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Development of methods and software algorithms for state forecast of the ultimate stressed rock massif

Anton Slashchov[1,4], Oleksii Yalanskyi[2], Ihor Slashchov[1] and Illya Siromaschenko[3]

[1]Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, Simferopolska Str., 2a, Dnipro, 49005, Ukraine
[2]National Technical University Dnipro Polytechnic, Dmytra Yavornytskoho Ave., 19, Dnipro, 49005, Ukraine
[3]Westphalian University of Applied Sciences, Westfälische Hochschule, Neidenburger Str. 43, Gelsenkirchen, 45897, Germany

[4]Corresponding author: AISlashchov@nas.gov.ua

Abstract. The article covers a live scientific problem consisting in development of new and improving of existing digital technologies for forecasting a stress-strain state of ultimate stressed rock massif. The analysis of the researches has shown that the approaches based on the synthesis of mine monitoring methods and analytical forecasting methods are promising for assessing the state of ultimate stressed rocks. The existing hazard indicators can be beaded by the integral indicators of the stress-strain state of the rock massif determined with the help of geo-information systems. However, there are no methods, algorithms and software for figuring these indications. As a result of the research, methods of implementation and functions of software elements have been developed for determining integral indicators characterizing the state of an ultimate stressed rock massif. The "Methodological recommendations ..." have been developed, which describes specificity of using the information system for forecast integral parameters of the rock massif stress-strain state and assessing the conditions for the rock destruction. The use of the designed methods, algorithms and software decreases geomechanical risks of gas-dynamic phenomenon occurrence, reduces cost of breakdown elimination and increases economical efficiency of the mining enterprises.

1. Introduction

Geo-technological systems of mines pose a risk to workers due to the manifestations in the workings of a number of negative factors. Statistics show that injuries from landslides, rock strikes, gas and dust explosions account for about half of the victims. Material costs also remain significant. The experience of underground mining shows that as a result of intensification of rock shear processes there is a decrease in the cross sections of mine workings, intensive emissions of methane gas into the mine atmosphere, increasing the likelihood of rock bursts, sudden outbursts of rocks and gas, which makes it necessary to significantly increase the cost of restoring the operability of mine workings support systems and increasing air losses.

The peculiarities of the gas-dynamic dangerous states of the coal-rock mass are the differences in the rates of their manifestations, their location in space, and the time of flow. As a consequence of the massif dangerous manifestations, there is an increase of methane emissions, an increase of the mixture radioactivity, dust content, pressure and speed of the outgoing air jet, acoustic vibrations, electromagnetic radiation, etc. [1-7]. Existing methods for assessing of the coal-rock massif hazardous state in mining are based on the analysis of the main informative parameters that determine the gas-dynamic phenomena: the magnitude and structure of the rock pressure, the output of the gas contained in the coal, the physical and mechanical properties and the state of the coal-rock massif.

One of the most pressing problems of mining is the development of methods and algorithms for forecasting of the rock massif parameters based on modern digital technologies. First of all, there is a need to improve the system for forecast potentially hazardous states of the geological environment of mines, which allows you to make operational decisions on safety at work. In this sense, the most promising methods for forecasting sudden rock and gas outbursts are alternative approaches, including the synthesis of mine control methods and the stress-strain state integral parameters forecast of the ultimate stressed rocks by geo-information systems.

The purpose of the research is to develop new and improve existing digital technologies for forecasting of the ultimate stressed rocks stress-strain state.

2. Methods

Implementation of software elements to improve the information subsystem to determine the integrated indicators of the ultimate stressed rock massif state was carried out using known methods of organizing computational processes and building software models of information systems.

The reliability and validity of the results is confirmed by the use of proven methods of geomechanical processes mathematical modeling using the finite element method, which is widely tested in practice. Estimation of reliability of the developed algorithms is confirmed by the series of numerical experiments.

3. Results and discussion

When calculating the rock massif stress-strain state, we have plenty of input data and parameters that were obtained as a result of modeling. Input data for calculations are obtained in the laboratory or empirically, conducting directly in the mine or at a controlled facility with the series of field studies. These methods, for example, determine: physical and mechanical properties of rocks (adhesion, modulus of elasticity, bulk density, Poisson's ratio, etc., initial stresses in the rock massif, impact forces on the supports, shear contours of workings and etc. [8-14]). The initial (calculated) data are obtained using a mathematical module of any geo-information system, in particular, using the finite element method.

