be used alone as a quick preview of the situation or with other multi-decision factors. The proposed methodology of determining the loading factor can be applied for different types of metallic profiles used as support so as for different types of rocks.

2. The minimum and maximum loading factor criteria according to the Static of constructions theory

The deformations caused by internal forces correspond to a quantity of mechanical work, called internal mechanical work. Internal mechanical work is negative because the internal forces oppose the deformation. The development of these forces represents the response of the material to the action of external forces and therefore their directions are opposite to those in which the respective deformations occur. [6]

The minimum load factor criterion can be stated as follows: the load factor λ_c is the smallest of the factors obtained by considering all possible failure mechanisms for the given structure and loads. [7]

The maximum load factor criterion can be stated as follows: the load factor λ_c is the largest of the factors that can be obtained for the given structure and loads, considering all bending moments diagrams that satisfy the conditions of static equilibrium and plasticity. [7]

The criterion thus reflects the capacity of the structure to adapt by redistributing efforts so as to support the highest values of applied loads that the bearing capacity allows. [7]

The path on identifying the plastic release state consist in finding the right value of λ_c by sorting possible solutions that perform two conditions so the third condition to be use for verification, Table 1. The static condition must be satisfying in any case so two other alternatives remain and these are the mechanism condition and the plasticity condition. [7]

Table 1. The explained conditions for the minimum and maximum criteria

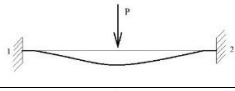
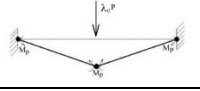
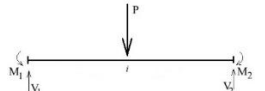
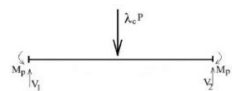
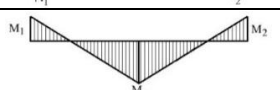
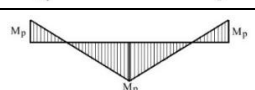
Elastic domain		Collapse	
	Continuity	Mechanism	
	Continuity	Mechanism	
	Continuity	Mechanism	
	Static equilibrium		
	Static equilibrium		
	Static equilibrium		
	Elasticity	Plasticity	
	Elasticity	Plasticity	
	Elasticity	Plasticity	

Figure 1 presents the conditions that must be applied when referring to the minimum and maximum load factor. Therefore, summarizing the above, the following representation of the loading factor possibilities of use for the three conditions that characterize plastic failure is described. [7]

$$\lambda = \lambda_c \begin{cases} \text{plasticity condition} \\ \text{static equilibrium condition} \\ \text{mechanism condition} \end{cases} \begin{cases} \lambda \leq \lambda_c \\ \lambda \geq \lambda_c \end{cases}$$

Fig. 1. Representation of the loading factor possibilities of use

By imposing the conditions simultaneously, the unique solution corresponding to λ_c is reached, while by imposing only two of the conditions, a lower or an upper limit is obtained. The minimum and maximum criteria thus serve to approach to the solution corresponding to instability. [7]

The condition is written [7]:

$$\lambda \sum P_i \delta_i - \sum M_j \theta_j = 0 \quad (1)$$

The application of condition (1) requires establishing the correlation between the displacements δ_i in the directions of the loads and the rotations θ_j in the joints. The mechanism having a single kinematic degree of freedom, one of the rotations θ_j is chosen as a parameter with an arbitrary value, for example equal to unity, and all the other displacements are determined depending on them. In some cases, the correlations are established directly and the static equilibrium condition can be expressed by virtual mechanical work. [7] In equation (1) the bending moment was denoted by M_j , with P_i was noted the load and λ represents the loading factor.

Figure 2 shows an example of a metallic structure that is the subject of the study, namely a metallic support system that is made of metallic profiles connected to each other by metallic clamps. [8] Such a structure is designed to work in the elastic domain where the displacements are direct proportional with the loadings which is why it is for interest to know the conditions in which it works as a mechanism or it enters the plastic domain, in respect with the static equilibrium condition.

