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New formula for evaluation of strength pillar in the underground mine of Chaabet El-Hamra (Setif, Algeria)

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Abstract: This study aims to evaluate the characteristic strength of pillars in mining contexts, taking into account the effects of size and shape. The characteristic strength is estimated in terms of the probability of exceeding a specific value of pressure; when once exceeding, the failure appears. Also, the higher number of defects leads to a high probability of failure.

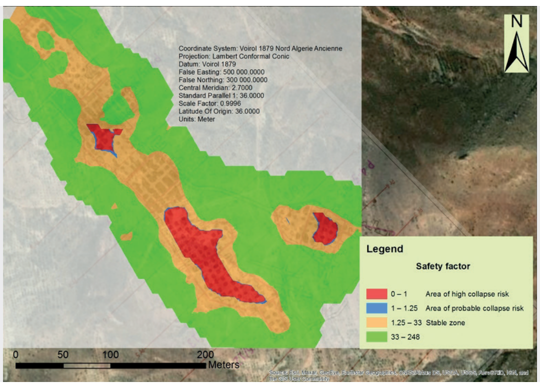
In this study, a new analytical formula is applied, which considers the effect of scale (size and shape) with the notion of probability in evaluating the risk of failure to assess the condition of the mine pillars without resorting to pillar level experiments, which would reduce costs and efforts.

It is used a data set from an underground mine (rock samples of zinc) in Setif-Algeria. The results shows the strength's decrease with an increase in volume. Furthermore, the pillars with a higher width to height ratio (w/h) have more strength than a slender one.

One of the advantages of the probabilistic strength measurement is its functional relation with the deformation at the pillars' level and the progress of the mining sites' works. It is necessary to choose an optimal critical size for the pillars to ensure good operation and safety.

Key words: Weibull criteria, back analysis method, scale effect, pillar stability, probability of survival

Graphical abstract



Highlights

- A new analytical formula was developed and applied to estimate large-scale strength from intact rock, which leads to more realistic values than the usual techniques used in geomechanics and field control.
- New formula takes into account the scale effect in the strength for a pillar as well as the estimate of its failure probability.

1 Introduction

The evaluation of the mechanical properties of a massif is influenced by the effect of scale for mining structures (Zengchao et al., 2009; Zhang et al., 2011), as well as the analysis of the risks associated with the exploitation of resources, particularly in mines, quarries, shafts, tunnels, etc.

In this study, we focused mainly on the pillars of underground mines where compressive strength is an essential parameter in stability studies, taking into account that the pillars are established in fractured rocks, where the stability must be inspected by testing (York & Canbulat, 1998; Medhurst & Brown, 1995).

The influence of the scale effect observed experimentally in solid mechanics can be attributed to the presence of defects in the material with increasing volume; and many scholars (Martin & Maybee, 2000; Cuisiat & Haimson, 1992; Heuze, 1980; Salamon & Munro, 1967) confirm that when the probability of defect increases, the mechanical properties (strength and hardness) decrease proportionally with size.

These probability random effects that govern the scale effect were for the first time studied by Weibull (1939).

This research scientist used the concept of probability of survival to assess the risk of failure. Weibull introduced the probabilistic criterion of failure that enables one to deduce a pillar's strength only as a function of its size, without considering the shape effect.

Experimental observations led Weibull to choose a power law to represent λ the parameter of Poisson distribution characterizing the population of defects in the material by:

$$\lambda = \frac{1}{V_0} \cdot \left(\frac{\sigma}{\sigma_0}\right)^m \tag{1}$$

Where:

σ – applied stress,
V_0 – the reference volume,
σ_0 – the solicitation stress associated with a survival probability of 37 %,
m – the Weibull module.

The Weibull module m is a material parameter that characterizes the dispersion of the defects within the material: a small value of this parameter indicates a higher value of dispersion of the material's defects.

By recovering the Poisson distribution writing that $P_F = 1 - P_S$ (P_F: probability of failure and P_S: probability of survival) with a volume V, we can estimate the probability of failure P_F.

$$P_F = 1 - \exp\left(-\frac{V}{V_0} \cdot \left(\frac{\sigma}{\sigma_0}\right)^m\right) \tag{2}$$

Many researchers have studied the assessment of the strength of pillars in-situ from laboratory tests (Hudson et al., 1972; Salamon & Munro, 1967; Zengchao et al., 2009; Zhang et al., 2011). When estimating a given material's mechanical properties (coal for example), each prediction's accuracy will depend on how accurate the sample characteristics reflect the massif to characterize. Thus, Hudson et al. (1972) reported that the difference in the length/diameter ratio of a sample has a significant effect on the compressive strength of rocks and the shape of the stress-strain curve post-peak segment. This is also evident, where he developed an analytical equation that considers the effect of the geometry of a pillar (by the w/h ratio) and the volume (Galvin et al., 1996).

The tests carried out on different rocks demonstrate that the strength is inversely proportional to the size of the samples analysed (York & Canbulat, 1998). This implies that a sample with a much more size will have a reduced strength. However, the laboratory results show the strength's stabilization as the size increases for coal, iron ore and altered quartzitic diorite. There is at least a specific limit size beyond which no further decrease in the strength is apparent (the absence of the scale effect from a critical volume for each type of rock). However, it should be noted that the largest volumes studied have a length of about 1 to 2 m and remain lower than those of a real pillar.

If the in situ pillar does not include a geological lamination joint, macro fracture, the rock can be described as an intact rock (York & Canbula, 1998). In this case, the rock mass's critical strength (for a size beyond which no additional decrease in the strength appears) can be taken as the strength of the in situ rock mass (the result found in the laboratory is considered the same as in the large scale). On the other hand, the latter cannot be used as the rock mass's critical strength if the pillar has natural or anthropogenic discontinuities (induced by blasting operation for example). In this case, the rock mass's critical strength can be evaluated through different methods that incorporate several factors. Either the rock mass can be approximated as a continuum (homogenizing approach a continuous model represents the rock mass behavior), the rock mass cannot be estimated as a continuum (presence of discontinuities).

Another school of thought suggests using a parameter as a representative of the strength value of a cube of one meter (retrospective method or back analysis method).

Salamon & Munro (1967): $\sigma_P = k h^a w^b$ (3)

With:

h – the height of the pillar (m),
σ_P – the pillar strength (MPa),
w – the width of the pillar (m),
k (MPa) – the coefficient characterizing the value of the strength representative of a cube of one-meter side, a and b two numerical constants to be defined for each geomechanical context.

