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DESIGNING OF ANCHORING REINFORCEMENT IN UNDERGROUND WORKINGS USING DOPROC METHOD

VYUŽITÍ METODY POPV K NAVRHOVÁNÍ KOTEVNÍ VÝZTUŽE DŮLNÍCH DĚL

Abstract

The anchoring reinforcement (roof bolting) ranks currently among important reinforcing solutions available in the mining industry and underground engineering. The reinforcement is sized on the basis of various theoretical assumptions and empirical pieces of knowledge. Generally it is assumed that the input values are clearly deterministic. This is valid for both the geotechnical conditions under which the anchors will be applied as well as for properties of the anchors that are influenced also by installation procedures. But most data used as inputs in various anchor sizing methods are random. Recently, applied Direct Optimized Probabilistic Calculation (DOProC) has started developing for the assessment of the reliability of building constructions. DOProC is also applicable for the design of anchors. An assumption for the application is a sufficient database of random quantities relating to the environment where the anchors will be installed, properties of the anchors and anchoring technologies, anchor design computational models and suitable and efficient tools for the probabilistic design of the anchoring reinforcement.

Keywords

Direct Optimized Probabilistic Calculation, DOProC, anchoring reinforcement, underground working, probabilistic calculation, reliability assessment, probability of failure, reliability function, random variable.

Abstrakt

Při navrhování kotevní výztuže se vychází z různých teoretických předpokladů a empirických poznatků. Zpravidla se přitom předpokládá, že vstupní hodnoty jsou jednoznačně dány deterministicky. Předložený příspěvek ukazuje postup pravděpodobnostního navrhování a posuzování spolehlivosti kotevní výztuže při aplikaci metody POPV (Přímého Optimalizovaného Pravděpodobnostního Výpočtu).

Klíčová slova

Přímý Optimalizovaný Pravděpodobnostní Výpočet, POPV, kotevní výztuž, důlní dílo, pravděpodobnostní výpočet, posudek spolehlivosti, pravděpodobnost poruchy, funkce spolehlivosti, náhodné proměnné.

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1 INTRODUCTION

Recently, stochastic (probabilistic) methods have become more and more popular for the appraisal and designing of structures. These methods have provided more information about reliability and resistance of carrying structures [8], [9], [10]. The reason is that the input data used when designing and evaluating the structures are of a rather random nature. They are, however, frequently processed as data that are clearly defined by their deterministic nature. Use of the probabilistic method in the regular appraisal and designing procedures has started recently only.

Anchoring supports ranks currently among important bracing solutions that are used in the mining industry and underground engineering. The support is sized on the basis of various theoretical assumptions and empirical pieces of knowledge. Generally it is assumed that the input values are clearly deterministic. This is valid for both the geo-technical conditions under which the anchors will be applied as well as for properties of the anchors that are influenced also by installation procedures. But most data used as inputs in various anchor sizing methods are random. In some places, the empirical and analytical methods have been used successfully to design the anchor supports based on theoretical analysis and processing of data gained from extensive empirical measurements. In case of those methods, the probabilistic approach can be used to design an anchor support only if it assumed that the initial basic data that describe dimensions of underworking, features of rock pillar, anchors or anchor types are not of a deterministic nature, but are random data in line with respective input parameter histograms.

2 PROBABILISTIC CALCULATIONS

There are many probabilistic calculation methods [Novák 2005]. They include simulation methods (based on Monte Carlo, LHS, or Importance Sampling), approximation methods (such as FORM and SORM) as well as numerical methods, incl. Direct Determined Fully Probabilistic Calculation - DDFPC. The method was published first in 2002 (Janas Krejsa) - it was originally developed as a Monte Carlo alternative to SBRA (Marek, Guštar, Anagnos 1995 [9]). The name of the method - Direct Determined Fully Probabilistic Calculation (DDFPC) means that the calculation procedure for a certain task is clearly determined by its algorithm, while Monte Carlo generates calculation data for simulation on a random basis. It, however, followed from a number of consultations and discussions that the word "determined” is somewhat misleading. The method requires high-performing information systems for complex tasks. Therefore, efforts have been made to optimize calculations in order to reduce the number of operations, keeping, at the same time, reliable calculation results. Chances of optimising the calculation steps seem to be extensive. Having consulted the issue with experts in construction reliability (Šejnoha, Novák, Keršner, Teplý 2009), the name of the method was made more precise and reads now Direct Optimized Probabilistic Calculation – DOProC. The random nature of quantities entering the probabilistic calculation is often expressed by the histogram created on the basis of observations and, frequently long-lasting measurements. Those histograms are used then to assess the reliability of structures. In probabilistic calculations, the individual random variables might be multiplied, divided, added, or subtracted. Sometimes, more complicated operations are needed. The needed random variable operations are expressed in histograms. The operations can be carried out using general principles of the probabilistic theory. It is possible to use any histogram expressing any random variable that enters the calculation. Let the histogram B be an arbitrary function f of histograms A_j, where j ranges from 1 to n. Then:

