# METHOD OF DIAGNOSTICS OF FILLING MATERIAL STRENGTH BASED ON TIME SERIES

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*Abstract. The method of forecasting of the filling concreting process according to the observational data of the stowing material's state indices is carried out at earlier time series. The method of predicting the hardening process is based on pattern recognition methods. An algorithm for the case when the training set contains sets of time series of several classes is proposed.*

Keywords: forecasting, process status, filling material, safety, time series

## METODA DIAGNOZOWANIA WYTRZYMAŁOŚCI MATERIAŁU WYPEŁNIAJĄCEGO Z WYKORZYSTANIEM SZEREGÓW CZASOWYCH

*Streszczenie. W pracy omówiono metodę prognozowania wypełnień w procesie betonowania, na podstawie danych obserwacyjnych stanu materiału sztauerskiego, w oparciu o zarejestrowane uprzednio szeregi czasowe. Zaproponowane rozwiązanie dotyczące procesu utwardzania bazuje na metodach rozpoznawania wzorców. Zaproponowano algorytm dla przypadku, gdy zestaw uczący zawiera zestawy szeregów czasowych dla kilku klas.*

Słowa kluczowe: prognozowanie stanu procesu, materiał wypełniający, bezpieczeństwo, szeregi czasowe

## Introduction

Application of intelligent information processing methods based on mathematical modelling is a new step in improving production efficiency by introduction of modern technologies, including digital transformation tools. As a rule, the creation of operations to solve specific problems without complete or partial formalization is carried out by experienced specialists mostly intuitively, and solving every new task requires all the work anew. The result is that very often a rather large part of the data remains unprocessed and unclaimed. This is a significant disadvantage of the current situation, which determines the main requirement for promising approaches to solving applied data processing tasks: the simplicity and reliability of complex procedures excluding intuitive work of specialists must be provided [3].

The paper touches upon the methodological problems of forecast risks in mining operations related to human security and ecology, and shows the advantages of using recognition algorithms based on the precedent approach. This helps to reduce losses, dilution of mined ores with safe mining, as well as to justify decisions in mining. Stressing the importance of traditional approaches, we note that using the proposed approach allows to obtain a more accurate and objective result, to operate with structured data sets, to optimize production costs, to calculate mining efficiency with a minimum environmental impact and increased safety of people.

In mining stowing is defined as filling the goaf with stowing material, which is formed in the entrails of the earth as a result of mineral extraction. Stowing materials can be crushed rock formation, and production wastes. Stowing is solid if all the goaf is filled, and partial when certain parts (as tapes or layers) of it are filled. Depending on the way of transportation and stowage hydraulic, pneumatic, hydro-pneumatic, mechanical, self-flowing and manual are distinguished.

The use of stowing on mining enterprises caused by the process safety of the performance of mining operations, preservation of buildings on the surface of the earth, safety and the environment control, etc. For this purpose, goaf is filled with stowing material, which is after reaching a certain state of the material should serve as supporting pillars.

The goals of the use of stowing material depend on the purpose. Stowing is used to control rock pressure, to reduce losses and dilution of extracted minerals in mining, to prevent mine fires, to reduce surface deformations of the earth and to protect the objects on the earth surface from damage, to improve the safety of mining operations, for improving the ventilation of underground workings, to reduce transport costs.

## 1. Formalization of the stages of the filling hardening process

Requirements for filling properties can be different and depend on its purpose. Thus, the requirements for filling used to prevent subsidence of the earth surface and thus the protection of buildings and structures is much higher and it is especially important to forecast its states of stowing, than in cases when for example, stowing serves as the filler of voids and prevention of ore dilution and loss.

Depending on the purpose and field development systems dry, hydraulic, hardening and other stowing are used. It is reasonable that properties and methods of their creation are different.

At hardening stowing binder component is added, that significantly increases the cost of stowing due to the high cost of binding material. This type of stowing greatly exceeds the cost of others and is used in strictly defined cases and only under condition of full recoupment of materials and works on the stowing.

There is a problem of definition of readiness of the state of hardening filling to perform intended functions [1].

Since the end of the 50s different methods of modelling have been used to solve the problem of forecasting technological processes states. According to these methods, complicated process is divided into physically different components, they are studied separately, and then their interference is determined by mathematical methods using computers.

This is because the direct field experiment is often too long, expensive, dangerous, and impossible, in most cases, for reproducing in the lab all the features of the real process, accompanied by processes of mass and heat transfer.

It is well-known that investigation of any process consists of sequential stages [2]:

- statement of purpose and problem;
- study all the information about the process;
- construction of physical and chemical structure of the process model;
- preliminary construction of a mathematical model;
- solving problems on optimal operating conditions of the process;
- carrying out computational experiments under different conditions;
- planning and implementation of natural laboratory experiment;
- comparison of the results of natural and computational experiments.

Naturally, a number of stages may be missing or combined into one. As a result of these stages a model of the process, ready for industrial implementation is created. Therefore the development of process models becomes more actual. The models with the optimal design have particularly great importance, when it is required to estimate the optimal parameters of the behaviour of processes under different conditions.

In this case, the mathematical model has to satisfy a number of important requirements of adequacy, sufficient simplicity, stability relative to errors in the original data, simplicity, productivity, clarity, cost of obtaining initial data and a number of other conditions [2].

During the creation of hardening filling, which consists of filling and forming with the artificial array, due to shrinkage of stowing materials, it is difficult to conduct field studies under industrial conditions on a wide range of indicators characterizing its condition.