Bieniawski (1968): $\sigma_P = C + M\,(w/h)$ (4)

With:

h – the height of the pillar (m),
M – a constant linked to the nature of the studied rock,
w – the width of the pillar (m),
C (MPa) – the rock mass's critical strength (for a size beyond which no further decrease in the strength can appear).

Bieniawski's (Eq 4) linear formula cannot consider the volume and saves the geometric effect of the increase in the w/h ratio. On the contrary, Salamon & Munro's (Eq 3) formula distinguishes the shape effect of the scale effect. Subject expressing the pillar volume as a function of w and h ($V = w^2h$ for a square section pillar), equation 3 can be rewritten in the form of equation 5 (Galvin et al., 1996).

$$\sigma_P = kV^{\alpha}\,(w/h)^{\beta} \tag{5}$$

With

- h – the pillar height,
- σ_P – (MPa) The pillar's strength,
- w – the width of the pillar,
- V – it's the pillar volume,
- k (MPa) – a coefficient characterizing the value of the strength representative of a cube of one-meter side. α and β represent two constants being defined for each mechanical geo context.

Our work aims to estimate the strength of pillars via grouped two approaches, the first which allows considering the shape properties and the size of the rock mass, and the second that makes it possible to integrate the concept of probability of failure in the assessment of the risk of failure.

The basic methodology of this hybrid approach was identified and validated by estimating the pillars' compressive strength in the case of coal (Cheikhaoui et al., 2020, 2021). We used the Australian coal case study data of Galvin's study to compare results, which gave us very similar results found in previous works.

2 The study area

As far as the location of the Chaabet El-Hamra deposit is concerned, it is situated as the crow flies about 250 kilometers South-East of Algiers and 50 km south of Setif, namely in the area of Chouf-Bouarket, 4.5 km from Ain-Azeland and 12 km SE of the Kherzet Youssef mining complex as shown in Fig 1.

According to the WGS 1984 coordinates scheme, it is located between 35° 45' N and 35° 48' N latitude and 5° 31' E and 5° 32' E Longitude.

2.1 Geological setting of the region

The Chaabet El-Hamra is located within the geological context of the Hodna district in the joint of three geological zones known as Tellian Atlas, the Sahara Atlas and the high plains, as demonstrated in Fig. 2.

During the Mesozoic time, the high plains overlaid a carbonate platform that remained shallow. From the Upper Triassic to Albian, the carbonate platform was fragile and subsiding (Lower Cretaceous). It is made up of over 2300 meters of sediments, terrigenous and carbonates (dolomitic series included). Many dolomitic sequences are mainly on the platform's northern and southern margins, distinguished by their significant mineralization. A tectonics of the horst and graben-type has resulted in asymmetrical folding, with diapir forming in the cores on occasion.

It is characterized mainly by Cretaceous deposits, of which the Hauterivian is of the most significant interest, as it contains the mineralization (Fig. 3):

a) Valanginian (n_2): The Valanginian (sterile) deposits outcrop east of the eastern fault and west of the deposit and are represented by alternating grey aleurolite with light grey quartz sandstones, sandstone and clay dolomites, limestones and grey-green marls.

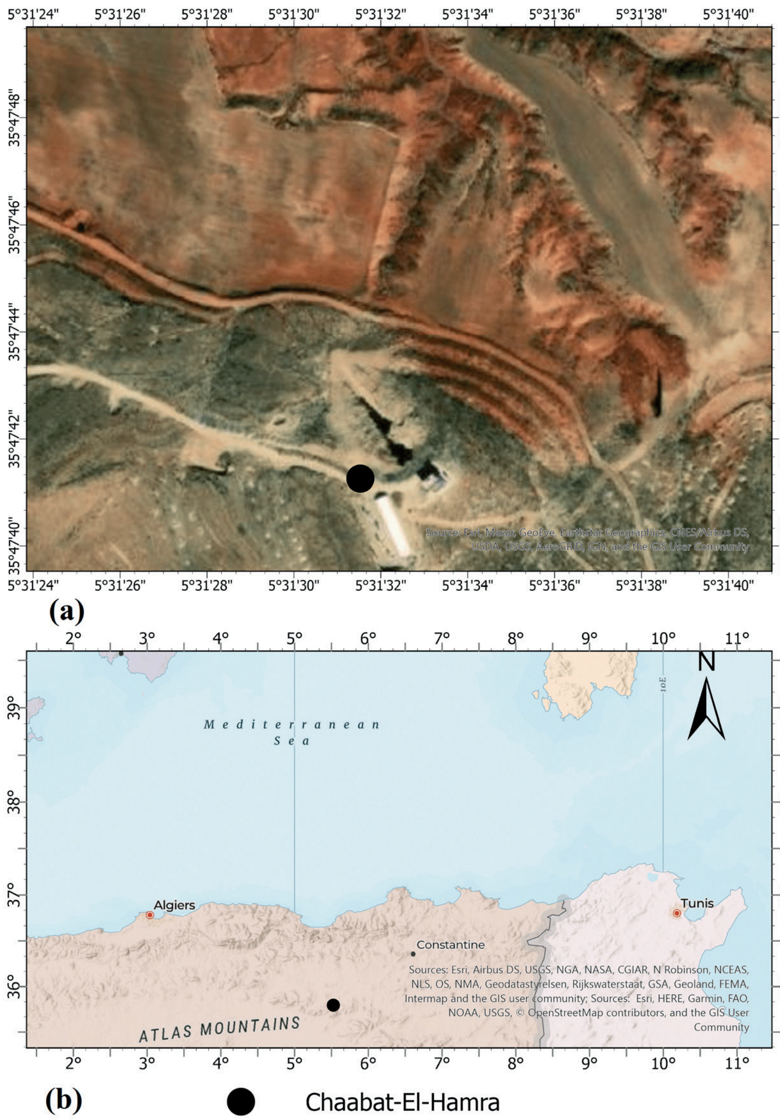


Fig. 1. The position of study area in the map of northern Algeria (b) and its satellite photo (a).