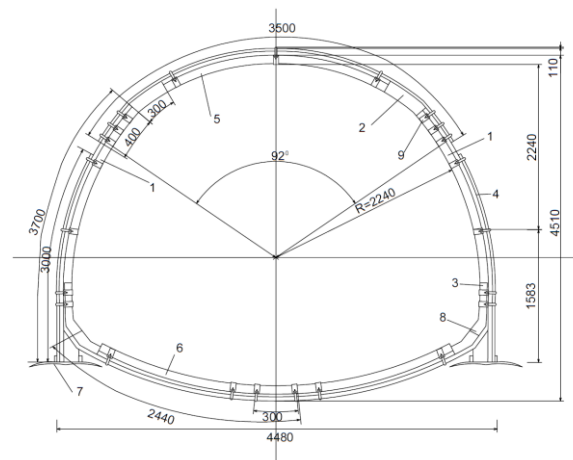


Fig. 2. Example of metallic support system designed to work in the elastic domain

3. The philosophy of rock-support equilibrium in mining constructions

Ground control or management is a process to predict and manage rock behavior and failure conditions in underground openings. The knowledge of ground condition plays a considerable role in pillar design, support design, stability analysis of slopes, instrumentation selection, roof controls and so on. [3]

The behavior of rock pressure is a natural and inevitable phenomenon during coal seam mining, resulting in numerous casualties and equipment damage annually. The ability to predict and assess the strength of rock pressure in the coal face beforehand has become crucial in preventing rock pressure accidents. [9]

Evaluation of rock mass stability is the main concern of squeezing problems due to the deformation of rock mass which may happen. Squeezing ground behavior is identified by large scale deformation in underground excavations. [3]

Rockbursts, like earthquakes, from the perspective of public awareness and disturbance, are the rare exception to an otherwise relatively stable and equilibrium state of the earth's near-surface rock mass. Unlike earthquakes, rockbursting and its associated seismicity derives from relatively shallow mining activity and the removal of a rock volume to form an underground excavation of some kind. [10] Any onset of a rockbursting condition in the context of a civil or mining excavation confronts the worker, engineer and management alike with safety and production-related decisions. While more remote and robotic methods of excavation are serving to help mitigate worker exposure at the advancing face of an excavation, in mining at least conditions are dynamic on a temporal and spatial scale that relates to changes with on-going production throughout the mine. [10] Ground condition and potential hazards are used to determine the type of rock support and reinforcement systems in underground excavations. [11] Also note that there is no need to use the term “dynamic” when referring to ground support component systems, all of which have some deformability and energy absorbing capacity in response to vibration and impact loadings during the creation of excavations. [11]

Identifying areas of underground coal mines with a higher propensity for roof deformation is crucial for mitigating geotechnical risk proactively. [12] More recent research has identified that surface support systems may also be classified within a limited number of categories. This classification is necessarily more complex given the greater number of variables associated with the loading and response of ground support systems than those associated with the responses to loading of reinforcement systems. [11] The focus of suppliers to mine operations has been on developing ground support elements that meet a set of acceptable, or desirable, mechanical proprieties under quasistatic or impact loading conditions. [13]

The use of qualitative concepts is also consistent with developing ground support specifications based on observations and previous experience. [11] It is important to consider the factors related to mining practices before embarking on a campaign of ground support. If mining practices cannot be modified to improve ground stability, then appropriate ground support (i.e., reinforcement and support) must be designed. [11] Ensuring the stability of underground excavations under dynamic loading conditions remains a critical challenge in deep mining operations, where sudden energy release events can impose extreme loads on ground support systems. As underground mining operations extend to greater depths, they are increasingly exposed to higher stress conditions and dynamic loading environments. In these high risk environments, ground support systems play a crucial role in maintaining excavation integrity and protecting personnel and infrastructure. An effective ground support system must be capable of withstanding large displacements at high strain rates and dissipating the substantial energy released during dynamic events such as rockbursts and seismic activity. [14] Most of the potential energy available to such events is on a scale that can be absorbed by yielding support systems through the energy relationship. [10]

4. Methodology

To determine the limit state and evaluate the structural behavior of the underground metallic support systems, an analytical methodology based on the Virtual Mechanical Work principle is established. The framework correlates the laboratory-derived displacement criteria of the support structures with the intrinsic geomechanical characteristics of the surrounding rock mass. The methodology is systematically executed through the following four steps:

Step 1: Definition of the Energy Balance Equation

The internal and external mechanical work (L_i and L_e) within the rock-support interaction is balanced according to the fundamental equation derived from the Statics of Constructions:

$$\lambda \sum c_j \varphi_j - \sum P_i \delta_i = 0 \quad (2)$$

$$\lambda = \frac{\sum P_i \delta_i}{\sum c_j \varphi_j} \quad (3)$$

where P_i represents the applied structural load, δ_i is the measured displacement along the support contour, c_j is the rock cohesion, φ_j is the internal friction angle, and λ constitutes the target loading factor.