$$B = f(A_1, A_2, A_3, ... A_j ... A_n), \tag{1}$$

Each histogram A_j consists of i_j interval where each interval is limited with $a_{j,i}$ from below and $a_{j,i+1}$ from above.

This means, that for the interval $i_j = 1$, the values will be as follows:

$$a_{j,1} \leq a_j \leq a_{j,2} \tag{2}$$

where

$$a_{j,2} = a_{j,1} + \Delta a_j \leq a_{j,2} \tag{3}$$

where

$$\Delta a_j = \frac{a_{j,\max} - a_{j,\min}}{i_j} \tag{4}$$

In i_j, the following formula is valid:

$$a_{j,i} \leq a_j \leq a_{j,i+1} \tag{5}$$

Let us express a_j in the interval as $a_j^{(ij)}$. Similar relations are valid for the B histogram. if there are i intervals, the values of the histogram in the i^{th} interval range from b_i to b_{i+1}, this means $b^{(i)}$. The values can be expressed as follows:

$$b^{(i)} = f(a_1^{(i1)}, a_2^{(i2)}, a_3^{(i3)}, \ldots, a_j^{(ij)}, \ldots, a_n^{(in)}) \tag{6}$$

for the specific combination of arguments: $a_1^{(i1)}$, $a_2^{(i2)}$, …, $a_j^{(ij)}$, … $a_n^{(in)}$. The same value - $b^{(i)}$ can be derived for other values too (or at least for some values too) - $a_j^{(ij)}$. If the potential combination of values $a_j^{(ij)}$ is marked as l, the following general formula can be derived:

$$b^{(i)} = f(a_1^{(i1)}, a_2^{(i2)}, a_3^{(i3)}, \ldots, a_j^{(ij)}, \ldots, a_n^{(in)})_l \tag{7}$$

The probability p_{bl}^{i} of occurrence of $b^{(i)}$ is the product of $p_{aj}^{(ij)}$ (probabilities of occurrence of a_j^{ij} values). Then:

$$p_{bl}^{i} = p_{aj}^{(i1)} \cdot a_{aj}^{(i2)} \cdot a_3^{(i3)} \cdot \ldots \cdot a_{aj}^{(ij)}{}_j \cdot \ldots \cdot a_{aj}^{(in)} \tag{8}$$

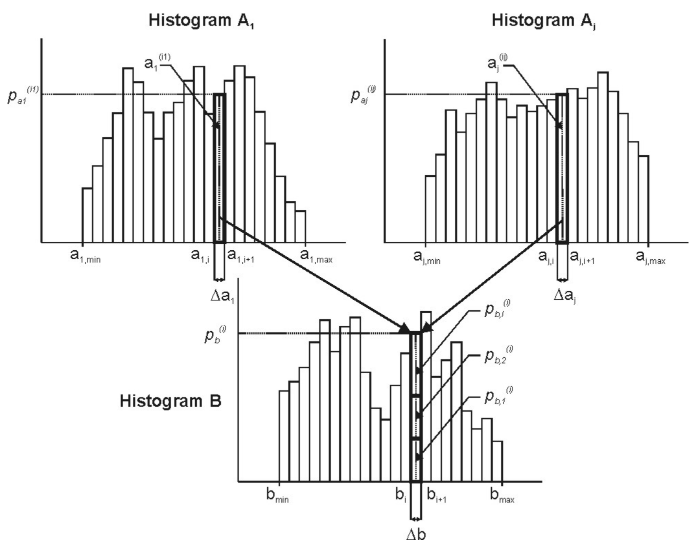

Fig.1: Principles of numerical operations with two truncated histograms

Probability $p_b^{(i)}$, being the probability of occurrence of all potential combinations $(a_1^{i1}, a_2^{i2}, \ldots, a_j^{ij}, \ldots a_n^{in})_l$ of f, with the result of $b^{(i)}$ is the sum of $p_{pl}^{(i)}$ probabilities pursuant to (9):

$$p_b^{(i)} = \sum_{l=1}^{l} p_{pl}^{(i)} \tag{9}$$

The number of intervals (i_j) in each histogram (A_j) can vary similarly as the number of i intervals in the histogram (B). The number of intervals is extremely important for the number of needed numerical operations and required computing time. On top of this, the accuracy of the calculation depends considerably on the number of intervals. DOProC optimising methods as mentioned, for instance, in [6]. However, not more details are available there.