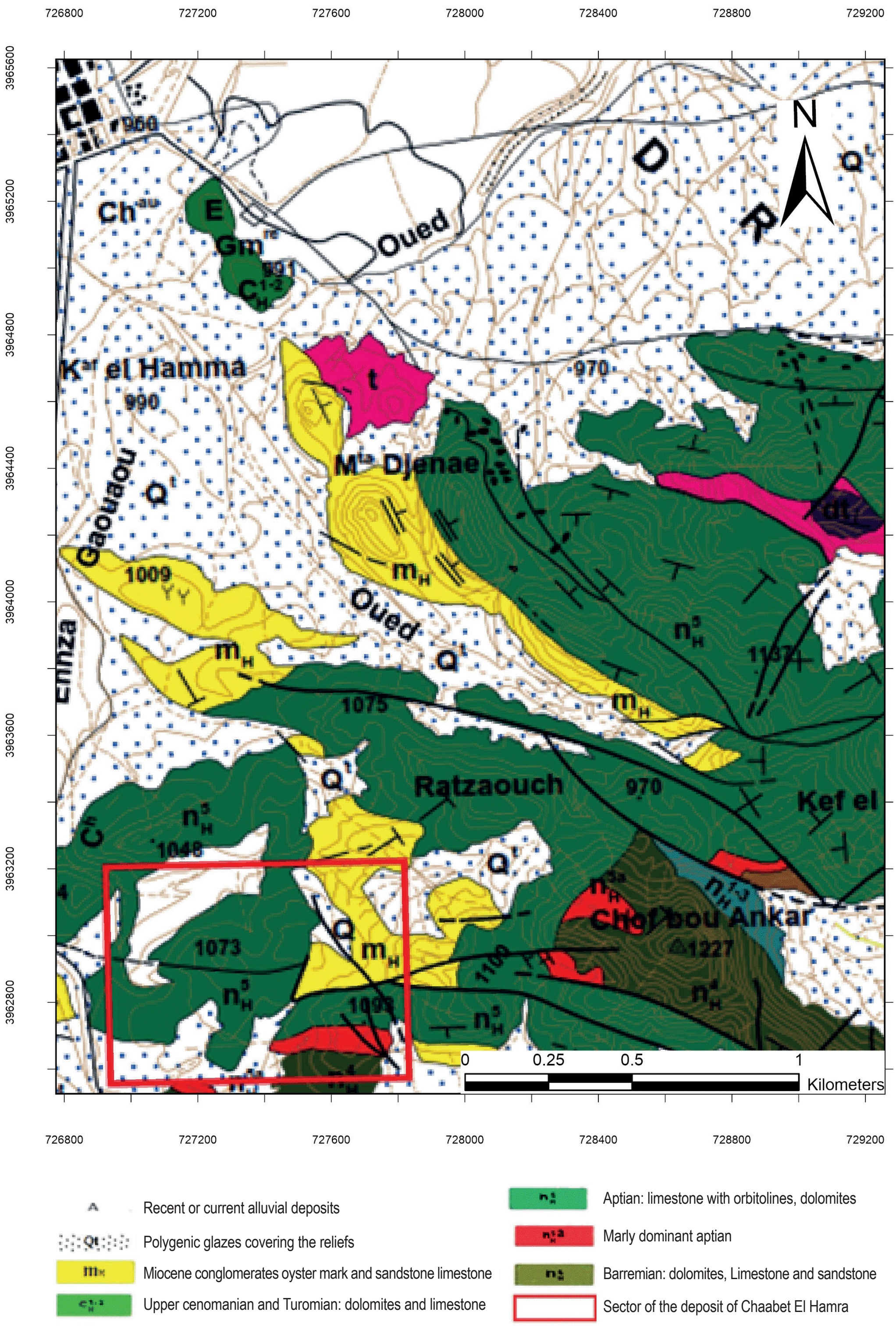


Fig. 2. Geological map of the studied area (taken from Vila, 1977).

b) Hauterivian (n_3): The zinc mineralization of industrial interest is located in the lower part of the Hauterivian, which varies from 100 to 150 m.

c) Barremian (n_4): It is developed to the northwest and south of the deposit.

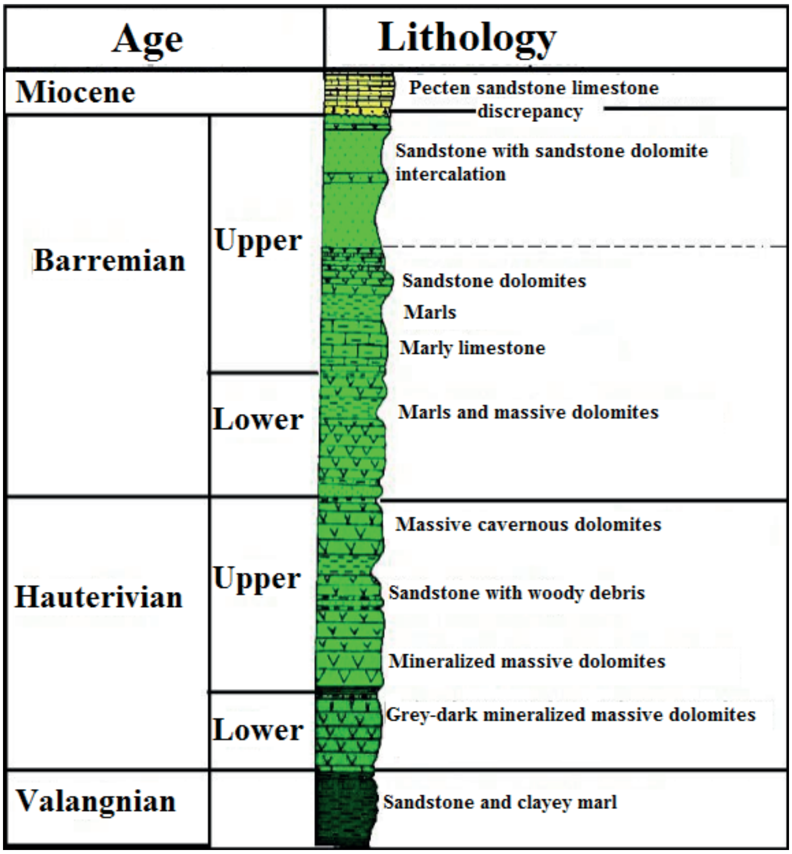


Fig. 3. Lithostratigraphic column of Chaabet El-Hamra ore deposit (Boutaleb, 2001).