Step 2: Laboratory Experimental Baseline

The structural capacity of the metallic support system is established via full-contour laboratory compression testing or by measuring the displacements suffered by the metal supports already installed underground. This step quantifies the exact displacement response (δ_i) across critical monitoring points (left wall, right wall, floor, and ceiling sections) under incremental load steps (P_i) converted into uniform stress units (daN/cm²).

Step 3: Synthesis of Geomechanical Boundaries

The boundary conditions of the underground environment are integrated by collecting and converting the maximum, minimum, and medium physical-mechanical properties (cohesion c_j and friction angle φ_j) of the localized rock formations.

Step 4: Analytical Calculation of the Limit Loading Factor (λ)

By isolating the loading factor from the energy balance equation, the final operational algorithm is applied to map every structural state as described in (3).

The computed values are subsequently categorized to determine whether the support retains an elastic energy reserve ($\lambda < 1$), operates at perfect static equilibrium ($\lambda = 1$), or enters the plastic range of irreversible deformation requiring alternative reinforcement strategies ($\lambda > 1$).

5. Calculation of the load factor for different types of rocks found in the Jiu Valley basin

It should be noted that the static equilibrium condition can be expressed in terms of virtual mechanical work and under the action of loads in the structure, a stress state occurs, which is characterized by the appearance of external forces and deformations at all points of the material. Considering the static application of loads on the structure for the stress state, the same growth process results as for loads and displacements in the sense that the internal forces and deformations gradually increase from zero to the final value and the law of proportionality, which has the form of Hooke's law, is respected between them. Thus, both the final deformed position and at each intermediate moment there is a state of equilibrium between the quantities corresponding to the external and internal forces. [6]

In practice the underground metal support will be loaded with a load factor given by the surrounding rocks and the possibility of the surrounding rocks to move along the contour, unlike laboratory tests that only illustrated the bending moments and associated yielding for the given loads. Therefore, the equilibrium equation will consider the load factor dependent on the rock cohesion and its friction angle, these producing the mechanical work of the external forces and the loading with the specific displacement determined for the metal support in the laboratory will constitute the mechanical work of the internal forces.

By applying the terms of the equilibrium equation (1) to the specific interaction between the metallic support system and the surrounding rock mass, the analytical framework defines the values for the components of equations (2) and (3) as follows: P_i is the loading value, Table 3 [8], δ_i is the displacements value measured in different points around the metallic support, Table 3, [8] c_j represents the cohesion value of the rocks that can be found around the metallic support in Jiu Valley basin and φ_j is the internal friction angle of the rocks found around the metallic support in Jiu Valley basin. In Table 2 the values of the cohesion and the internal friction angle are given for different types of rocks found in the Jiu Valley basin. [15]

The metallic support system have been tested in the laboratory and loaded along the entire contour. [8]

Table 4, 5 and 6 gives the values for the minimum and maximum loading factor calculated as described above and summarized in the equation (3). The values of cohesion from Table 2 were converted and calculated in Table 4, 5 and 6 in daN/cm². The values for pressure given in Table 3 were also converted in daN/cm² for the calculation and values given in Tables 4,5 and 6. The values of the minim and maximum displacements that were taking in consideration were kept in the same measure units in the calculations tables as they were given in Table 3, respectively in centimeters.

The first loading step at which significant displacements occurred had a value of 30 atm. and the second loading step had a value of 20 atm.

At a load value of 50 atm, respectively 50.66 daN/cm², the minimum displacement is 2 cm, and the maximum displacement is 8 cm, which resulted in the product $P_i\delta_i$ used for applying equation (3) in Tables 4, 5 and 6 of 101.325 for the minimum displacement, respectively 405.28 for the maximum displacement.

At a load value of 80 atm, respectively 82.656 daN/cm², the minimum displacement is 3 cm, and the maximum displacement is 12 cm, which resulted in the product $P_i\delta_i$ as a value of 247.968 for the minimum displacement, respectively 991.872 for the maximum displacement.

At a load value of 100 atm, respectively 101.325 daN/cm², the minimum displacement is 5 cm, and the maximum displacement is 15 cm, which resulted in the product $P_i\delta_i$ with a value of 506.625 for the minimum displacement, respectively 1519.875 for the maximum displacement.

