A reliability indicator based on assessment entropy of mining building and structure elements

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Abstract. The quality reconstruction of the mine industrial facilities is the maximum possible elimination of the identified defects. Assess the suitability of the object for further operation or reconstruction based on the inspection results of a building or structure as actual values of the controlled parameters. Provide the science-based methodology for diagnosing the technical state, assessing the reliability and physical wear for mining buildings and structures by using the probabilistic and statistical methods. A retrospective analysis of the results of surveys, collection, processing and generalization of information on states (diagnoses) and characteristic defects (diagnostic features), based on the probabilistic-statistical apparatus of technical diagnostics and elements of information theory. An assessment of state and reliability, physical wear of structures of all levels. The Kulbak-Leibler distance as a key indicator in the method of estimating the "survivability of the element" provides for the probability distribution of the tensile strength. Developed methods of using technical diagnostics based on probabilistic statistical methods – the Bayes method, statistical solutions - including the concepts of theory information. When performing a probabilistic analysis of the technical condition of all elements, the numerical solution showed the effectiveness of the proposed diagnostic methodology. The innovative method is to analyze and assess the reliability of mine facilities using a mathematical modeling to determine the probabilistic characteristics of defects in structural elements. The analysis method in the survey allows for determining the technical state of the object, the set of further measures, effective planning the operating and restoring costs.

1. Problem statement
The high-quality reconstruction of the mine industrial facilities implies the maximum available identification of existing defects. A survey of surface objects stands for determining their technical condition. The survey findings as actual values of controlled parameters enable to assess the suitability of an object for further operation, reconstruction or to find the need for restoration, strengthening, and repair of structural elements. This task reflects the utmost importance, since undetected defects can cause structural failures during the operation of mine industrial facilities.

2. Unsolved aspects of the problem
Updated scientific and production methods for determining the actual state of structural elements (SE) of mine surface objects are based on standard concepts. Developing new ways to comprehensively determine the actual state of surface objects prolongs their safe operation.
3. Analysis of the recent research
To address the above challenges for determining the technical state, reliability and wear of structural elements and building, as well as to upgrade the current normative references in a survey, it is proposed for the first time to use the mathematical mechanism of technical diagnostics based on probabilistic-statistical methods with including information theory elements in the diagnostic procedure. The Bayes method is one of the main statistical methods of technical diagnostics used in research. It was further developed by I. A. Birger, A. Zehner for complex technical systems [1, 2]. I. A. Birger notes in his works that the technical diagnostics is aimed at increasing the reliability and service life of systems and should be considered as one of the main sections of the general theory of reliability. Thus, the technical state and its key feature - reliability, reliability and its important section - technical diagnostics, technical diagnostics and survey of the technical state should be links of one process that ensures normal up-to-date functioning of buildings and structures. The links in this “chain” must be inseparable, in aggregate and interconnected. The scientists V.V. Bolotin, S.L. Butorin, B.A. Garagash, A.P. Kudzis, O.V. Luzhyn, V.D. Raiser, A.R. Rzhanitsyn, A.G. Roitman, N.N. Skladnev, V.S. Utkin, S.G. Shulman, G.S. Shulman considered the reliability of building structures based on probabilistic approaches [3–14]. Also, the foreign scientists G. Augusti, A. Baratta, F. Kashia, made significant progress with the theory of reliability [15]. This paper depicts a fairly detailed use of a probabilistic-statistical approach to detect the technical state of building systems and their elements within mathematical methods of technical diagnostics, as well as material on estimating their reliability parameters.

4. Previously unsolved part of the general problem
The technical condition of structural elements of buildings and structures is assessed by comparing the maximum limits (calculated or standard) and actual values of strength, stability, deformability and operational characteristics of structures. When designing surface objects, the operational characteristics are not set up. The physical wear of structural elements and the object is not modeled. In the design phase of the building, it is almost impossible to forecast the future reliable operation costs.

5. Objectives of the article
A retrospective analysis of the previous examinations to collect, process and summarize information on states (diagnoses) and characteristic defects (diagnostic signs), and develop the methods based on the probabilistic-statistical apparatus of technical diagnostics and elements of information theory. This allows for assessing state, reliability, and physical wear of all structures at all levels.