3 PROBABILISTIC CALCULATION OF ANCHOR SUPPORTS

For purposes of probabilistic calculation of the anchor support, it is necessary to draft:

- guidelines to be followed during the sizing of the support,
- database of parameters needed for probabilistic calculations (random quantity sets for proposals of the anchors),
- software tools for probabilistic calculations.

Many guidelines exist for the designing process of the anchor supports (Pruška 2002 [11]). There are many procedures based on empirical and/or analytical and experimental methods that can be used for the sizing of the anchor supports. The empirical-analytical methods are based, typically, on simplified analytical solutions. They, however, use in the calculation coefficients that depend on relatively easy-to-determine parameters. They include properties of materials (in this case, the properties of rock are determined typically in laboratories) as well as parameters that can be measured on site or determined by observations. A valuable source of information is the results of convergence measurements, determination of "non-elastic deformation range" in mining workings and underworking that might load, by its weight, the support which should be, if necessary, stabilised by means of anchors.

Though the empirical and analytical methods apply only to the area where the necessary knowledge was acquired, they can be used in other situations, once the necessary data are verified and specified. For dozens of years, they have been used in coal mines in the Ostrava - Karviná Colliery for purpose of designing of the bracing supports in long mining workings as well as when for designing of bolt supports. In order to design single and combined roof bolting of underworkings in the Ostrava - Karviná Colliery, a calculation programme ANKER was developed (Šňupárek, Janas, Slavík [13]).

When designing the bolt support for certain conditions, following parameters need to be defined:

- the length of bolts,
- the number and location of the bolts near the mining working or underworking,
- parameters of the bolts (the type, diameters, material, anchoring method...)

Extensive measurements were carried out in the mining workings in the Ostrava-Karviná Colliery (Škrabiš 1977 [12]). It follows from the measurements that the convergence, this means dislocation of rock into the mining working, can be calculated from the following formula:

$$u = 0{,}1B \cdot \left(1 - e^{-0{,}015t}\right) \cdot \left(e^{\frac{1{,}2H - q}{45\sigma_r}} - 1 \right) \tag{10}$$

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Following parameters characterize the conditions and are used in the formula (10):

H	...	the efficient depth under the surface [m],
B	...	the dimension (typically, the width) of the mining working [m],
t	...	the time in days,
q	...	the load-carrying capacity of the support [kNm^{-2}],
σ_r	...	the reduced strength of the rock [MPa].

The reduced strength of the hanging rock, σ_r, is determined as follows:

$$\sigma_r = \beta \frac{\sum_1^n \sigma_{di} m_i}{2B} \tag{11}$$

where β is the stratification coefficient pursuant to Table 1, σ_{di} is the strength in one-axis compression of the i^{th} strata and m_i is the thickness of the i^{th} strata.

Tab.1: Stratification coefficient - β

Number of strata	1	2	3	4	5	6	7	8	9	10
β	1,0	0,95	0,90	0,86	0,82	0,79	0,76	0,73	0,71	0,70

In past, geo-physical and extenso-metric measurements were used to determine the non-elastic deformation range, B_n, that is the basis for specification of loading and length of the bolt. Evaluations have, however, indicated that the non-elastic deformation range can be defined on the basis of the convergence measurements using the formula (12) (Škrabiš 1977 [12]):

$$B_n = K_n \cdot B^{0,4} \cdot u^{0,6} \tag{12}$$

Once (10) is used in (12), for $t \rightarrow \infty$ the formula is following

$$B_n = 0{,}251189 \cdot B \cdot K_n \cdot \left(e^{\frac{1,2H-q}{45\sigma_r}} - 1 \right)^{0,6} \tag{13}$$

K_n characterizes the relation between the non-elastic deformation in the mining working or underworking with the B dimension and convergence in (12). In past, a single one deterministic value, K_n = 8.3, was used ([2], [3] a [12]). The reason was that even with a variable value, or, better to say, with a set of K variable values, it was difficult or rather impossible to make flexible calculations in spite of the fact that the data were available. The calculations of B (the dimension) or σ_r (the reduced strength) were similar – deterministic values were used even if that was not the case in reality.