To assess the conditions for the transition of near-contour rocks from an inelastic rheological deformation process to dynamic or gas-dynamic destruction scenarios, it is necessary to use integral indicators of the rocks stress-strain state. The possibilities of using integral parameters for assessing the ultimate stressed rocks are given in table 1.

Determination of new integral parameters requires changes to the source codes of the geo-information system programs. At the same time, for many applications (including commercial ones) this is not available option due to the fact that it is impossible to extend or modify them for new conditions without having an input code (software systems are presented only with compiled codes), it is impossible to determine the adequacy of the mathematical model embedded in calculation module. Most often, the programs that are offered for geomechanical calculations were created for other purposes, for example, for the design of parts, assemblies and shells in mechanical engineering, soil analysis, building foundations, building structures, and more. That is, the programs, in the overwhelming number of cases, are designed to assess the state of the material of machine parts, mechanisms, aircraft bodies, etc. and calculate exclusively elastic media, which does not correspond to the model of rock deformation.

It is clear that this is a problem in calculating geomechanical processes in sedimentary rocks, since for the actual conditions of field development, elastic models give only approximate idealized stress distribution and only at the time when elastic deformation occurs [15]. Such calculations often lead to incorrect results that are not confirmed by real measurements in mine workings. GEO-RS© software for calculation of rocks stress-strain state by finite element methods (FEM) and initial stress method

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[4, 10] is deprived of these shortcomings. The developed software, as a result of calculations, produces large data arrays containing the values of stresses, deformations, displacements, forces and other indicators for each element and node of the finite element model. Data in the information system is stored in the vector form. A vector is a structure that contains a set of values (vector elements) to each of the elements of which can be referenced by index. The number of elements in a vector depends on the amount of data they contain and, as a rule, for systems using FEM, is equal to the number of nodes or elements in the design scheme (in this case, the vector index will be the number of the node or element, respectively).

Table 1. Integrated parameters for assessing the geomechanical condition of ultimate stressed rocks and their use for safety of mining.

Parameter name	Designation	Unit	Integral parameters used to forecast the hazardous state of rocks
Potential strain energy	E^{def}	J	Energy balance of the massif and the degree of its danger by sudden manifestations of rock pressure
Full offsets of nodes	u^{xy}	m	Displacements and convergence of the mine roadway contour
Changes in maximum stresses σ_1 over time	$\sigma_1^{t+\Delta t}$-σ_1^{t}	MPa	Changes in support loads
Changes in the orientation of maximum stresses σ_1 over time	$d\alpha_\sigma^{xy}/dt$	deg/day	Changes in the distribution of increased fracturing depending zones on the influence of the parameters of mining technology
The intensity of the change in the maximum stresses σ_1	$d\sigma_1/dt$	MPa/day	Potentially hazardous areas of the rock massif
Stress deviator	$\sigma_1 - \sigma_3$	MPa	Stress field unequal components
Strain deviator	$\varepsilon_1 - \varepsilon_3$	-	Changes in the shape of the rock massif sections in the process of destruction
Orientation platforms shear forces	β_1, β_2	degree	Changes in the orientation of main cracks
Destruction type	ps_1, ps_2	sign	Possible volumes of rock caving
Areas of inelastic deformation zones	S_{ZID}	m^2	Volumes of inelastic deformations zones
Change in the areas of inelastic deformations zones	$S_{ZID}^{t+\Delta t}$	m^2	Destruction of rock massif over a period of time
Areas of discontinuity zones	S_{ten}	m^2	The volume of possible collapse of rocks
Changing the areas of elements	ΔS	m^2	Changes in the pore-fracture space

To determine the integral indicators characterizing the state of the ultimate stressed rock massif, implementation methods, functions and software elements have been developed. Calculation of one of the integral parameters is performed by element-by-element or node-by-node calculations according to a certain formula that determines this indicator. Both input and calculated data vectors are used. To perform the calculation and obtain the values of one of the integral parameters vector, an object instance is created, which is an implementation of the interface with the "get a number" function. In return, for each of the integral parameters, an object instance is determined by a specific ratio obtained on the basis of the rock mechanics laws. This ratio is entered into the main program as a string, that is, a sequential set of characters (letters, numbers, and signs).