6. Presentation of the main research
When operating the surface complex of the mines of the Kryvyi Rih iron ore basin, a number of accidents and disasters were caused by the structural destruction of mining buildings. A number of external factors and underground mining may cause the destruction of structures. All mining structures are located close to the zone of rock shifting, which sometimes might damage the structural integrity of buildings. The mines of Kryvbas have used mining with massive ore collapse and overlying rocks so far, which resulted in damaging the integrity of the rock mass [16,17]. Thus, the foundations of mining structures were partially destroyed. Transiting to chamber mining systems [18,19] increased the active zone of rock shifting from 60 to 75 degrees and significantly decreased harmful impact of underground mining on mining structures. The following structures on the surface- high tower headframes, trestle bridges connecting buildings, steel headframes, loading bunkers, processing plants, administrative and household plants of modern architecture- characterize primarily the architectural and construction design of modern
Mining enterprises. Most of the mine structures have a service life over 30-40 years under significant physical wear. The structures in the limit state endanger the life and health of the technical personnel of the mine. The current regulatory methods for determining the technical state of structures are general guidelines and do not sufficiently consider the actual operation of these structures. It is very difficult, and sometimes impossible, to promptly identify emergency conditions by technical operation services and the engineering staff of specialized organizations, since the centers of physical wear of structures are in hard-to-reach places. Kryvyi Rih National University systematically carries out technical diagnostics, strengthening and reconstruction of building structures of mining objects [19]. To date, we have diagnostic data for seven major enterprises: ShidGZK, NothernGZK, KZuRK, SUKHA BALKA, CentralGZK, PivdenGZK, InGZK. We present the graphs of the development of the defects intensity to consider the current situation of the objects under study. The empirical values of the defects of headframe elements and overhead buildings over time are presented in (figure 1).

![Figure 1. Corrosion processes in the elements of headframes and mine buildings over time.](image-url)

For 35-38 years, we observe a uniform development of defects in all elements, without progress jumping. Further, up to the 57th year of operation, the structural defects are jumping in the main elements. After 60 years, we see a sharp increase. To establish the main regularities of physical wear, the methods are as follows: the factor analysis as sequential two-sided classifications identifies characteristic operational damage and zoning of structures [20]; the statistical methods for processing diagnostic data determine the conditional rates of corrosion and abrasive wear of elements of metal structures [20]; the accelerated laboratory tests determine corrosion rates at characteristic points [21,22]; the method of analyzing the elastoplastic system destruction assess the impact of operational damage [23]. The failure of even one element can have drastic consequences for complex systems. Therefore, the primary task is to select the best design and mechanical parameters of the system in view of cost, reliability, weight and volume. Hence, assessment of the elements reliability is required at the design stage. The reliability calculations are based on the fact that each element has a certain strength in relation...
to loads. The design method including the safety and the capacity factor does not show the probability of element failure. In addition, the same safety factor can vary the probability of failure widely. Using a safety factor is justified only when its value is set on extensive experience in using elements similar to the mentioned above. Besides, design parameters are often random variables, which are completely ignored by conventional design methods. The usual deterministic approach to design is not satisfactory in terms of reliability analysis. Another design method is therefore required that would consider the probabilistic nature of the design parameters and assess the reliability of the elements at the design stage. Here, all design parameters are specified, which determine the stress and strength distributions. If both distributions are defined, then the probability of failure-free operation of the element can be calculated (figure 2).

![Figure 2](image)

**Figure 2.** Statistical distributions of the probability density of the tensile strength of steel (blue histogram), and the actual distribution of stresses in the rods (red histogram).