The load to be transferred by the bolted support should be suitable for the non-elastic deformation range (B_n), rock weight (γ) as well as for a certain level of self-bearing capacity of rock strata that does not exist in the non-elastic deformation range. Using RMR (a geo-mechanical classification parameter) proved to be a good solution (Bienawski (1989) [1]). Then, the load of the bolted support was determined by the following formula:

$$Q = B_n \cdot B \cdot \gamma \cdot \frac{100 - RMR}{100} = 2{,}51189 B^2 \gamma \frac{100 - RMR}{100} K_n \left(e^{\frac{1{,}2H - q}{45\sigma_r}} - 1 \right)^{0{,}6} \tag{14}$$

In (14), γ is the specific gravity of rock [10^3 kg/m^3] and Q is the total load of the bolted support per running meter in the working [kN].

The appraisal of reliability of bolted supports in mining workings is based on the reliability function analysis that is described with the following formula:

$$FS = Q_{sv} - Q \tag{15}$$

where Q_{sv} is the load-bearing capacity of the bolts and Q is the bolt loading per running meter in the working.

The load-carrying capacity of the bolts is based on the following formula:

$$Q_{sv} = n_{sv} q_{sv} = \frac{n \, .q_{sv}}{d_s} = \frac{n\pi (d_1 - d_2)^2 .\sigma_{sv}}{4 d_s} \tag{16}$$

where n_{sv} is the total number of anchors per running meter in the working, n is the number of anchors in a row, typically, vertically to the working's axis, q_{sv} is the load-carrying capacity of one bolt, d_1 is the bolt's outside diameter, d_2 is the bolt's inside diameter, d_s is the span between the anchor rows and σ_{sv} is the normal stress in one bolt.

In addition to the load or the required load-carrying capacity of the anchor support, the length of anchors ranks among important parameters that need to be determined. The length of the anchors should correspond to the non-elastic deformation range, B_n, next to the mining working or underworking. It has followed from practical observations and measurements in mines that, if the anchor supports are installed, the convergence into the mining working is less that that calculated from (10) where the convergence is determined for the workings supported by bracing supports. The reason is that the resistance against dislocation of rock pillar appears only after the rock-support contact is established. This results in more extensive deformation of the rock pillars, if compared with the anchor supports. Data resulting from the comparison of deformation in the workings supported by the anchor supports and u in (10) can be used to calculate the length of anchors, l, in the hanging wall as follows:

$$l = 0{,}251189 .K_n .B.K. \left(e^{\frac{1{,}5H - q}{45\sigma}} - 1 \right)^{0{,}6} \tag{17}$$

In (17), K is a set of experimental data. The working name of this quantity is a convergence coefficient. Unlike the parameter resulting from the deterministic calculation in (Šňupárek et al [13]), this parameter is of a random nature.

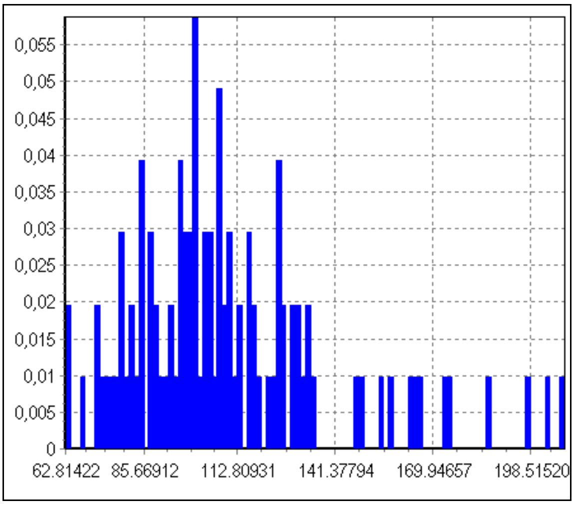

Fig.2: Histogram of primary data for compression strength in carboniferous sandstone [MPa]

Specific databases of the random input variables were created on the basis of measurements done by manufacturers of the anchoring components and in mines where the bolt supports were installed. The width of the mine working, which depends, in particular, on the heading technology, was measured in the Ostrava-Karviná Colliery mines in roadways supported by the bolt supports. The database of the one-axis strength and specific density parameters of the rock was prepared on the basis of an extensive laboratory research of test drill cores from the carboniferous rock pillar (the data have been collected in the past forty years by the Coal Research Institute and Institute of Geonics established at the Czech Academy of Science). The both coefficients, K and K_n, are also based on extensive measurements of convergences in mine gate roads in the Ostrava-Karviná Colliery (carried out in past by the same institutes). The database of tensile strength of the anchoring components was provided by the archive of the manufacturer, Ankra Petřvald, and by Minova Bohemia s.r.o. The measurements were conducted in state-authorized testing laboratories and in the Institute of Geonics.