It is to be considered that the loading factor is unitary when all three conditions, the plasticity condition, static equilibrium condition and mechanism condition, presented in Figure 1, are met.

Rock masses are characterized by a large number of geometric, physical, petrological and mechanical parameters, which manifest themselves in sufficiently large limits. However, for solving most practical problems for calculating the construction elements of underground works, knowledge of a few basic mechanical parameters is sufficient. For solving practical problems, it is not always advisable to take into account the anisotropy of the mining rock massif because these are related to the composition of the complicated, excessively voluminous computing apparatus, with a large number of physical constants, especially since there are means of indirectly highlighting anisotropy in practical calculations. [16] The lower the rigidity of the support and the more cohesive the surrounding rocks, the more evenly the external load and internal efforts, especially bending moments, are distributed along the contour of the support. [17]

The geomechanical parameters of the rock types were extracted from established regional literature [15] and the SG23 metallic support was tested in the University of Petroșani laboratory [8]. The subsequent formulation of the equilibrium state and the mathematical processing to isolate the limit state constitute the author's analytical contribution.

Table 2. The values of the cohesion and the internal friction angle for different types of rocks found in the Jiu Valley basin [15]

Rock type	Cohesion [MPa]			Internal friction angle [°]		
	minimum	medium	maximum	minimum	medium	maximum
calcareous sandstone	3.8	7.54	11.0	35	51	67
marly sandstone	4.8	7.2	10.0	47	58	66
siliceous sandstone	4.4	8.0	11	36	57	72
siliceous sandstone	4.4	8.67	12.6	44	48	61
micro conglomeritic sandstone	4.8	6.3	9.2	46	58	62
clay	0.9	1.8	2.7	16	61	72
siderite clay	5.6	6.2	6.9	48	62	75
compacted clay	2.1	4.14	6.2	35	5.1	64
sandy clay	1.25	6.29	10.2	25	54	66
marly clay	4.8	6.2	7.2	48	5.7	68
fine-grained clay	4.1	5.07	5.7	35	4.9	67
compact limestone	2.3	5.63	8.4	22	46	63
compact marl	2.8	4.16	6.0	51	62	71
sandy marl	3.5	5.35	7.2	37	53	68
microconglomerates	4.8	6.0	8.1	46	52	62
fossilized clay		2.6			58	

Table 3. The values of displacements for SG23 metallic support that appeared at different loading steps [8]

Loading [atm.]	Displacements [cm]				
	left wall	right wall	floor	Ceiling left	Ceiling right
50	8	2	0	4	0
80	10	3	10	7	12
100	12	5	12	9	15

Table 4. The values for loading factor calculated for the values of cohesion and the friction angle given in Table 2 on columns 2 and 5 (minimum)

Rock type	$\frac{P_i \delta_i}{c_j \varphi_j}$	101.325	247.968	405.28	506.625	991.872	1519.875
calcareous sandstone	1330	0.076	0.185	0.304	0.3809	0.745	1.142
marly sandstone	2256	0.044	0.109	0.179	0.224	0.439	0.673
siliceous sandstone	1584	0.063	0.156	0.255	0.319	0.626	0.959
siliceous sandstone	1936	0.052	0.128	0.209	0.261	0.512	0.785
micro conglomeritic sandstone	2208	0.045	0.112	0.183	0.229	0.449	0.688
clay	144	0.703	1.722	2.814	3.518	6.888	10.556
siderite clay	1012	0.1001	0.245	0.4004	0.5006	0.9801	1.501
compacted clay	735	0.137	0.337	0.551	0.689	1.349	2.067
sandy clay	312.5	0.324	0.793	1.296	1.621	3.173	4.863
marly clay	2304	0.043	0.107	0.175	0.219	0.4305	0.659
fine-grained clay	1435	0.0706	0.172	0.282	0.159	0.691	1.059
compact limestone	506	0.2002	0.49	0.8009	0.160	1.9602	3.003
compact marl	1428	0.0709	0.173	0.283	0.161	0.694	1.064
sandy marl	1295	0.078	0.191	0.312	0.391	0.765	1.173
microconglomerates	2208	0.045	0.112	0.183	0.162	0.449	0.688

Table 5. The values for loading factor calculated for the values of cohesion and the friction angle given in Table 2 on columns 4 and 7 (maximum)

