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Assessment of the risk of loss of stability of the steel arch support of the underground excavations

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Abstract. The stability of underground excavations depends on many natural, mining, technical and technological factors. The conducted research has shown that the data accepted for design are often characterized by considerable variability both in time and in space. In order to take into account the variability of parameters characterizing the conditions of maintaining the excavation stability, the probabilistic structure analysis method was used in which the probability of failure was assumed as the risk measure and the values of parameters accepted for analysis as random variables with normal distribution. The paper presents solutions for assessing the safety of excavations based on probabilistic methods of level II and level III. For practical purposes, classification of the degree of risk of loss of excavation stability was proposed, in which the probability of loss of stability (level II method) and probability of dangerous state (level III method) were assumed as a criterion. The general characteristics of the excavation support behaviour were indicated for individual stages. The whole is supported by practical examples from over 20 exploitation fields in several mines of the Upper Silesian Coal Basin. The proposed method can be used both at the stage of design and use of the excavation.

1. Introduction

Ensuring the stability of underground excavation is possible under three conditions [1]:

- good design – recognized geological and mining conditions, well-defined properties of the massif, good design methods, flawless calculations;
- exact execution - accurate breakthrough, accurate support (material quality, support quality, assembly accuracy);
- proper maintenance - conducting diagnostics of the excavation and support as well as performing necessary maintenance works.

Past experience shows that in underground excavations, the support during the exploitation period is characterized by high variability of bearing capacity caused mainly by the quality of its performance and often uneven level of technical wear. Similarly, the condition of the rock mass in the vicinity of the excavation may significantly differ both on individual sections of the excavation as well as during its use.



In this situation, it can be assumed that the basic parameters determining the stability of the excavation support are in the nature of random variables, for analysis of which it is appropriate to use the probabilistic method.

When treating data assumed in the excavation design process as random variables with a given probability distribution or range of variability in the theory of reliability and safety of structures using probabilistic methods, the measure of risk of loss of stability of the excavation may be its probability. The probability of loss of stability of the excavation is affected by the so-called the safety stock (the difference between the load capacity of the structure and its load) and the variance of the basic data used to determine it.

2. Theoretical basis of the risk assessment method for loss of stability of excavations based on probabilistic structural analysis methods

Estimation of the safety of the mining excavation support construction is possible using the theory of safety and reliability of the structure.

The safety measure expressed in the form is the measure of construction safety in the probabilistic solution of level I (commonly used in design practice) [2,3,4]:

$$n = \frac{P_0}{q_0} \geq 1,0 \quad (1)$$

where: P_0 – design load capacity of the support,
 q_0 – design load of the support.

The construction safety assessment in the level II probabilistic solution is based on the assumption that the stability condition of the support can be saved in the form of:

$$Z_0 = P_0 - q_0 \geq 0 \quad (2)$$

where:

Z_0 – safety reserve,
 P_0 – bearing capacity of the support,
 q_0 – support load.

Two parameters of probability distributions are decisive here, namely expected value and standard deviation. Safety of structures, based on the idea of the "weakest link", allows to take as design values the design values of the load capacity P_0 and the load of the support q_0 determined from the formulas:

$$\begin{aligned} P_0 &= \bar{P}_0 - t_{P_0} \cdot s_{P_0} \\ q_0 &= \bar{q}_0 + t_{q_0} \cdot s_{q_0} \end{aligned} \quad (3)$$

where:

\bar{P}_0, \bar{q}_0 – the average values of the bearing capacity of the support and its load,
 s_{P_0}, s_{q_0} – standard deviations of the load capacity of the support and its load,
 t_{P_0}, t_{q_0} – parameters of assurance level.

The random values of the bearing capacity of the excavation and its load with the assumption of a normal probability distribution (figure 1) can be saved in the form [2]:

$$f(P_0) = \frac{1}{s_{P_0} \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{P_0 - \bar{P}_0}{2 \cdot s_{P_0}}\right) \quad (4)$$

$$f(q_0) = \frac{1}{s_{q_0} \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{q_0 - \bar{q}_0}{2 \cdot s_{q_0}}\right)$$