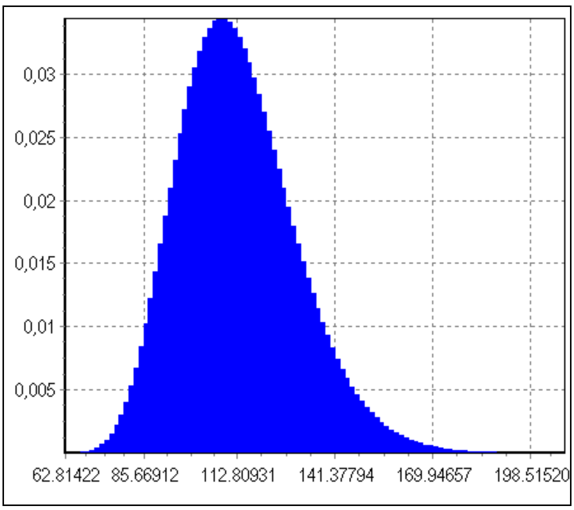

Fig.3: Histogram of parametric distribution for compression strength in carboniferous sandstone [MPa]

Using SW applications, the measured data can be processed to create histograms and derive parameters. The best distribution is chosen from among of dozens of known parametric distributions on the basis of a coefficient that is referred to as a tightness coefficient. Fig.2 shows the histogram of primary data prepared on the basis of 102 measurement data when the compression strength was measured in carboniferous sandstone. The horizontal axis shows the compression strength in [MPa], while the vertical axis shows the probability of occurrence. The number of classes was chosen in the same way both for the primary data and for the parametric distribution Gamma that is shown in Fig.3. In this case, the solution is the best – the tightness is 0.951. If another distribution or more classes are chosen, the tightness will decrease.

4 SOFTWARE FOR THE PROBABILISTIC CALCULATION OF RELIABILITIES OF THE ANCHOR SUPPORTS

A software application named Kotvení ("Anchoring") was created for the probabilistic appraisal of reliabilities of the anchor supports used in the mining working. This software application is based on the Director Optimized Probabilistic Calculation ("DOProC"). Fig.4 shows the application workplace in the Anchoring application.

Values of a random value are entered into the input form sheet. They include the width of the mining working, *B,* (Fig.5), thickness and strength of individual strata in the one-axis compression, σ_d, K_n coefficient (Fig.6), coefficient of influence of the anchor support on convergence decrease, *K*, specific gravity of rock γ, resistance of bracing support, *q,* if a combined support is used, and the strength of the bolt, σ_H. The values can be chosen from an existing database that is available in the software.