The method for creating the main operation is the implementation of calculating a certain ratio by calculating the integral parameter (figure 1). The set of characters (string) entered into the program is divided into tokens. A token is a sequence of characters that logically unites parts of a string and is most convenient for processing data as a whole (for example, a number that determines the maximum principal stresses parameter "σ_1" or the operator "+" itself).

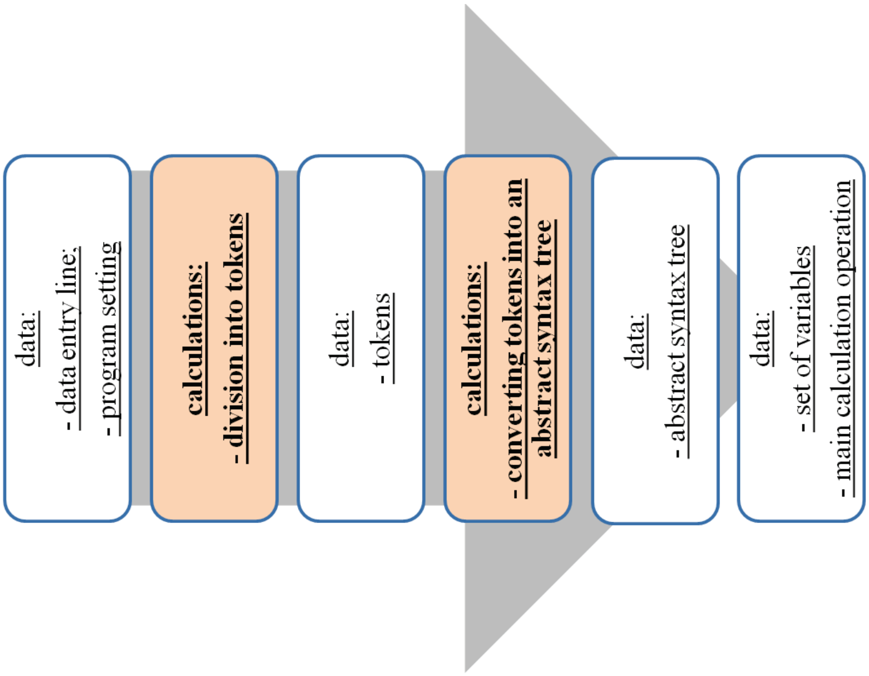

Figure 1. Diagram of the method for creating the main operation for calculating the integral parameters (the stages of calculations are highlighted in bold).

In turn, tokens are divided into types (figure 2), which are selected depending on the characters in the string. If the characters are numbers or dots, then the token type will be a number. If the symbol is an arithmetic sign, then the type will be an operator. The choice of the type of operation depends on the type of token. An abstract syntax tree is built from a sequence of tokens, taking into account mathematical rules.

Let's consider an example of creating an abstract syntax tree and extracting the main operation from it (table 2). First, the formula of the integral parameter is entered in the form of a row (2 row of the table). Then it is split into tokens (3 row of the table). An abstract syntax tree is built on the basis of tokens (4 row of the table). Note that the action "×" (multiply) must be performed first, but is at the end of the calculation formula. Therefore, the first operation in the syntax tree is "×" with two references to the variable "σ_2" and the constant "12". According to the sequence of mathematical rules, the second operation in the tree is "–". The subtraction operation "–" refers to the parameter variable "σ_1”" and the operation "×". The tree of operations reflects the mathematical sequence, including parentheses.

An operation is an interface with one function "get the result" of performing an intermediate or final operation. The program has several implementations of this interface (figure 3). The result of the main operation is calculated by traversing the abstract syntax tree in depth. The operation of the operator "–" is the value from the operation of returning the variable "σ_1" and the result of the operation of the operator "×". When the result of the operator operation "×" is requested, it receives data from the operation of returning the variable "σ_2" and the operation of returning the constant "12" and returns their difference. Then, element-by-element or node-by-node calculations are carried out for each element of the integral parameter vector (figure 4).