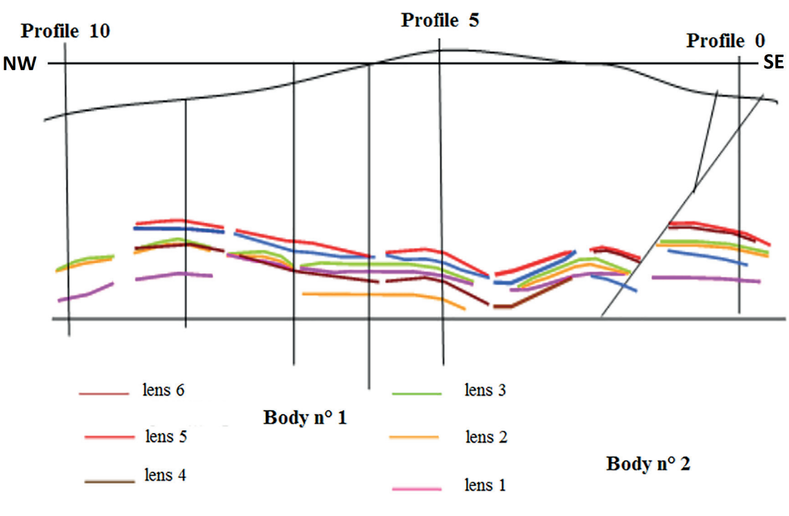


Fig. 4. Longitudinal section of the lenticular mineralization of Chaabet El-Hamra.

2.2 *Ore exploitation in mine*

The mineralization is flat dipping and sits in an anticline, extending over 500 meters along strike, 150 meters across strike, and ranging from 100 to 160 meters underneath the surface. As far as the thickness of mineralization is concerned, it ranges from 1 to 20 meters. Ore was trucked from the Chaabet El-Hamra mine to Kherzet Youcef to be processed into zinc concentrate.

In order to access the mineralized zone, there is an inclined shaft (decline) situated in the lowest point of the area, at Hill 1020, over a length of 830 meters in the waste rock. It is utilized for personnel circulation, equipment and ore transport. Also, it is considered as a fresh air intake to underground mining spaces.

2.3 *Deposit description and its vicinity*

The zinciferous ore of Chaabet El-Hamra deposit is composed of two main bodies called body No. 1 for the upper body and body No. 2 for the lower body as shown in Fig. 4 and as it is mentioned in the report of the Entreprise Nationale Des Produits Miniers Non Ferreux, ENOF (2013). These bodies are elongated in a band over 2700 m in direction and 100 to 400 m in dip. The ore bodies dip at an angle of 10° to the northwest.

The ore is hosted in porous or brecciated dolomite located in the lower part of the Hauterivian stage (Lower Cretaceous). The roof of the upper body (body No. 1) is dolomite with marly beds, while the wall of the lower body (body No. 2) is massive dolomite with concretions (spotted dolomite). The two ore bodies are stratiform, subparallel, and separated by an intercalary level consisting of poorly mineralized and sometimes sterile dolomite of variable strength. This level may be absent so that the two bodies merge into one continuous ore body. The average thickness of body No. 1 (upper body) is 5 meters, and that of body No. 2 (lower body) is 4 meters.

The Canadian mining group SIDAM Inc. (1992) has evaluated the geological reserves by the influence polygon method with an average cut-off grade of 3 %, a minimum exploitable thickness of 2 m, and a density 2.87.

3 Methodology

The main proposition supposes that the strength R_p of a pillar is explained by the strength K (of the intact rock), by corrective functions of shape F(f) volume G(v) and function of the probability effect H(ps) (Eq. 6).

Suggestion:

$$R_p = K \,.\, \mathrm{H(ps)} \,.\, \mathrm{F(f)} \,.\, \mathrm{G(v)}$$

Where:

F (shape): It depends on the geometry of the pillar.
G (volume): It depends on the pillar volume.
H (probability of survival): It is the probability of survival associated with an applied constraint, such as the probability of survival (P_S) = 1 – (P_F) probability of failure.
K is the strength of the specimen (MPa).

Tab. 1
Uni-axial compression strength (MPa) of zinc rock samples from Setif-Algeria.

Sample number	Uni-axial compression strength (MPa)	Sample number	Uni-axial compression strength (MPa)
1	47.4	8	43
2	82.6	9	90.5
3	159.9	10	102.3
4	92.5	11	61.1
5	40.4	12	112
6	108	13	155.5
7	80.9	14	93.2

Tab. 2
Weibull parameters of zinc rock sample.

Weibull parameters	Value	Geometric parameters	Value
m	2.36	W_{Ep}/H_{EP} (l/d ratio)	0.5
σ_0 (MPa)	103.61	V_0 (m^3)	2.159×10^{-4}

The equalization of Eq. 7 developed in our previous works (Cheikhaoui et al., 2020) and (Cheikhaoui et al., 2020, 2021), taking into account scale and shape effects, is given as follows:

$$Rp(PS) = \sigma_0 \,.\, ln(1/P_s)^{1/m} \,.\, (w/h)^{\frac{ln\left(V_0 \frac{1}{m}\right)}{ln(Wep/Hep)}} \,.\; V^{-1/m}\ \text{(MPa)} \quad (7)$$

Furthermore, if there is a set of N values of compressive strength measured experimentally on test specimens of the same material, volume V_0, and slenderness W_{ep}/H_{ep}, it is then possible to obtain the parameters of the Weibull's law m and σ_0.

That is to say, in general form:

$$R_{p,Ps}(MPa) = \sigma_0 \,.\, H(Ps) \,.\, G(volume) \,.\, F(shape) \quad (8)$$

We consider a set of 14 uni-axial compression tests to samples of zinc rock (see Table 1) with $V_0 = 2.159 \times 10^{-4}$ (m^3) and the length to diameter ratio l/d = 0.5 allowing the different parameters of Weibull's law to be calculated. The results are summarized in Table 2. The tests of compression are executed by the national company of non-ferrous mining products.

3.1. Pillar strength in chaabet El-Hamra mine

The strength formula of a *zinc* pillar found using Weibull parameters is written as follows:

$$R_{p(PS)} = 103.61\ ln(1/P_s)^{0.42}(w/h)^{5.15}V^{-0.42}\ \text{(MPa)} \quad (9)$$

The strength formula of a zinc pillar according to the probability of survival Ps = 93 % meaning 7 % of the risk, is written as follows:

$$R_{p(0.93)} = 23.60(^{w}/_{h})^{5.15}\ V^{-0.42}\ \text{(MPa)} \quad (10)$$

The curve in (Fig. 5) shows a decrease in strength with an increase in volume. This phenomenon represents the scale or size effect.