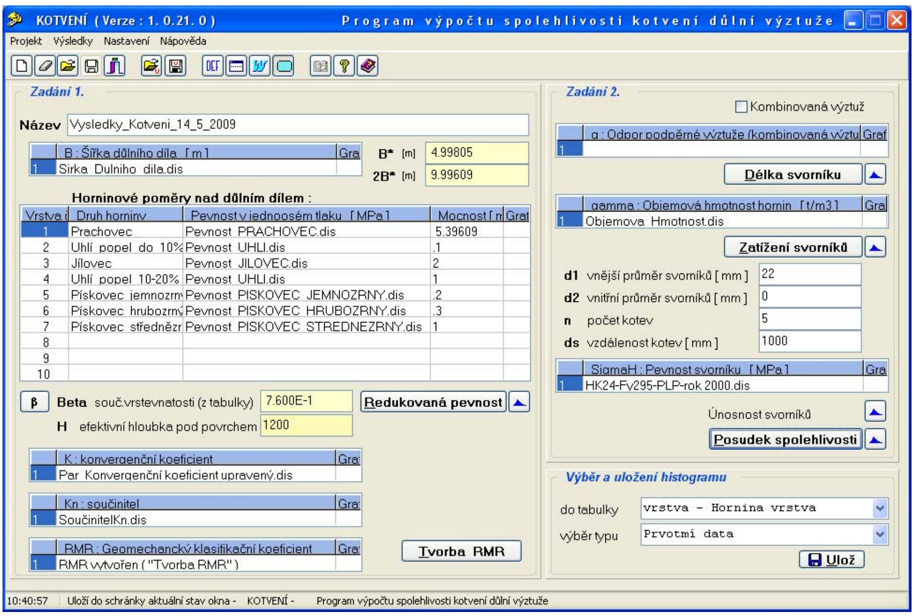

Fig.4: Application workspace in the Anchoring software

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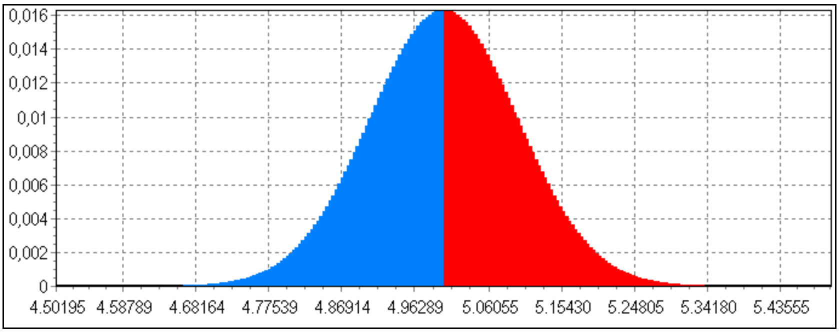

Fig.5: Histogram of the width of the mining working B [m]

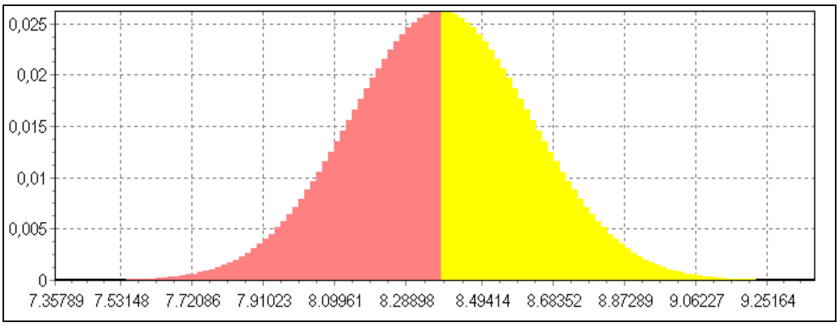

Fig.6: K_n coefficient

There are still some input variables that are expressed by deterministic description: stratification coefficient, β, efficient depth under the surface, H, thickness of individual strata, m_i, outside and inside diameters of the bolts, d_1 and d_2, and distance between the anchor rows, d_s.

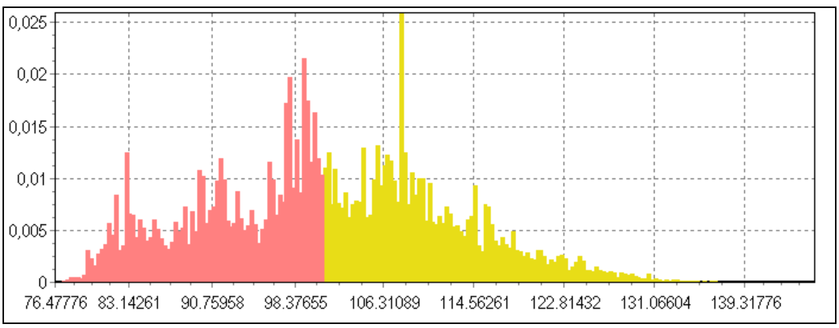

Fig.7: Histogram of the reduced strength of hanging rock [MPa]