As a result of the research, the architecture of the subsystem for the analysis of integral indicators for assessing the rocks stress-strain state was created, which is adapted to the new version of the geo-information system GEO-RS v. 8.3 (figure 5, 6). The multi-window main interface (figure 5) consists of a title bar, main menu, toolbars, a workspace with scroll bars, and a status bar. The program allows you to generate a geomechanical design scheme, send the output data for execution to the computational processor of the finite element method, and perform a numerical and graphical analysis of the results in a postprocessor or an external application. The interface, scenarios of the user interaction with the system, functions of initial data control and analysis of results are completely unified, which provides a logical sequence of modeling operations.

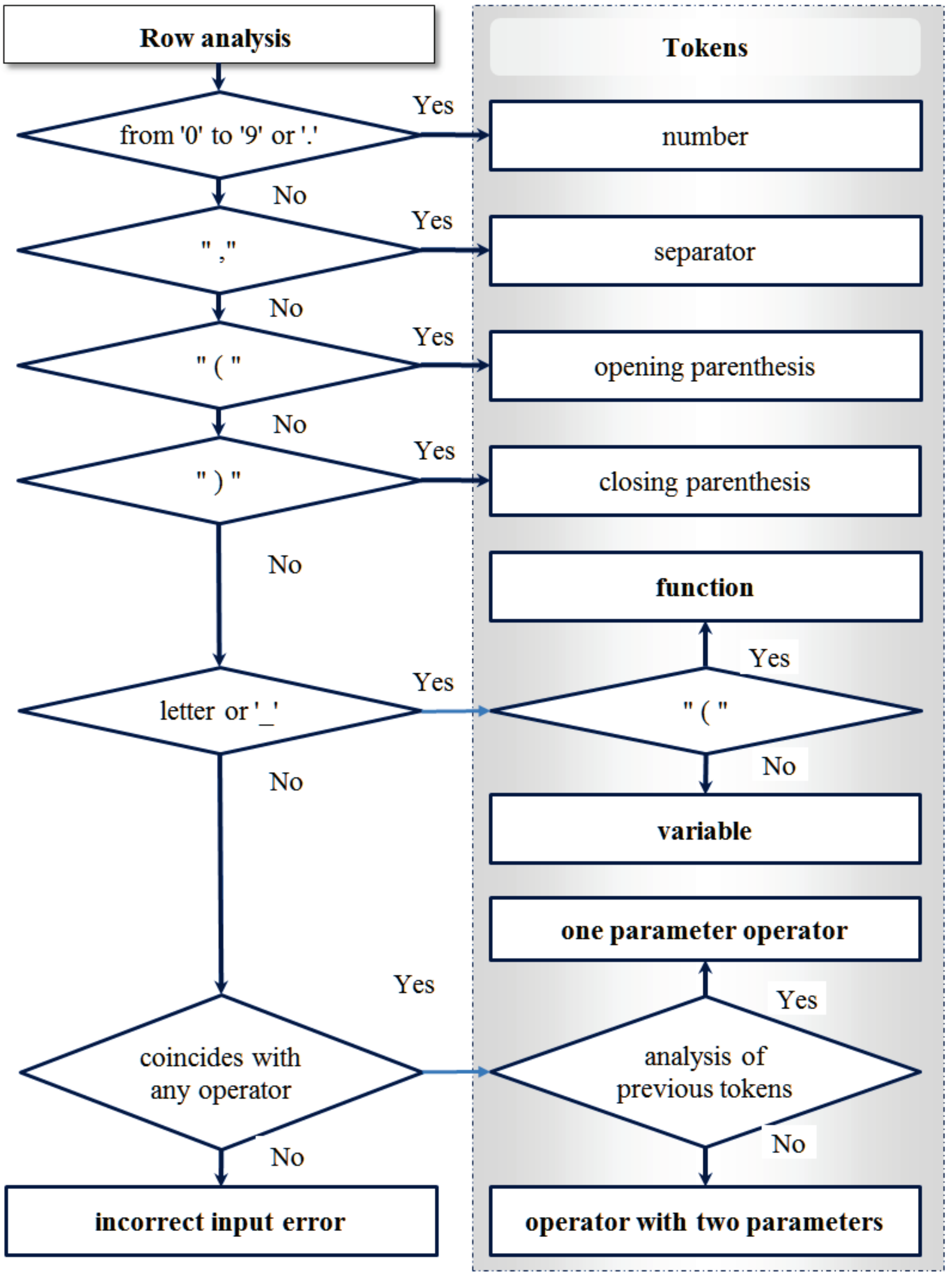

Figure 2. Types of tokens and conditions for their receipt.