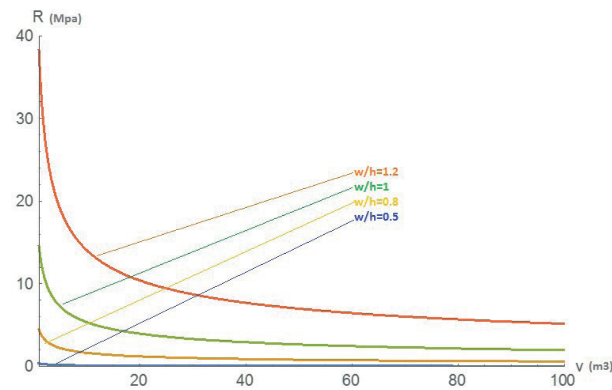


Fig. 5. Size effect on the strength of zinc pillars for different shapes (w/h = 0.5, 0.8, 1, and 1.2) according to the risk of 7 %. The formula developed using Weibull parameters m and σ0.

The strength variation follows a power law such that there is a decrease with increasing volume, which is consistent with previous research. We notice the shape effect in Fig. 5 such that the strength values increase with the increase of the shape ratio w/h.

The scale effect on pillar's strength is due to the various (micro) fractures (weaknesses) such as cracks in it.

The probability of survival is a statistical value depending on the number and types of fractures present in the rocks. In smaller volumes, the likelihood of finding of defects is more negligible, so the strength is higher.

It is noticed that the strength begins to stabilize after a specific volume that is called critical volume, or there is no variation of strength with the increase of the volume. This critical volume depends on the form w/h ratio for the same type of rock.

It is suggested that the reduction in strength is due to the greater opportunity for inevitable failure, the building blocks of the intact rock, as more and more of the weaknesses are included in the test sample. Eventually, when a sufficiently large number of weaknesses are included in the sample, the strength reaches a constant value.

Figure 6 shows the shape effect where the strength increases with the increase in the w/h ratio of the pillar.

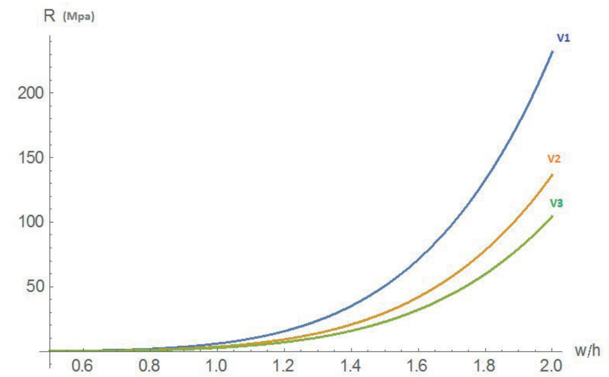


Fig. 6. Shape effect on the strength of a zinc pillars of different sizes (V1 = 18 m^3, V2 = 27 m^3 and V3 = 50 m^3) according to the risk of 7 %. The formula developed using Weibull parameters m and σ0.

In our case, m = 2.36, we notice an exponential evolution of strength with the increase of the w/h ratio. The size effect is always present such that the small volume has the highest strength values and a critical value of w/h ratio such that the strength tends rapidly to a large value.

A rock mass's strength is usually described as a constant cohesive component and normal stress or confinement-dependent component. Hence for pillars with w = h or ratios greater than 1, the strength should increase as the confining stress increases.

3.2 Probability of survival for pillars

Formula 7 allows us to introduce the probabilistic distribution of defects and the probability of activation of these defects, that is to say, the probability of failure. If there is a series of defects, when one of these defects (the discontinuities) is activated, the failure occurs. The relation proposed as an analytical approach for estimating the strength of a pillar such that $R_p = \sigma_f$ The stress to be applied for at least one of the defects is activated (the failure), so:

$$P_s = EXP\,[({}^{w}/_{h})^{a}\,.\,v^{-m})/(-m\sigma_p)] \text{ with } a = \frac{\ln(v_0{}^{-m})}{\ln({}^{w_{ep}}/_{h_{ep}})} \tag{11}$$

Such as:

v_0	–	specimen volume (m^3).
v	–	pillar volume (m^3).
$^{w_{ep}}/_{h_{ep}}$	–	ratio of the shape of the specimen.
$^{w}/_{h}$	–	pillar shape ratio.
m	–	the parameters of the Weibull's.
σ_p	–	the stress applied (MPa).

$$P_s = EXP\,[({}^{w}/_{h})^{5.15}\,.\,v^{-0.42})/(-0.42\sigma_p)] \tag{12}$$

Tab. 3

Summary of the calculations of the ratio and the average slenderness for all the blocks.

Block	Number of pillars of the block	Average width of the pillars [m]	Average height of the pillars [m]	w/h (average)	Average extraction ratio τ [%]
4/1	32	2.4	5	0.5	82.8
4-5/2	10	3.7	2	1.84	81
5-6/4	22	3.9	2.7	1.5	72.3
5-6/3	20	2.5	2.4	1	82.4
6/3	12	2.4	2.5	1	84.3
4-5-6/13	23	2.3	6.5	0.4	83
5-6/12	9	3	2.5	1.2	77.8
4-5-6/5	17	3.4	4.5	0.8	76.4
5/1	29	3.1	2	1.6	77.1