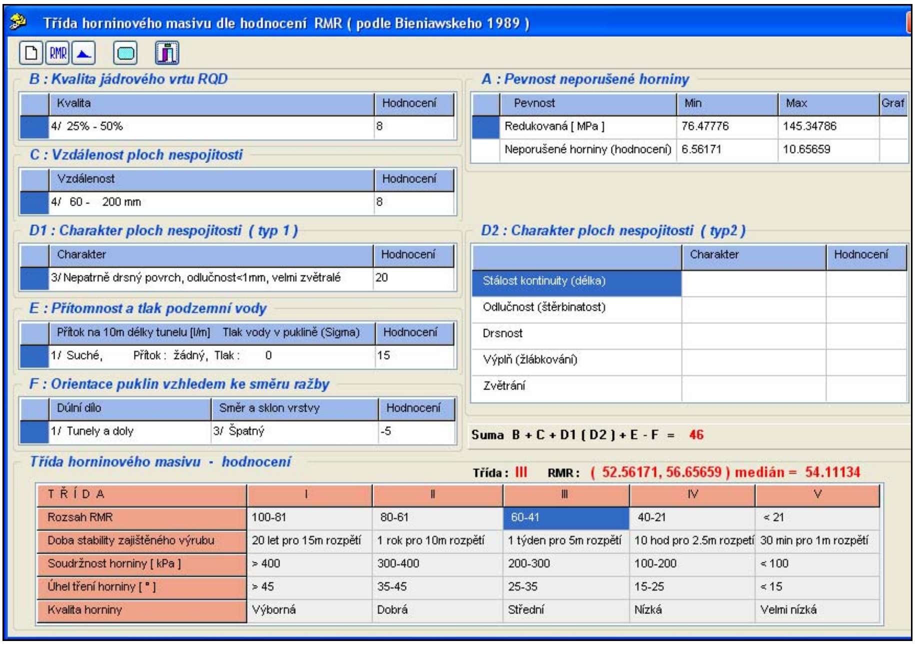

Fig.8: Workplace with a table for determination of RMR
(the geomechanical classification coefficient) by Bienawski's method (1989)

In the first stage of the probabilistic calculation, the histogram is determined for the reduced strength of the hanging rock, σ_r, pursuant to (2) (Fig.7). This histogram is needed for determination of the length and the loading of the anchors and for the geomechanical classification coefficient, RMR, (to be defined by Bienawski's method (1989). For that purpose, a separate table in the application is used (Fig.8). Values to be entered describe the conditions in the environment where the anchor support is installed. The result is the histogram for the geomechanical classification coefficient, RMR (Fig.9).

Then, it is possible to determine the histogram for the l length of the designed bolt pursuant to (8) (Fig.10). It follows from the histogram that the bolt should be 2.54 m long to reach the reliability of 0.9999.

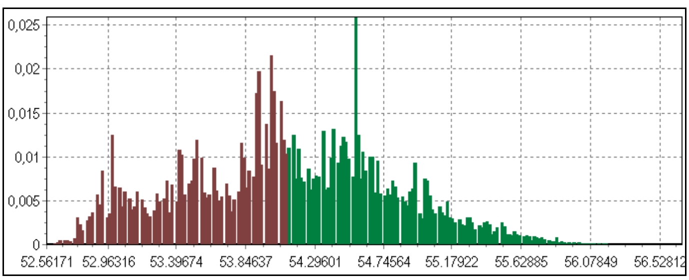

Fig.9: Histogram of RMR (the geomechanical classification coefficient)
by Bienawski's method (1989)

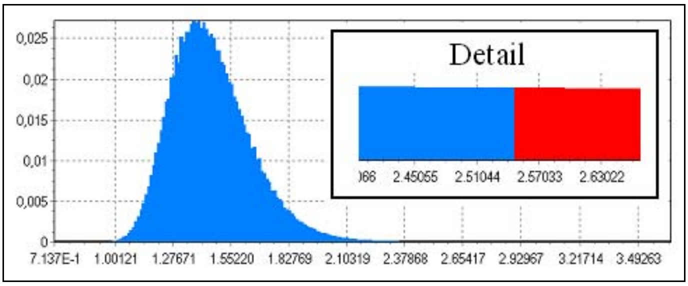

Fig.10: Histogram of the bolt length, *l* [m]

The histograms for the Q loading and Q_{sv} load-carrying capacity of the bolt are determined on the basis of (5) and (7), respectively. The histograms, Q and $Q_{sv,}$ can be used in the reliability function (6). Then, the resulting probability appraisal is made on the basis of the failure probability P_f (Fig.11).