The average value and standard deviation value of the total design load of the support in simplified terms, omitting certain, parameters of the rock mass, eg faults or edges can be determined from the formulas [2,5]:

$$\bar{q}_0 = \int_{\Omega} q_0(S_W, W_W, H, R_c, E, \nu, \varphi, \varepsilon_g, \gamma) \cdot g(S_W, W_W, H, R_c, E, \nu, \varphi, \varepsilon_g, \gamma) \cdot d\mu_1 \quad (5)$$

$$s_{q_0} = \sqrt{\int_{\Omega} [q_0(S_W, W_W, H, R_c, E, \nu, \varphi, \varepsilon_g, \gamma) - \bar{q}_0]^2 \cdot g(S_W, W_W, H, R_c, E, \nu, \varphi, \varepsilon_g, \gamma) \cdot d\mu_1} \quad (6)$$

$$d\mu_1 = dS_W \cdot dW_W \cdot dH \cdot dR_c \cdot dE \cdot d\nu \cdot d\varphi \cdot d\varepsilon_g \cdot d\gamma, \quad \Omega = R^9 \quad (7)$$

where:

S_W – width of the excavation breakdown, m,

W_W – the height of the excavation breakdown, m,

H – the depth of the excavation location, m,

R_c – compressive strength, MPa,

E – modulus of elasticity, MPa,

ν – Poisson's coefficient,

φ – Internal friction coil,

ε_g – ultimate elastic deformation of rocks, mm/m,

γ – specific of rocks, MN/m³.

However, the mean value and the standard deviation value of the support load can be determined from the formulas [2,4]:

$$\bar{P}_0 = \int_{\Omega_2} P_0(f_d, M_{\max}, W, N_o, \varphi, A, N, N_z) \cdot f_1(f_d, M_{\max}, W_x, N_o, \varphi, A, N, N_z) \cdot d\mu_2, \quad (8)$$

$$s_{P_0} = \sqrt{\int_{\Omega_2} [P_0(f_d, M_{\max}, W, N_o, \varphi, A, N, N_z) - \bar{P}_0]^2 \cdot f(f_d, M_{\max}, W_x, N_o, \varphi, A, N, N_z) \cdot d\mu_2}, \quad (9)$$

$$d\mu_2 = df_d \cdot dM_{\max} \cdot dW \cdot dN_o \cdot d\varphi \cdot dA \cdot dN \cdot dN_z, \quad \Omega_2 = R^8 \quad (10)$$

where:

M_{\max} – the extreme value of the bending moment on the perimeter of the support rings, MN·m,

N_o – the value of the axial force at the place of extreme value of bending moment on the perimeter of the support rings, MN,

W – value of the bending index of the section of the support section of the support, m³,

φ – value of the buckling coefficient,

A – value of the cross-section of the section of the support structure, m²,

N_z – the value of the load-bearing capacity of the chassis LP, MN

N – value of axial force at the joint location, MN,

f_d – value of tensile strength of the support material, MPa.

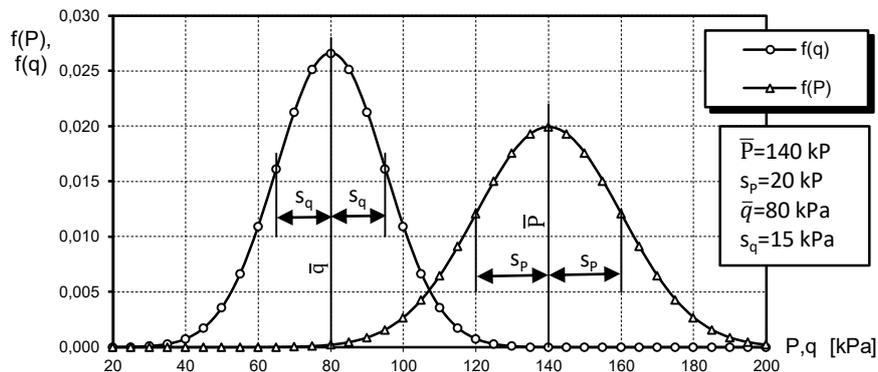


Figure 1. Example of load distribution and load capacity of the support as random variables with a normal probability distribution.

The reliability factor Cornell t is taken as a safety measure:

$$t = \frac{\bar{P}_0 - \bar{q}_0}{\sqrt{s_{P_0}^2 + s_{q_0}^2}} \quad (11)$$

The value of cumulative distribution of the reliability coefficient $p(t)$ means the probability of the support structure's safety, whereas the value of $[1-p(t)]$ means the probability of structure failure (loss of stability through the casing).