As the exploitation in the mine do by chambers and pillars, the stress σ_p (MPa) applied to the center of the pillar is related to the extraction ratio τ and σ_v (MPa) the vertical stress linked to the higher ground load. The formula can be written as follows (in Brady & Brown, 1985):

$$\sigma_p = \sigma_v \frac{1}{1-\tau} \tag{13}$$

Such as

$$\sigma_v = \gamma_{av}.h_{av} \tag{14}$$

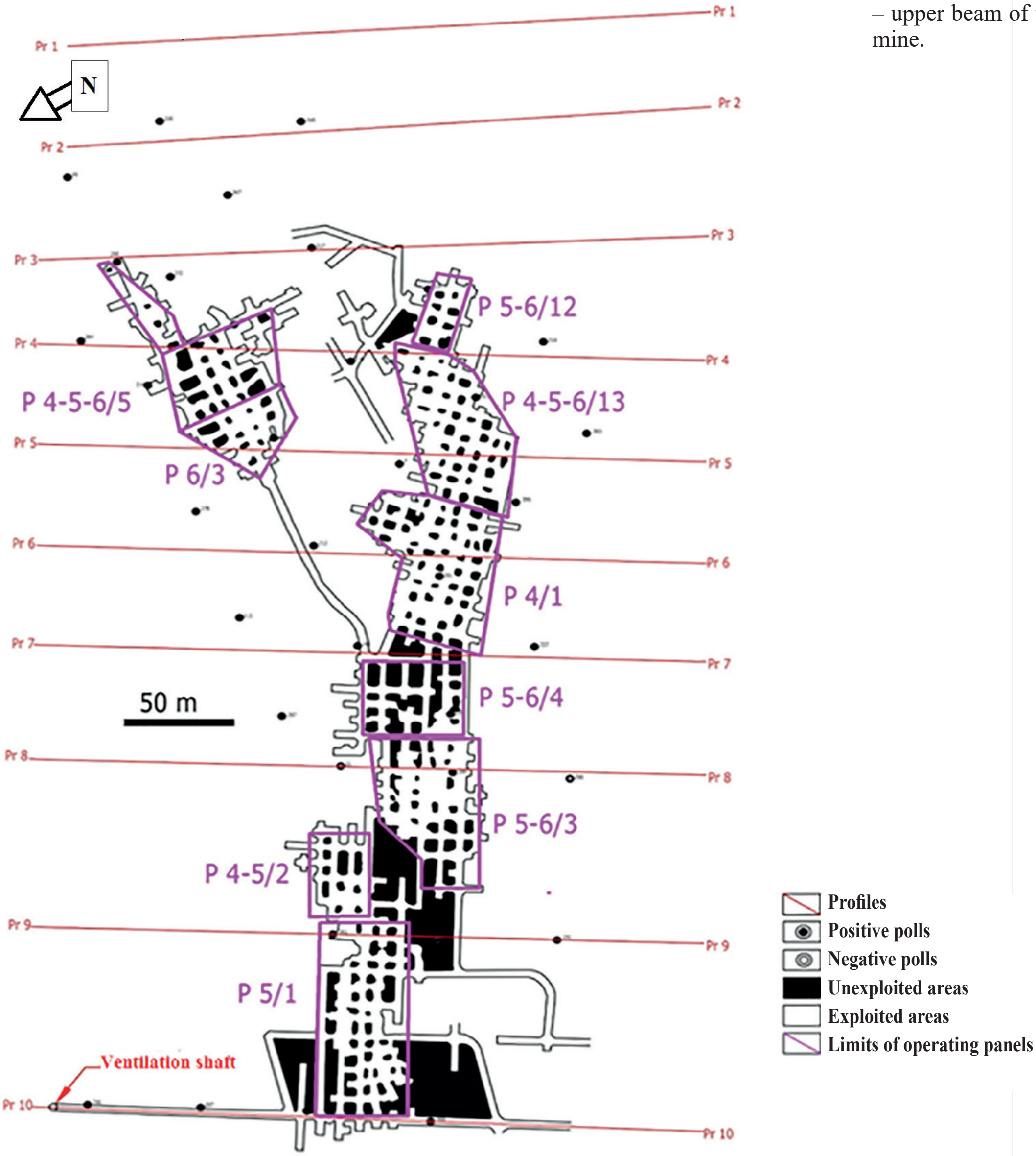


Fig. 7. Operating plan for the upper part – upper beam of the Chaabet El-Hamra mine.

γ_{av} – The average specific gravity (N/m^3),

h_{av} – The thickness average of the cover land (m).

In our case:

$\sigma_v = \gamma_{av}.h_{av} = 106.5 \text{ x } 27.4 \text{ x } 10^3 = 2918.1 \text{ kN/m}^2 = 2.9 \text{ MPa}$.

Table 3 summarizes the geometric parameters and the calculation of the ratios for all the blocks (see Fig. 7).

It appears from this table that the extraction ratio varies from 0.72 (lowest rate for the 5-6/4 panel) to 0.85 (largest for the 6/3 panel). The lowest rate corresponds to the largest average pillar width, and conversely, the largest corresponds to the smallest pillar width.

4 Results and discussion

4.1 Probability of survival in chaabet El-Hamra mine

The blocks (5-6/4), (4-5/2) and (5/1) in the mine are the most insusceptible to failure with an estimated probability of failure less than 16 % (see the Tab. 4); this is because w/h ratio of this pillar is greater than 1.5 (the shape effect). For the other blocks, the risk of failure is more than 49 % (essentially, when the w/h ratio of the pillar is less than 1, the risk of failure is significant).

$P_{Soverall} = [Ps_{(4/1)} + Ps_{(4\text{-}5/2)} + Ps_{(5\text{-}6/4)} + Ps_{(5\text{-}6/3)} + Ps_{(6/3)} + Ps_{(4\text{-}5\text{-}6/13)} + Ps_{(5\text{-}6/12)} + Ps_{(4\text{-}5\text{-}6/5)} + Ps_{(5/1)}]/9$ so : $Ps_{overall} = 37.52$ %.

$P_{Foverall} = [Pf_{(4/1)} + Pf_{(4\text{-}5/2)} + Pf_{(5\text{-}6/4)} + Pf_{(5\text{-}6/3)} + Pf_{(6/3)} + Pf_{(4\text{-}5\text{-}6/13)} + Pf_{(5\text{-}6/12)} + Pf_{(4\text{-}5\text{-}6/5)} + Pf_{(5/1)}]/9$ so : $Pf_{overall} = 62.48$ %.

And this is confirmed by the following relation $P_F + P_S = 1$.

Tab. 4

Stress σ_p applied, σ_v the vertical stress, probability of survival (Ps), and probability of failure (Pf) of each panel of the mine.