Here, the measure of reliability is the probability that the maximum stress arising under the action of the load will not exceed the bearing capacity (strength) of the element, then:

\[ H = P (R > S). \]  

(1)

where \( H \) is the reliability; \( P \) is the probability of the event; \( R \) is the bearing capacity; \( S \) is the effective maximum stress. More generally,

\[ P (R > S) = \int_{-\infty}^{\infty} f(S) \left[ \int_{-\infty}^{\infty} f(R) dR \right] dS \]  

(2)

Using this expression, we can also calculate the probability of failure-free operation of the element in various combinations of the distribution laws of the bearing capacity and load. That is, in normal distribution of load and bearing capacity, the probability of failure-free operation is defined as,

\[ P (R > S) = \frac{1}{2} + \Phi \left( \frac{m_R - m_S}{\sqrt{\sigma^2_S + \sigma^2_R}} \right) \]  

(3)
Where $\Phi()$ is the normalized Laplace function; $m_R$ and $m_S$ are the mathematical expectations of $R$ and $S$; $\sigma_R$ and $\sigma_S$ are the standard deviations of $R$ and $S$. In real, the bearing capacity and durability of the element depend on the geometric dimensions, material characteristics and external factors. The geometric parameters are deterministic values, the characteristics of the material are random variables with given distribution laws, the intensity of external factors is mostly stochastic, which makes it impossible to define them both theoretically and empirically. Thereby, we reasonably replace the random processes with slices of one-dimensional random variables. It follows that the reliability system is based on statistical methods operating with the distribution function parameters, which describe both the stress state of structural elements and the change in time (figure 3).

**Figure 3.** Stresses distribution in the nodes of the tower headframe elements at the 54th marks of the Yubileyny mine and stress changes depending on the corrosion.

The indicator (3) allows to substantiate the quantitative relations between the decrease in the ”bearing capacity” of structures elements and the ”states” of construction objects. In practice, this reduces the objectivity of assessing the actual state of operated buildings and structures and runs the risk of an emergency. Therefore, using the risk theory in our research helps significantly improve the reliability of buildings and structures in operation. We use the Kullback-Leibler distance to assess the ”survivability of the element” considering the risk and a priori given values of the ultimate strength distribution. The Kullback-Leibler Distance (divergence) ($D_{KL}$) or relative entropy $H(P\|Q)$ is a non-negative functional, which is an asymmetric measure of the distance from each other of two probability distributions on the common space of elementary events, is defined as,

$$D_{KL} = \sum_{i=1}^{n} p_i \frac{p_i}{q_i}$$  

The Kullback-Leibler divergence is a non-dimensional value, regardless of the dimension of the initial random variables. This is due to the fact that the identified law forms of stress distribution in the SE change both in height and design. We established that the form of the law degrades
over time under corrosion, mechanical wear and the accumulation of other damage. Therefore, to estimate the residual resource of the system and its constituent elements, it is preferable to use estimation methods that are not sensitive to the distribution law, namely, to use non-parametric indicators such as the Kullback-Leibler divergence ($D_{KL}$), which is more preferable than the Bayes method. In the study, we calculated the values of the Kullback-Leibler divergence. Our goal is to assess the "survivability" of structural elements

| Corrosion, % | Kullback-Leibler Divergence ($D_{KL}$) |
|-------------|---------------------------------------|
| 0           | 14.03                                 |
| 20          | 8.659                                 |
| 40          | 4.616                                 |
| 60          | 1.885                                 |
| 80          | 0.468                                 |

From the table 1, the Kullback-Leibler divergence is inversely related to the value of the SE corrosive wear. Thus, the maximum parameter ($D_{KL} = 14.03$) corresponds to the calculated (design) value, while the minimum parameter ($D_{KL} = 0.468$) refers to the SE emergency state. A graphical representation of the change in the Kullback-Leibler distance under the corrosion processes in the elements is shown in (figure 4).

This is because the law of stress distribution in the elements shifts towards the law of ultimate strength distribution. The above graphs depict theoretical probability distribution densities corresponding to the selected model samples (in red is ultimate strength, corresponds to the density of normal distribution; in blue is stress distribution in the structural elements; the distribution density of the "complex" law is set in the first-staged algorithm). This reduces the distance between the laws of distributions and decreases the residual tensile strength of both the element and the system.
7. Conclusions and direction of further research
In determining an accurate technical state, reliability and wear of structures and structural elements, for the first time we developed the theoretical apparatus of technical diagnostics based on probabilistic-statistical methods- the Bayes method, methods of statistical solutions-including the concepts of theory information. When performing a probabilistic analysis of the technical state of all elements, the results of a numerical solution confirmed the general possibility of the proposed diagnostic methods. We proposed an analysis algorithm without a strict binding to a specific distribution law. Also, we calculated the Kullback-Leibler divergence in order to assess the "survivability" of structural elements. To sum up, with an increase of corrosion, the value $D_{KL}$ decreases and shows the wear of the elements, while the maximum value corresponds to the calculated (design) value and the maximum reliability of both structural elements and the entire system.