In the level II method according to [2,3,6], the following conditions apply to this level of calculation:

$$p \leq p_a \quad (12)$$

where:

p – probability of failure,

p_a – acceptable level of probability of failure.

The method of safety estimation analysis presented above can be used in forecasting the reliability of atypical construction objects, such as objects requiring individual estimation of safety reserves due to the lack of current standards or regulations, objects with unusual loads or structures, whose bearing capacity was determined by experimental methods [2].

In the probabilistic level III method [2,3] it is assumed that the load capacity of the support and its load are random variables with distribution functions $f(q_o)$, $f(P_o)$ and distributors $F(q_o)$, $F(P_o)$. The range of values q_o and P_o is limited, i.e. the extreme values q_o and P_o and differing from the central one are unlikely, however possible. Unlimited distribution curves $f(q_o)$ and $f(P_o)$ are considered absolute characteristics of distributions. In addition, the conditional characteristics of $f'(q_o)$ and $f'(P_o)$ are distinguished, for which the range of variation lies on one side of variation q_o and P_o (figure 2).

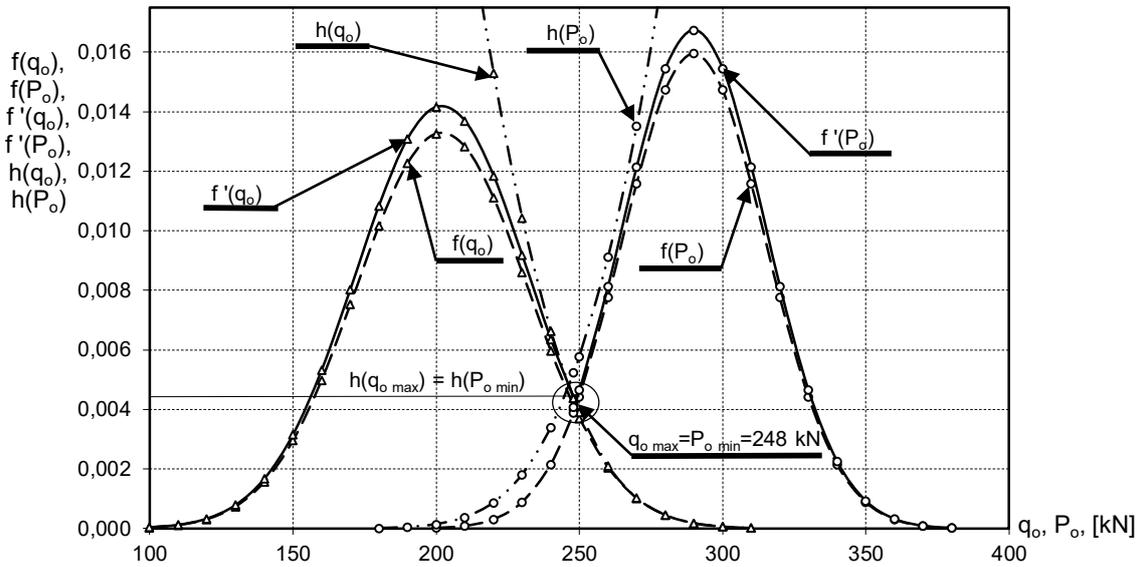


Figure 2. Example of load distribution and load capacity of the support as random variables with a normal probability distribution for level III.

Conditional characteristics of distributions $f'(q_o)$ and $f'(P_o)$ take the form:

- the load capacity of the support is limited by the left-hand value $P_{o\ min}$:

$$\begin{aligned}
 f'(P_o) &= 0 && \text{dla } P_o \leq P_{\min} \\
 f'(P_o) &= \frac{f(P_o)}{1 - F(P_{\min})} && \text{dla } P_o > P_{\min}
 \end{aligned}
 \tag{13}$$

- the support load function is limited by the right $q_{o\ max}$:

$$\begin{aligned}
 f'(q_o) &= \frac{f(q_o)}{F(q_{o\ max})} && \text{dla } q_o < q_{o\ max} \\
 f'(q_o) &= 0 && \text{dla } q_o \geq q_{o\ max}
 \end{aligned}
 \tag{14}$$