Block of pillars	w/h (average)	Depth [m]	σ_v in [MPa]	σ_p in [MPa]	Probability of survival Ps	Probability of failure Pf = 1 – Ps
(4/1)	0.5	106.5	2.91	23.5	1.39913E-34	1
(4-5/2)	1.84	106.5	2.91	20.3	0.922	0.0771
(5-6/4)	1.5	106.5	2.91	13.1	0.8385	0.1614
(5-6/3)	1	106.5	2.91	30.7	0.1129	0.8870
(6/3)	1	106.5	2.91	32.9	0.2509	0.8994
(4-5-6/13)	0.4	106.5	2.91	27.3	2 E-134	1
(5-6/12)	1.2	112.3	3.07	20.4	0.5107	0.4892
(4-5-6/5)	0.8	106.5	2.91	19.8	0.00056	0.9994
(5/1)	1.6	100	2.74	16.5	0.8908	0.1091

We can estimate the probability of survival (overall mine stability) by:

4.2 Stability of Chaabet El-Hamra mine

In our case study of Chaabet El-Hamra, the mine depth varies between 106.5 and 112 m. In the mining method room and pillar; the pillars are generally square in shape and variable dimensions according to the adopted extraction ratio. This extraction rate varies between 72 % and 84 %. Former mechanical tests were performed to determine the uniaxial compression strength of the zinc rock. The range of variation is between 40.4 and 159.9 MPa. Also, nine blocs (contain 174 pillars) were analysed to distinguish between stable and unstable pillars in the mine.

We performed an estimation of the safety factor based on estimation of strength with a probability of failure P_F = 7 % and the direct data collected from the mine's pillars (in particular width and height).

The pillar stress was calculated using an analytical method (tributary area) to estimate the average vertical stress on the pillars. Figure 8 shows the distribution of the safety factor for underground zinc mines using interpolation with a gaussian kernel, the yellow and the green zones correspond to stable zones; the red zone is the most sensitive to collapse and the blue for probable collapse zones. We note the average safety factor for stable mines is equals to 1.2.

The safety factor values indicate that there are blocs in the mine at risk of failure, so there are pillars to intervene in first to be stable. Further detailed analysis is recommended for the pillars with an average safety factor is less than one and still stable.

5 Conclusion

New formula developed by combining two formulas, based on a relationship between the back-analysis aspect of Galvin et al. (1996) and the probabilistic aspect of Weibull (1939), explicitly reproduces the effect of volume and shape. It allows us to interpret the influence of both factors on the strength of

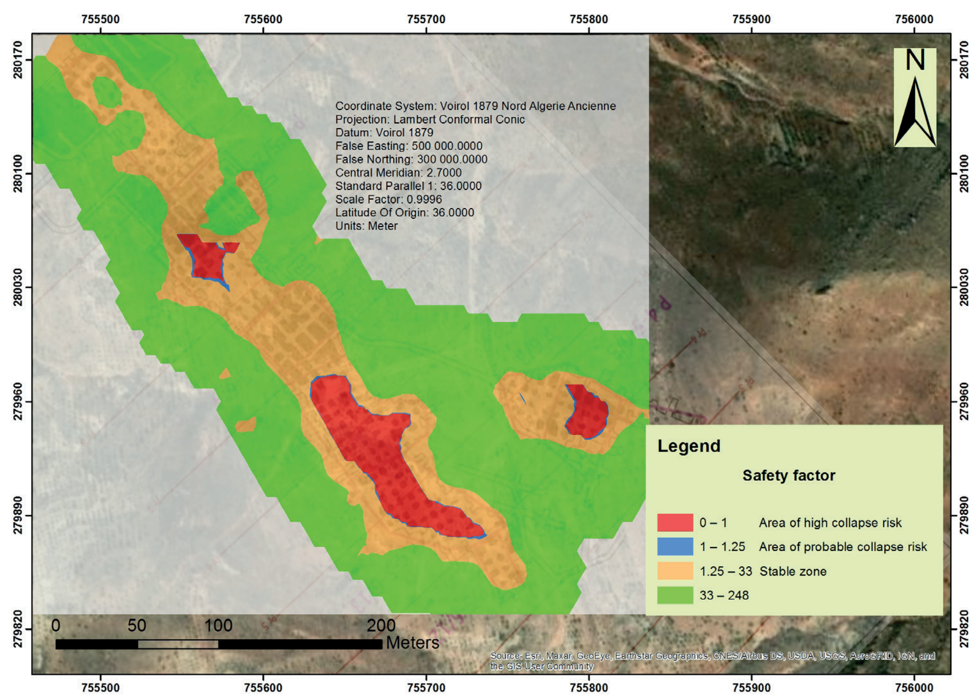


Fig. 8. Safety factor map.

a pillar. We have used the Weibull's parameters derived after an approximation with Galvin's formula. The results described in this research show that the strength decreases when volume increase but increases when width increases (a substantial pillar is more resistant than a slender pillar).

The analysis of the stability of the pillars of the Chaabet El-Hamra mine (those pillars which exist in the Hauterivian lithology containing mineralization) indicates that the pillars in blocks (5-6/4), (4-5/2), and (5/1) in the mine are insusceptible to failure with an estimated probability of failure of 11 % and 16 % but in other blocs the risk of failure is very high. The probability of survival (overall mine stability) is $Ps_{overall} = 37.52$ %.

One of the advantages of the probabilistic strength measurement is its functional relation with the deformation at the pillars' level and the progress of the works of the mining sites. They possibly have the most significant impact on the overall strength of the mine. Therefore, it is necessary to choose an optimal critical size for the pillars to ensure good operation and safety.

In conclusion, the new formula (Strength – Probability of Survival) of the pillar considers the pillar stress ratio and pillar of strength. The stress can be determined using the tributary area and the pillar strength through Weibull's parameters. Sophisticated tools are helpful to understand the rock mass and mines (pillars) behavior. However, the influence of the geostatic distribution of discontinuity is to be considered in our next contributions.

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Nový matematický postup hodnotenia pevnosti pilierov na príklade banskej prevádzky Chaabet El-Hamra (Setif, Alžírsko)

Článok prezentuje zdokonalenú metodiku určovania charakteristickej pevnosti ochranných pilierov so zohľadnením ich veľkosti a tvaru. Táto metodika bola aplikovaná v podzemnom dobývacom priestore na Zn rudy Chaabet El-Hamra (Setiv, Alžírsko).