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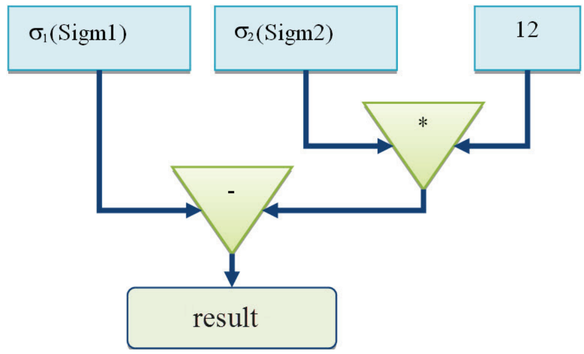
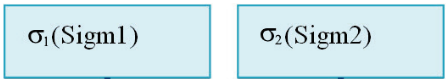
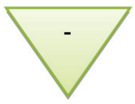
Table 2. Example of creating a main operation.

Sequence of calculations	Data in memory
An example of an integral indicator formula	σ_1-$\sigma_2\times$12
String (consists of characters)	s i g m 1 - s i g m 2 * 1 2
Breakdown into tokens that logically combine parts of a string	sigm1 - sigm2 * 12
In-memory creation of an abstract syntax tree	
Selection of variables for future data substitution into the main expression to obtain the calculation result	Set of variables  The main operation 

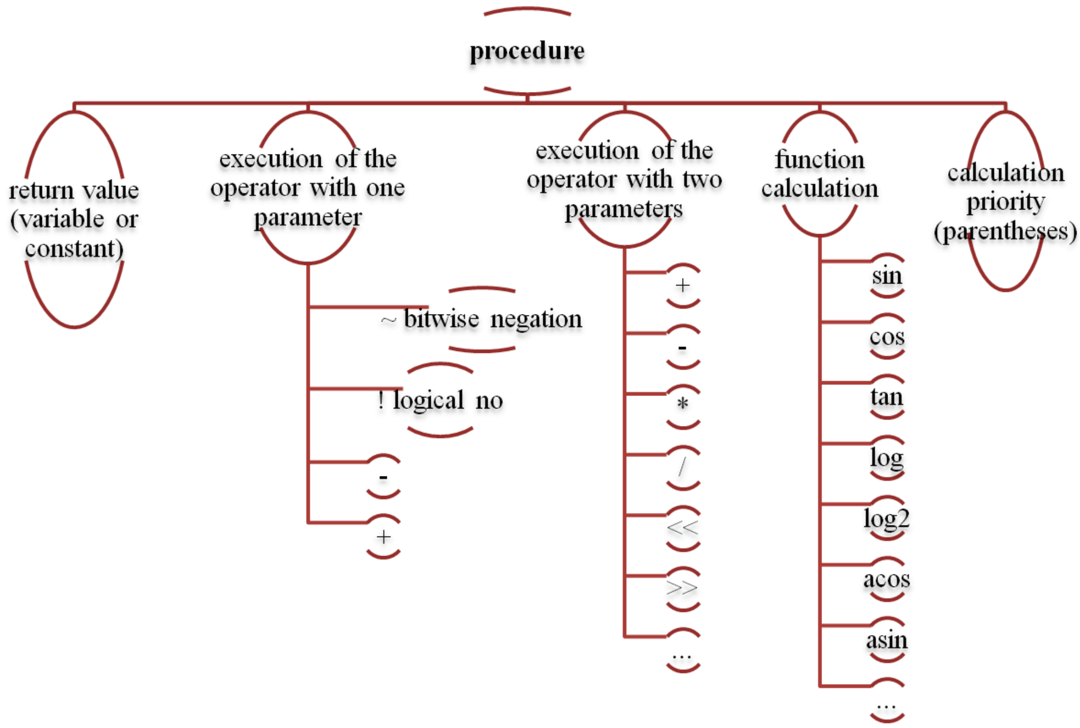


Figure 3. Implementation of the operation interface.