As a measure of safety, the risk functions $h(P_{o\ min})$ i $h'(q_{o\ max})$ of exceeding the value $P_{o\ min}$ down and $q_{o\ max}$ up in the form of:

$$h(P_{o\ min}) = \frac{f(P_{o\ min})}{1 - F(P_{o\ min})}
 \tag{15}$$

$$h'(q_{o\ max}) = \frac{f(q_{o\ max})}{F(q_{o\ max})}
 \tag{16}$$

The risk function is called the intensivity of probability at which unreliability increases relative to reliability:

$$h(t) = \frac{f(t)}{1 - F(t)}
 \tag{17}$$

The scale of the coordinate threat to the state of the structure is expressed by the formulas:

$$\frac{1}{k_p} = P_{o\ min} \cdot h(P_{o\ min})
 \tag{18}$$

$$\frac{1}{k_{q_o}} = q_{o\max} \cdot h'(q_{o\max}) \quad (19)$$

where:

k_{p_o} , k_{q_o} – load capacity of the support and its load scales of the threat.

Assuming a constant optimization criterion scale of the threat

$$\frac{1}{k_{p_o}} = \frac{1}{k_{q_o}} = \frac{1}{k} \quad (20)$$

an equation of dangerous condition of the structure can be obtained in the form:

$$p_f = 1 - [1 - F(P_o)] \cdot F(q_o) \quad (21)$$

where:

$F(P_o)$, $F(q_o)$ – load capacities and support loads.

The optimum measure of safety in the discussed method is to minimize the failure of the construction $p_f = \min$.

3. Classification of the degree of risk of loss of stability of underground excavation

On the basis of the analysis and assessment of the behaviour of the workings in relation to the calculated probability of loss of stability, the following classes of conditions for maintaining the stability of excavations and the degree of risk of loss of stability were outlined in Table 1 [3,6].

4. Analysis of risk assessment for loss of stability of excavations

4.1. Analysis of the estimated risk of loss of stability of designed excavations

The conditions for maintaining the stability of mining excavations are influenced by many natural and mining factors, which makes it difficult to define clear ones and simple classification criteria. An additional difficulty is caused by the variability of natural and mining conditions. Taking into account both the complexity of the issue and the results of the analysis of the behaviour of 250 preparatory excavations located in 22 regions of the USC mines, it was assumed that the risk of loss of mine work stability is the probability of loss of stability.

The analysis based on probabilistic analysis of level I structures carried out at work [3] showed that (figure 3):

- results obtained from commonly used methods for assessing the stability of underground excavation give similar values;
- only in the case of about 1% of all the excavations analysed, the basic condition for the safety of the structure is not met (safety factor above 1.0);
- in about 43% the safety condition recommended for underground excavations (safety factor above 1.5) is not met.

Table 1. Classification of conditions for maintaining the stability of underground excavations and the risk levels of its loss.

Degree of risk of loss of stability	Probability		Specification
	according to the level II method p_a	according to the level III method p_f	
I risk small	$P_o - q_o > 0$ and $p_a \leq 0,03$	$p_f \leq 0,12$	No risk of loss of stability (excavations will retain the original shape and size of the cross-section, there will be no deformation of the casing, small slides may occur and joints in the joints will not occur, there will be no visible deformations and damage to support accessories)
II slight risk	$P_o - q_o > 0$ and $p_a = 0,03 \div 0,10$	$p_f = 0,12 \div 0,30$	There is a possibility of deformation of the excavation without the need to perform its repairs (excavations will retain the original shape and required size of the cross-section, sporadic support deformations may occur, there may be visible protrusions in the joints and slight deformation of its accessories).
III medium risk	$P_o - q_o > 0$ and $p_a = 0,10 \div 0,20$	$p_f = 0,30 \div 0,35$	During the entire lifetime of the excavation, there is the possibility of deformation of sporadically requiring repairs (visible deformations in the form of chutes in the joints of the frames, slight plastic deformation of the support and its accessories and uplifting of the floor will occur).
IV big risk	$P_o - q_o > 0$ and $p_a = 0,20 \div 0,35$	$p_f = 0,35 \div 0,45$	During the entire lifetime of the excavation, deformations requiring at least 1 repair will occur (visible deformations will occur in the form of chutes in the joints of the frames, plastic deformation of the support and its accessories, and uplifting of the floor).
V very big risk	$P_o - q_o > 0$ and $p_a = 0,35 \div 0,45$	$p_f = 0,45 \div 0,60$	During the entire lifetime of the excavation, its deformations and damages will occur, requiring several repairs (there are significant deformations in the form of chutes in the joints of the frames, plastic deformation of the support and its accessories, and significant raising of the floor).
VI unacceptable risk	$P_o - q_o \leq 0$ or $p_a > 0,45$	$p_f > 0,60$	There is a risk of destruction of the excavation in the form of a slab or intense deformations requiring frequent repairs (there are significant deformations threatening the stability of the excavation in the form of significant slips in the joints of the frames, plastic deformation of the support and its accessories and significant raising of the floor).