Lokalita Chaabet El-Hamra (obr. 1 a 2) je situovaná na rozhraní troch geologických jednotiek: Tell Atlas (Malý Atlas), Saharský Atlas a Východná Meseta (Východomarocké náhorné stepi). Karbonátová platforma v období mezozoika postupne poklesávala. Je pokrytá terigénnymi sedimentmi a ďalšími karbonátmi v celkovej hrúbke vyše 2 300 m. Na severnom a južnom okraji platformy sa vyskytujú sekvencie dolomitov kriedového veku, ktoré sú nositeľmi bilančnej Zn mineralizácie (obr. 3). Ťažená časť stratiformného ložiska Chaabet El--Hamra (s rozmermi 500 x 150 m a hrúbkou 1 – 20 m; obr. 7) má sklon 10° na SZ. Hĺbka dobývacích priestorov je v rozmedzí 106,5 – 112 m. Použitá dobývacia metóda je typu komora – pilier. Piliere majú štvorcový prierez rôznych rozmerov v závislosti od lokálnej miery výťažnosti (obr. 7; znázornené čierne objekty v dobývacom priestore). Výťažnosť sa pohybuje v rozmedzí 72 – 84 %. Na začiatku ťažby boli mechanickými skúškami určené hodnoty jednoosovej kompresie ťaženého materiálu s obsahom zinkovej rudy, ktoré sa pohybovali v rozsahu 40,4 – 159,9 MPa. V súčasnosti sa v dobývacom priestore nachádza 174 pilierov. Odhad bezpečnostného faktora založeného na zistení pevnosti ťaženého materiálu, pravdepodobnosti zlyhania a rozmerov pilierov (šírka a výška) preukázal hodnotu 7 %.

Celé ložisko budujú dve hlavné mineralizované polohy (č. 1 – horná poloha s priemernou hrúbkou 5 m, č. 2 – dolná poloha s hrúbkou 4 m; obr. 4). Tieto pretiahnuté polohy dosahujú smernú dĺžku vyše 2 700 m a po sklone majú 100 až 400 m. Zn ruda sa nachádza v poréznych alebo zbrekciovatených dolomitoch spodnohoterivského veku. Rudné polohy sú paralelné a spravidla oddelené slabo mineralizovaným alebo nemineralizovaným dolomitom.

Ložisko je z povrchu sprístupnené úpadnicou dlhou 830 m. Vyťažená ruda z Chaabet El-Hamra sa dopravuje po cestnej komunikácii na susediacu banskú lokalitu Kherzet Youcef, kde sa z nej získava zinkový koncentrát.

Veľkosť podzemných dobývacích priestorov má vplyv na mechanické vlastnosti masívu (Zengchao et al., 2009; Zhang et al., 2011). Podstatným parametrom pri štúdiu stability je pevnosť v tlaku, pričom je dôležité zohľadniť aj primárnu frakturáciu v ochranných pilieroch (York a Canbulat, 1998; Medhurst a Brown, 1995). Pri charakteristickej pevnosti pilierov sa posudzuje hľadisko pravdepodobnosti prekročenia konkrétnej hodnoty tlaku, čo by spôsobilo vznik porúch v horninovom masíve. Výhodou novej metodiky je aplikácia nového analytického vzorca, ktorý zohľadňuje vplyv veľkostných proporcií (veľkosti a tvaru) a aspekt pravdepodobnosti pri hodnotení rizika vzniku porúch v banských pilieroch bez potreby experimentálnych meraní na úrovni pilierov. Týmto spôsobom nová metodika prináša úsporu finančných nákladov a času. Výhodou pravdepodobnostného určovania pevnosti je zohľadnenie vzťahu deformácie pilierov a postupu prác na banských lokalitách.

Aspekt veľkostných proporcií (mierky) v mechanike pevných látok zistený experimentálne súvisí s reálnou prítomnosťou väčšieho počtu diskontinuít v materiáli pri jeho väčšom objeme. Ak sa zväčšením objemu horninového prostredia zvyšuje pravdepodobnosť výskytov diskontinuít, mechanické vlastnosti tohto prostredia (pevnosť a tvrdosť) sa v ochranných pilieroch úmerne znižujú (Martin a Maybee, 2000; Cuisiat a Haimson, 1992; Heuze, 1980; Salamon a Munro, 1967).

Pravdepodobnostné kritérium, ktoré umožňuje odvodiť pevnosť piliera ako funkciu jeho veľkosti, tzv. efekt mierky, zaviedol Weibull (1939; matematické vyjadrenia 1 a 2). Pri štúdiu pevnosti pilierov v laboratórnych podmienkach (Hudson et al., 1972; Salamon a Munro, 1967; Zengchao et al., 2009; Zhang et al., 2011) sa zvýraznila dôležitosť reprezentatívnosti parametrov vzorky z daného horninového masívu. Ak pilier in situ neobsahuje geologické diskontinuity (napr. vrstvovitosť či tektonické porušenie) alebo antropogénne porušenie (napr. strelnými prácami), možno ho považovať za neporušené horninové prostredie (York a Canbula, 1998). V takom prípade kritickú pevnosť horninového masívu (pri danej veľkosti, nad ktorou sa už nevyskytne ďalšie zníženie pevnosti) možno považovať za reálnu pevnosť horninového masívu in situ (t. j. výsledky zistené v laboratórnych podmienkach sa považujú za korešpondujúce s reálnymi výsledkami v horninovom masíve).

Inú, retrospektívnu metodiku (tzv. metódu spätnej analýzy) zaviedli Salamon a Munro (1967) a Bieniawski (1968; matematické vyjadrenia 3 a 4).

V tomto článku prezentujeme metodiku určovania pevnosti pilierov spojením oboch metodík. Nový vzorec (6), ktorý bol vyvinutý kombináciou dvoch matematických vyjadrení z uvedených metodík na základe vzťahu medzi aspektom spätnej analýzy (Galvin at al., 1996) a pravdepodobnostným aspektom (Weibull, 1939), umožňuje interpretovať vplyv oboch faktorov na pevnosť pilierov (matematické vyjadrenia 7 – 14). Distribúciu bezpečnostného faktora znázorňuje obr. 8. Žltou a zelenou farbou sú v ňom vyjadrené stabilné oblasti, červená farba znázorňuje oblasti s rizikom zavalenia a modrá farba znázorňuje oblasti s vysokou pravdepodobnosťou zavalenia. Priemerný bezpečnostný faktor stabilných častí bane je 1,2.

Výsledky prezentované v tomto článku preukazujú, že keď sa zväčšuje objem piliera, jeho pevnosť klesá, ale so zväčšovaním šírky piliera sa jeho pevnosť zvyšuje (masívny pilier je odolnejší ako štíhly pilier).

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