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References
[1] Birger I A 1978 Technical diagnostics (Moscov: ed. "Engineering") p 240
[2] Zelnar A 1980 Bayesian methods in econometrics (M.: Statistics) p 434
[3] Bolotin V V 1981 Methods of probability theory and reliability theory in the calculations of structures (Moscov: Stroyizdat) p 351
[4] Butorin S L Shulman G S and Shulman S G 2012 Methods of NPP safety analysis in technological accidents (Moscov: Mashinostroenie) p 437
[5] Garagash B A 2012 Reliability of spatial adjustable systems "structure-base" with uneven deformations of the base (DIA Publishing House) p 888
[6] Kudzis A P 1985 Reliability assessment of reinforced concrete structures (Vilnius: Moklas) p 155
[7] Luzhin O V 1983 Probabilistic methods for calculating structures (M.: MISI im. Kuibysheva) p 122
[8] Raiser V D 1998 Theory of reliability in building design: Monograph (Moscov: DIA publishing house) p 304
[9] Rzhanitsyn A R 1978 Theory of calculation of building structures for reliability (Moscov: Stroyizdat) p 239
[10] Roitman A G 1985 Reliability of structures of operated buildings (Moscov: Stroyizdat) p 175
[11] Skladnev N N and Dreyer F E 1983 Strouf't'naya mekhanika i raschet sooruzheniy 3 1–4
[12] Utkin V S 2011 New methods for calculating the reliability of building structures (Vologda: VoGTU) p 98
[13] Shulman G S 2001 Reliability of engineering structures: textbook. allowance (St. Petersburg: Publishing house of St. Petersburg State Technical University) p 48
[14] Shulman G S 1991 Problems of reliability of hydraulic structures (St. Petersburg: VNIIG Publishing House) p 49
[15] Augusti G Baratta A and Kashiati F 1988 Probabilistic methods in building design (Moscov: Stroyizdat) p 584
[16] Andreev B M Brovko D V and Khvorost V V 2016 Prediction and ensuring the reliability of buildings elements and structures of surface complex at reconstruction Metallurgical and Mining Industry vol 9 (Metaljournal)
[17] Andreev B M Brovko D V and Khvorost V V 2015 Determination of reliability and justification of object parameters on the surface of mines taking into account change-over to the lighter enclosing structures Metallurgical and Mining Industry vol 12 (Metaljournal) p 378–382
[18] Brovko D V Khvorost V V and Tyschenko V Y 2018 Qualimetric assessment in calculation of the survivability level of the mine surface objects Scientific Bulletin of the National Mining University vol 4 (Dnipro) pp 66–71
[19] Karapetrou S Manakou M Bindi D Petrovic B and Pitilakis K 2016 "Time-building specific" seismic vulnerability assessment of a hospital rc building using field monitoring data Engineering Structures vol 112 (Elsevier) pp 114–132
[20] Kapyrin P Sevryugina N 2018 The procedural approach to reliability of objects of the raised level of responsibility IOP Conference Series: Materials Science and Engineering, 21st International Scientific
[21] Han KK Golparvar-Fard M 2017 Potential of big visual data and building information modeling for construction performance analytics: An exploratory study Automation in Construction vol 73 (Elsevier) pp 184–198

[22] Fenton G Naghibi F Dundas D Bathurst R and Griffiths D 2016 Reliability-based geotechnical design in 2014 Canadian Highway bridge design code. Canadian Geotechnical Journal vol 53 (NRC Research Press (Canada)) pp 236–251

[23] Yigit C 2016 Experimental assessment of post-processed kinematic precise point positioning method for structural health monitoring Geomatics, Natural Hazards and Risk vol 7, Issue 1 (Taylor and Francis Ltd.) pp 360–383