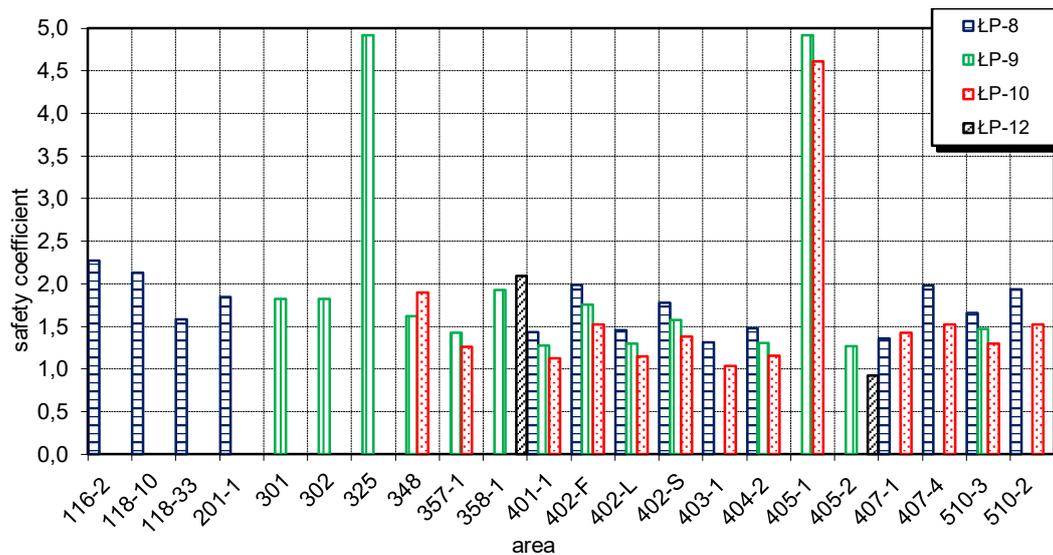


Figure 3. Formation of the value of safety coefficients for the construction of underground excavations in the analysed areas - probabilistic method of level I, q_0 and P_0 .

Using the probabilistic method of level II, in which the probability of loss of stability was assumed as a measure of the reliability of the support structure, analysis and calculations were carried out, which showed that the support used in the analysed excavations was characterized by a variable probability of loss of stability. This variability was not only due to the "economical" choice of support, but to a large extent on the variability of natural and mining conditions. For the analysed workings in selected areas of USC, the probability of loss of stability of the excavation support p_a reached values (figure 4):

- for 11.6% of excavations - $p < 0.05$;
- for 16.3% of excavations - $0.05 < p < 0.1$;
- for 30.2% of excavations - $0.1 < p < 0.25$;
- for 39.6% of excavations - $0.25 < p < 0.5$;
- in the case of 2.3% of excavations - $p > 0.5$.

Referring the obtained results to the recommended values of the probability of failure of civil structures – overground, it should be stated that in the case of underground facilities, the probability of achieving values is much higher. This is mainly due to the variability of geological – mining and technical – technological conditions causing relatively high variability of input data, and this results in higher probability of loss of stability of the excavation.

The assessment of the reliability of the excavation construction using the Tier III probabilistic method was carried out with the assumption of a constant hazard scale. As a measure of reliability, the probability of a dangerous condition of the structure (including excessive clamping due to slip in joints) was assumed. The results of the analyses carried out are shown in figure 5.

The probability of occurrence of dangerous states of underground excavation structures determined with the Tier III probabilistic method always reaches higher values than calculated by the level II probabilistic method. The size of the difference depends on the variability of the load and load capacity of the support and determines the interval between the state of danger and the state of loss of stability. This range decreases with the increase in the variability of input data, as the probability of loss of stability increases with a smaller increase in the probability of the dangerous state of the structure.