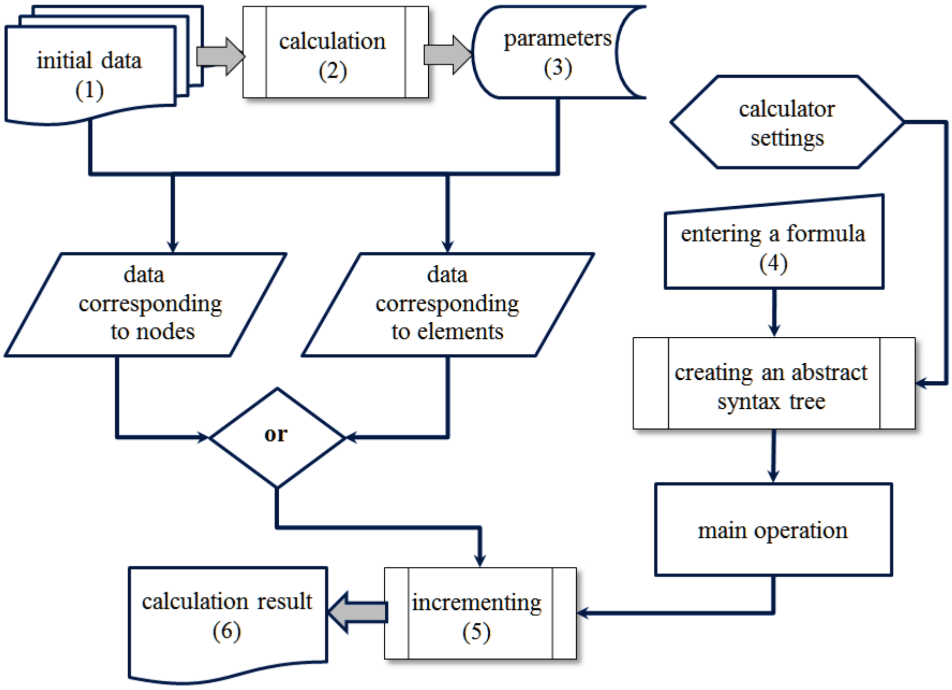


Figure 4. Implementation of the method for calculating the integral parameter with obtaining the initial data vector: 1 – initial data: scheme, physical and mechanical properties of rocks, forces; 2 – calculation of the stress-strain state; 3 – basic parameters of the stress-strain state of rocks; 4 – input of the integral parameter formula (string); 5 – incrementing integral parameters by elements or nodes of the design scheme; 6 – initial data: scheme, properties, forces.