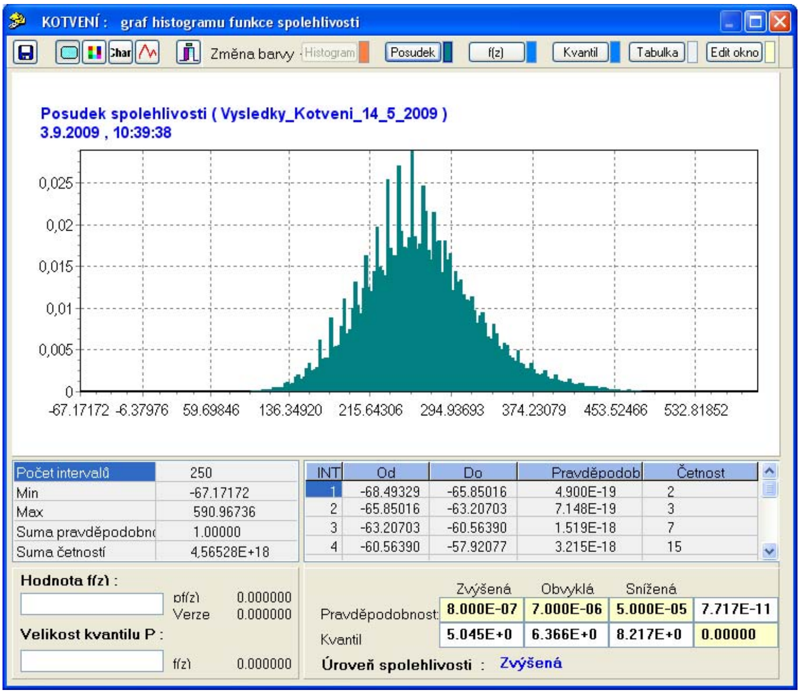

Fig.11: Histogram of the *FS* reliability function where the failure probability is $P_f = 7.72.10^{-11}$, for 5 anchors per one meter of the working.

In this case the resulting failure probability is P_f = 7,72.10^{-11}. According to strict criteria defined in ČSN 73 1404 – Designing of Steel Structures (1998), the anchor support would be sufficient because the designed probability, P_d , for the increased reliability is 8.10^{-7} and the reliability condition, $P_f \leq P_d$, is fulfilled (Fig.11). It was chosen to use 5 steel anchors per each running meter of the working. The diameter of each anchor was 22 mm. If less anchors were chosen (for instance, 4 anchors only), the situation would be different: even if the steel grade and anchor diameter were same, the failure probability would be P_f= 3.05.10^{-3}. The reliability condition, $P_f \leq P_d$, would not be fulfilled even for a decreased probability pursuant to ČSN (Fig.12). It is possible to design and size the anchor supports in the Anchoring software very flexibly. The Anchoring software

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has been authorized under File No. 001/26-01-2010_SW and is available on the web site: http://www.fast.vsb.cz/popv.

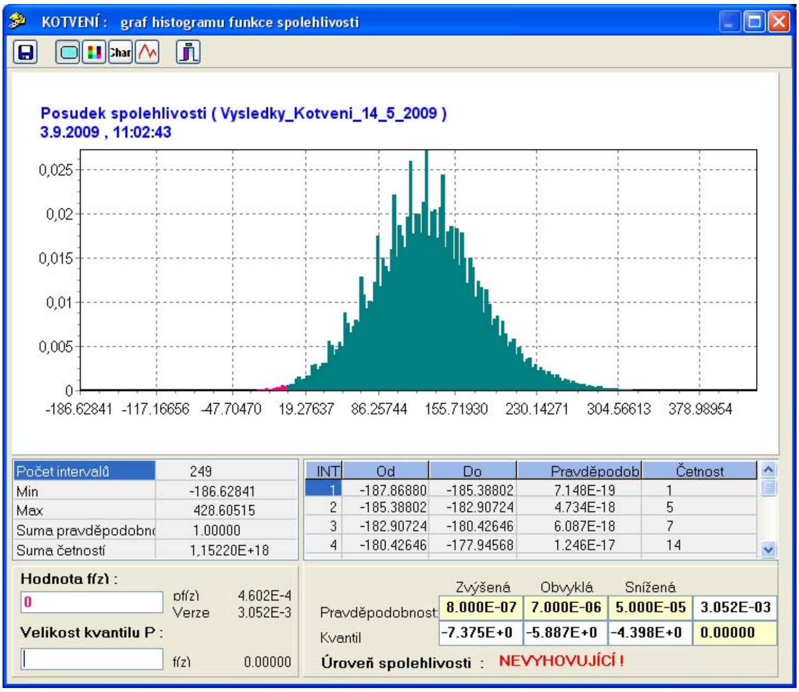

Fig.12: Histogram of the FS reliability function where the failure probability is $P_f = 3.05.10^{-3}$, for 4 anchors per one meter of the working

5 CONCLUSION

Using the proposed method, it is possible to apply probability calculations in the designing and appraisal of reliability of the anchor supports installed in long mining workings and underworkings. Thus, it is possible to determine the length, l, number, n, and load-carrying capacity, Q_{sv}. The pre-requisite is, however, a sufficient database of input quantities including the experience from practical operation because many input quantities cannot be based on models and laboratory measurements only. The probabilistic approach which has been described above in an example from the mining, as well as the available databases can be used for other structures and methods for calculation of underground constructions.

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