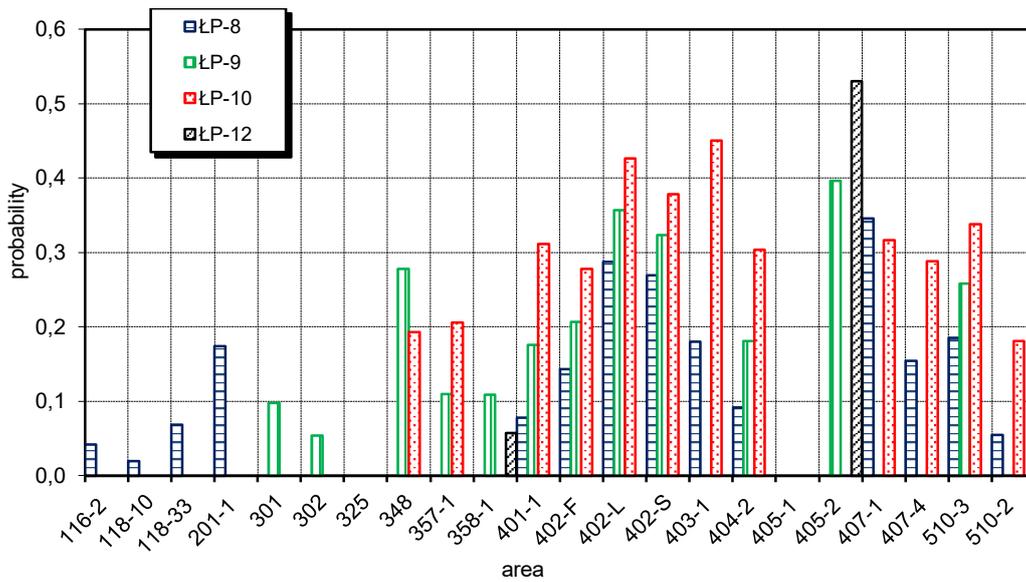


Figure 4. Formation of the probability value of loss of stability of underground excavations in the analysed areas – probabilistic method of level II.

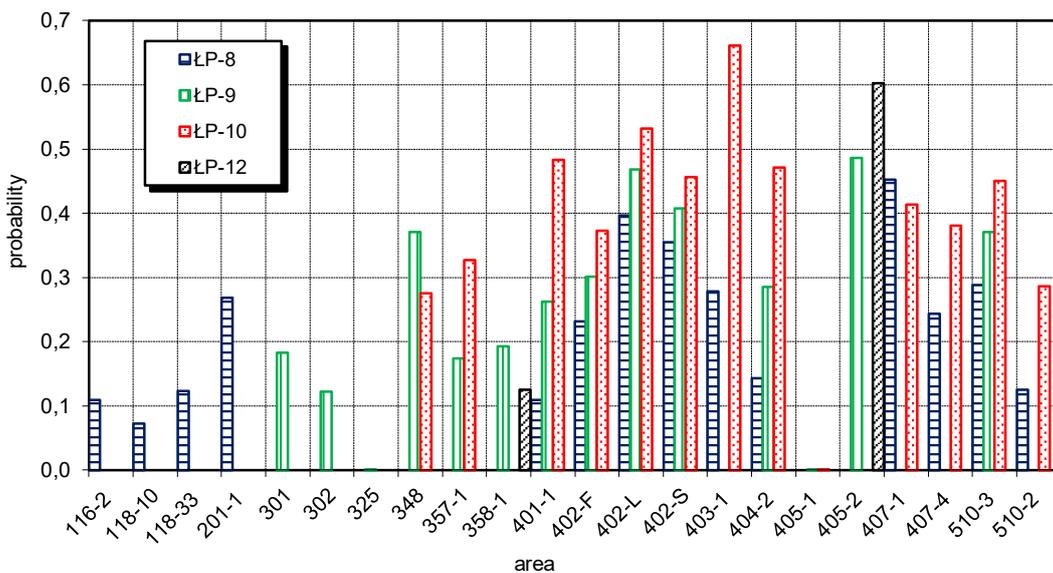


Figure 5. Shaping the probability of dangerous states of an underground excavation determined by the level III probabilistic method.