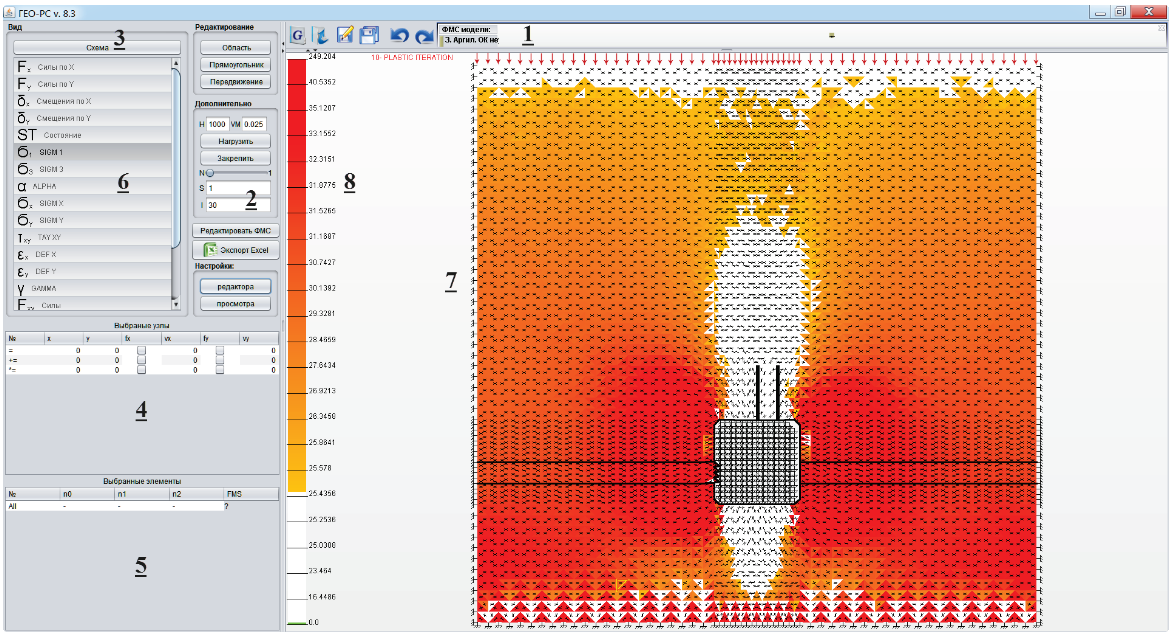


Figure 5. Multi-window main program interface: 1 – program menu; 2 – quick access control panel for data files and the editor of physical and mechanical properties; 3 – control panel of the results of calculations; 4, 5 – the main and duplicate panels of adjustment of settlement schemes; 6 – control panel display and integral parameters of the model stress-strain state; 7 – output window; 8 – differentiated color panel.

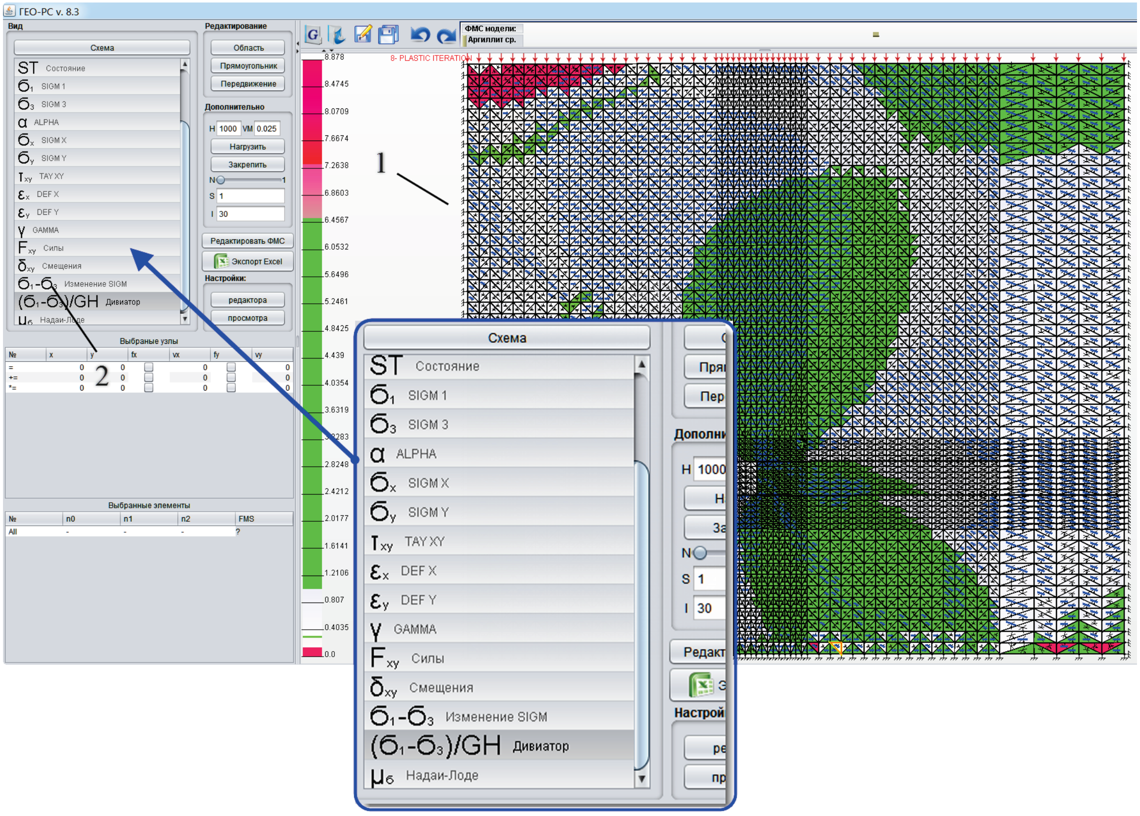


Figure 6. Interface for managing the integrated indicators of the ultimate stressed rocks stress-strain state in the geo-information system GEO-RS (v. 8.3): 1 – the main interface for analyzing the results of the calculation; 2 – control panel of basic and integrated parameters of the rocks stress-strain state.