Rock type	$\frac{P_i \delta_i}{c_j \varphi_j}$	101.325	247.968	405.28	506.625	991.872	1519.875
calcareous sandstone	7370	0.013	0.033	0.054	0.068	0.134	0.206
marly sandstone	6600	0.0153	0.037	0.061	0.076	0.1502	0.2302
siliceous sandstone	7920	0.012	0.031	0.051	0.063	0.125	0.191
siliceous sandstone	7686	0.013	0.032	0.052	0.065	0.129	0.197
micro conglomeritic sandstone	5704	0.017	0.043	0.071	0.088	0.173	0.266

Rock type	$\frac{P_i \delta_i}{c_j \phi_j}$	101.325	247.968	405.28	506.625	991.872	1519.875
clay	1944	0.052	0.127	0.208	0.2606	0.5102	0.781
siderite clay	8073	0.012	0.0307	0.0502	0.062	0.122	0.188
compacted clay	3968	0.025	0.062	0.102	0.127	0.249	0.383
sandy clay	6732	0.015	0.036	0.0602	0.075	0.147	0.225
marly clay	4896	0.0206	0.0506	0.082	0.103	0.202	0.3104
fine-grained clay	3819	0.026	0.064	0.106	0.132	0.259	0.3979
compact limestone	5292	0.019	0.046	0.076	0.0957	0.187	0.287
compact marl	4260	0.023	0.058	0.095	0.118	0.232	0.356
sandy marl	4896	0.0206	0.0506	0.082	0.103	0.202	0.3104
microconglomerates	5022	0.0201	0.049	0.0807	0.1008	0.197	0.302

Table 6. The values for loading factor calculated for the values of cohesion and the friction angle given in Table 2 on columns 3 and 6 (medium)

Rock type	$\frac{P_i \delta_i}{c_j \phi_j}$	101.325	247.968	405.28	506.625	991.872	1519.875
calcareous sandstone	3845.4	0.0263	0.064	0.105	0.131	0.257	0.395
marly sandstone	4176	0.024	0.059	0.097	0.121	0.237	0.363
siliceous sandstone	4560	0.022	0.054	0.088	0.111	0.217	0.333
siliceous sandstone	4161.6	0.024	0.059	0.097	0.121	0.238	0.365
micro conglomeritic sandstone	3654	0.0277	0.067	0.1109	0.138	0.271	0.415
clay	1098	0.092	0.2258	0.369	0.461	0.903	1.38
siderite clay	3844	0.026	0.064	0.105	0.131	0.258	0.395
compacted clay	211.14	0.479	1.174	1.919	2.399	4.697	7.19
sandy clay	3396.6	0.029	0.073	0.119	0.149	0.292	0.447
marly clay	353.4	0.286	0.701	1.14	1.433	2.806	4.3
fine-grained clay	248.43	0.407	0.998	1.631	2.039	3.992	6.117
compact limestone	2589.8	0.039	0.095	0.156	0.195	0.382	0.586
compact marl	2579.2	0.039	0.096	0.157	0.196	0.384	0.589
sandy marl	2835.5	0.035	0.087	0.142	0.178	0.349	0.536
microconglomerates	3120	0.032	0.079	0.129	0.162	0.317	0.487
fossilized clay	1508	0.067	0.164	0.268	0.335	0.657	1.007

6. Conclusions

In the case study the lowest value of the loading factor resulted as 0.012 for the rock types "siliceous sandstone" and "siderite clay" in the case of a load of 50 atm. and a displacement of 2 cm, respectively the lowest value of the load and displacement.

The highest value of the load factor resulted as 10.556 for the "clay" rock type with a cohesion value of 0.09 MPa and an internal friction angle of 16 degrees in the case of the maximum load value and maximum displacement produced by it.

The load factor resulted equal to 1.007 for the type of rock "fossilized clay" when the maximum load was applied and the maximum displacement produced by it was taken into account. It should be noted that for this case the load factor being unitary, theoretically all three conditions were met with a plus of 0.007, namely the plasticity condition, the static equilibrium condition and the mechanism condition (Table1, Figure 1) are fulfilled, but the support lost all its energy reserve being no longer able to take on any other load. In this case, for optimization, it would be recommended to use such a metallic support in rocks with values of cohesion and internal friction angle resulting from the application of equation (3) in a sub-unit factor, respectively the support retains a reserve of energy necessary for the case of a possible dynamic load, either from vibrations induced by human activities during exploitation, rockburst, rockfall, etc. Also doubling the metallic support profiles can be taken in consideration for cases where the load factor results higher than 1.

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