4.2. Analysis of changes in the risk of loss of stability of the mining support during its use

The conditions of co-operation with the rock mass during the exploitation of the excavation change due to, among others reduction of the bearing capacity of the support due to corrosion of the material in its construction, change of the rock mass to the support as a result of the development of the fracture zone in the surrounding rock mass due to changes in the state of stress and deformation, or changes in usable support loads [7]. Table 2 presents examples of the results of calculations of the enclosure structure safety for the initial state (without taking into account corrosion of the arch) and the current state (taking into account the average value of the corrosion defect of the arches).

Table 2. Sample results of calculations of the support structure safety for the initial state (without taking into account the corrosion of the frames) and the current state (taking into account the average value of the corrosion defect of the arches).

The name of the excavation	The size of the arch	Support profile	d [m]	$\frac{P_{sr}}{q_c}$	$P\left(\frac{P_{sr} - q_c}{\sqrt{s_p^2 + s_q^2}}\right)$		
				according to the project	according to technical condition tests	according to the project	according to technical condition tests.
Excavation into the shaft	ŁP-10	V29	0,50	1,55	1,07	0,000	0,362
			0,75	1,04	0,72	0,418	0,949
		V32	0,50	1,79	1,43	0,000	0,016
			0,75	1,19	0,95	0,144	0,605
Transport excavation	ŁP-10	V29	0,50	1,40	1,03	0,018	0,431
		V32	0,50	1,62	1,22	0,000	0,117
Main excavation	ŁP-10	V29	0,50	1,13	1,03	0,176	0,423
		V32	0,50	1,31	1,04	0,016	0,373
Belt excavation	ŁP-10	V29	0,50	1,03	0,91	0,412	0,739
		V32	0,50	1,19	1,04	0,070	0,396
Ventilation excavation	ŁP-8	V25	0,75	1,13	0,88	0,235	0,742
Ventilation excavation II	ŁP-8	V25	0,75	1,01	0,87	0,475	0,785

Based on the calculations made, it can be concluded that for the initial condition the support of the analysed sections of the excavation had the required load capacity. In all cases, the stress transfer factor reaches values above 1 and the probability of failure is from 0.000 to 0.118, which qualifies them to stages I ÷ III (risk small, slight and medium). After a period of use based on the results of measurements of corrosion losses and determination of the current load capacity of the support, it was found that the stress transfer coefficient reaches values lower than the initial ones, and in some cases below 1. The calculated probability of loss of stability reaches values from 0.016 - 0.949, i.e. acceptable value. Such a high probability of loss of stability is primarily caused by the effort of surrounding rocks and the variability of the rock mass as well as the significant corrosion of the support and the resulting variability of its bearing capacity.

5. Summary

Forecast stability of the excavation depends on many factors, the determination of which is possible only with some approximation. The main factors of information uncertainty include:

- variability of the structure and properties of the rock mass resulting from the variability of stress-deformation processes occurring in the rock mass in various states of mining works;
- variability of the dimensions of the cross-sections of the excavation along its run on the rock deformation, the quality of the breach, the brash, etc.;
- variation of stress-deformation fields in the rock mass resulting from changes in the properties of the rock mass, its tectonics, hydrogeological conditions, mining conditions and the impact of the developed underground and surface infrastructure;
- high degree of technical wear of the excavation resulting from its long life and unfavorable environmental impacts.

Considering the above, it should be stated that in mining design, information uncertainty will never be avoided. This is due to the specifics of this technical field. Therefore, one should strive to minimize the uncertainty of information by conducting research primarily for the most accurate diagnosis of geological and mining conditions. The scope of exploratory surveys should be determined depending on the variability of natural and mining conditions in the area in question.

Therefore, the use of probabilistic methods, accepting input parameters for design as random variables, can be considered justified, and the risk of loss of stability may be the probability of an unfavorable condition.

For practical purposes, on the basis of the analysis of the dependence of the behaviour of headings on the excavations from the probability of loss of stability, the proposed classification of conditions for maintaining the stability of excavations and assessing the risk of losing it may be used.

In the light of this classification, the designed and maintained excavation should qualify for class I, II or III conditions for maintaining the stability of excavations.

The proposed classification can be used as a tool for:

- assessing the degree of safety of the excavation at every stage of its existence;
- developing recommendations for the control and monitoring of the excavation support during its use at the design stage;
- estimating the necessary scope and costs of corrective and preventive actions;
- defining the schedule of corrective and protective actions existing in a given area of the excavation to reduce the risk of their infarction;
- occupational risk assessment.

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