The modules of the program allow: to form design schemes of a rock massif on the basis of triangular elements, taking into account its structure and configuration of mine workings; enter the strength and deformation characteristics of rocks layer by layer and for each element separately; download, adjust and preview the prepared design models. The preprocessor implements algorithms for calculating sixteen types of automatic discretization of the model, assigning distributed forces and displacements, coordinates of nodes, angles of incidence of rock layers.

Integral informative parameters calculated to assess the stress-strain state of ultimate stressed rocks: total displacement of nodes, deviator part of the stress tensor, orientation of planes of shear forces, areas of inelastic deformation and discontinuity of zones, concentration and intensity of change in time of principal stresses, orientation of principal stresses and deformations, the Nadai-Lode factor, etc. (see figure 6). The postprocessor implements technologies for processing, analyzing and visualizing large amounts of data, which makes it possible to differentiate the ranges of values of the calculated parameters automatically or at the choice of the researcher.

To forecast rocks and gas sudden outbursts, the most promising is the combination of the method for calculating the integral parameters of the stress-strain state of ultimate stressed rocks with mine control methods. The control of physical processes parameters in mines are often presented in graphical form, for example, in cases when oscilloscope data, from photographic carriers, recorders, ultrasonic recording devices, etc. are used to record signals. The most effective way to enter this information into a computer for further processing is scanning.

A method, an algorithm and a program for automatic conversion of graphic formats files have been developed and tested, which transforms the raster representation of signals and functional dependencies into data files of a text format. This data contains one-dimensional vectors of instantaneous signal values or table values of functions. The program complies with the international standard "Worldwide Standard for Technical Calculations" and allows you: to compensate for inaccuracies associated with insufficient resolution of the scanning device and possible scanning errors, to erase the center lines and lines of the scale grid according to the criteria of horizontal-verticality, continuity and relative length; save the results of all intermediate transformations; do a spectral analysis of the signal under investigation.

The transformation of an array of elements into a one-dimensional array of instantaneous signal values is carried out according to the formula

$$y_j = \frac{\sum_{i=0}^{n-1} \delta(x_{i,j},0)\cdot(n-i+1)}{\sum_{i=0}^{n-1} \delta(x_{i,j},0)}, \qquad (1)$$

where $\delta(a,b)$ – Kronecker symbol (1, if $a=b$, and 0; if $a \neq b$, a i b – integer expressions); $M(x_{i,j})$ – an array containing a black and white representation of the image; n – the number of rows of the array $M(x_{i,j})$.

If during transformation it is necessary to select image elements by color, then an arithmetic-logical expression is used

$$y_j = \frac{\sum_{i=0}^{n-1} (a_1 \le x_{i,j} < a_2)\cdot(n-i+1)}{\sum_{i=0}^{n-1} (a_1 \le x_{i,j} < a_2)}, \qquad (2)$$

where a_1, a_2 – the brightness limits of the pixel corresponding to the colors of the graph points.

The dynamic range is calculated by the formula

$$D = 20\lg\frac{A_{max}}{A_{min}} = 20\lg(N/2), \qquad (3)$$

where A_{min}, A_{max} – the minimum and maximum amplitudes of the signal; N – the number of the graph rows in the case of its full vertical scan.

The frequency range of the signal under study is determined by the resolution of the raster of the graph image along the abscissa axis. In any case, the dynamic and frequency ranges are limited by the corresponding parameters of the measuring path, with the help of which the signal graph was obtained.

The block for spectral analysis allows obtaining complex spectra, amplitudes and phases of harmonic components, calculating spectral density, sorting spectra vectors according to the growth of harmonic amplitudes. All results can be presented graphically and numerically.

4. Conclusions

Methods of implementation and functions of software elements for determining integral indicators, characterizing the state of the ultimate stressed rock massif have been developed. The subsystem for the analysis of integral indicators for assessing the stress-strain state of rocks is introduced into the new version of the geo-information system GEO-RS© (v. 8.3). Developed "Methodological recommendations on the peculiarities of the information system use for forecast integral indicators for assessing the hazardous states of ultimate stressed rocks", which contain elements of the method formalization for forecast the dangerous states of ultimate stressed rock massif, recommendations on the peculiarities of using software for determining integral parameters in groups of factors risks and complex indicators of the rock massif gas-dynamic readiness for a sudden release of rocks and gas.

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