To assess the state of filling it is possible to investigate its individual elements, drilling, for example, stowing to obtain core samples at certain points in time (week, month, etc.) and, by examining their characteristics, make prediction of the entire filling's state.

Another way of predicting the state of filling can be physical modelling with equivalent materials. In this case, the object of the study can be examined by mechanical, ultrasound, electrical and other methods. Assessment of change in strength of ultrasound, electrical and thermal parameters of stowing with the lapse of time generally constitute forecast picture of filling.

Attempts to solve the problem on the basis of similarity of macro kinetics theory and physical modelling were incomplete due to incompatibility of similarity conditions of chemical and physical components of the process. To solve the problems of macro kinetics, objective laws of proper chemical transformation should be known, which are not distorted by the influence of transport processes, and laws of mass- and heat transfer. Laws of chemical conversion are expressed in the form of kinetic equations reflecting the dependence of reaction rate on the composition of the reaction composite, temperature, pressure, catalyst properties (for catalytic processes), and others.

So the main methods which allow to control the state of filling are: radiometric control, ultrasonic method, local destruction methods, impact methods, acoustic method, material temperature measurement method, etc.

The disadvantages of radiometric methods include the need to work with radioactive materials, the presence of residual induced radioactivity. The accuracy of strength measurement by the ultrasonic method can be influenced by the type of cement, the hardening conditions, the age of the structure, the humidity and the surface temperature, and the type of surface, which, in general, can be considered the disadvantages of this method.

The disadvantages of using local destruction methods, impact, and measuring the temperature of a material are the determination of characteristics only at local points of the construction.

The core element of the abovementioned methods is that they require creating individual gradation dependencies based on the results of studies of standard sample cubes made of concrete of the same composition and age as the object under study, the structure, in our case, filling. This directly measures some indirect physical characteristic related to the strength by correlation dependence. To establish this dependence, and, accordingly, to establish the strength of the structure, it is firstly necessary to establish a grading characteristic between strength and some indirect characteristic – temperature, humidity, conductivity, etc.

In order to do this, the dependence of the strength P of the filling on its indirect characteristic, which varies over time, is derived – based on the least squares method, the dependence of the selected characteristic (temperature, humidity, acoustic parameter, electrical conductivity, etc.) on time t is constructed with the appropriate dispersion calculation, correlation coefficient, coefficient of determination, etc.

The values (characteristics) at the moment of time t, are taken as the parameters of the dynamic state of the filling at the moment of time $t$.

It should be noted that each characteristic separately determines the state of the filling not completely, but only one side of it, and cannot be an overall assessment of the dynamic state of the process.

Thus, the object of study has a set of the object characteristics, varying in time $t$.

Based on the above propositions, it can be stated that the determination of the state of the filling is an important and urgent problem, therefore there is a need to develop new ways and methods for determining the states of the technological process.

In all cases, forecasting assessment of filling seems necessary to measure at different time points $T = \{t_1, ..., t_T\}$ filling parameters characterizing the static state and the dynamics [1].

## 2. The formal model of the filling hardening process

The state of the stowing material will be understood as a set of values of the physical properties of the material at the moment $t$. These properties are mechanical, thermal, ultrasonic, electrical and other parameters of stowing material, measured at the moment $t$.

Let at the input of the suggested assessment of the state of filling the values of input parameters $X$ are fixed and the output takes the values of output parameters $Y$.

By an object model, we mean some operator $F(x)$ ($\hat{y} = F(x)$), which establishes a correlation between input and output variables, which allows, with a certain accuracy, to restore the output variables of an object using its input variables.

It is necessary to build a mapping of the $X \longrightarrow Y$ so that correct output signal $Y$. Would be formed to each possible input signal of the $X$.

The use of traditional methods of predicting the state of stowing by one feature has low reliability due to the complexity of the research object, which significantly reduces its scope in practice. In practice, the most common models are continuous regression ones, constructed for the entire set of objects. Their use is based on assumptions about the high-quality homogeneity of the considered set of raw data on the objects of research, the lack of breaks and jumps in a priori unknown dependence.

The idea of the proposed method for forecasting the state of the stowing is the partitioning of the feature space, characterizing the state of stowing material at certain times, to classes of close objects in the feature space, for each class in these times its own prediction function is built. Construction of particular models on selected areas brings together particular forecasting models into an integrated model of predicting the state of stowing. In other words, an attempt to take into account the structural heterogeneity of the original data on the state of the object of study in time is engaged, i.e. approximate real dependence of status of stowing on the physical parameters of the array of piecewise linear function with respect to time $t$ [4].

The practice of statistical modelling has shown that continuous regression models (linear and nonlinear), constructed for the entire sample of objects are the most commonly used. Their use is equivalent to the assumption of the qualitative homogeneity of the considered set of objects, the absence of discontinuities and jumps in the simulated dependency. Working with linear models imposes even more strict requirements on the original set – a multidimensional distribution of features describing an object must be close to normal. In this case, it is assumed that the character of the dependency and the model parameters are stable in all subdomains of feature space.

At the same time, in practice, these conditions, as a rule, are not observed, which makes it impossible to use continuous regression models as an operator $F(x)$. For example, spatial clusters of trajectories for the development of dynamic objects of one task are, as a rule, heterogeneous and have a certain structure. The latter means that the total set of object development trajectories is divided into a *number* of subsets with a specific character of the dependence of indicators on input variables.

Quite approximation methods are rather effective for approximating a function. The main idea of these methods is to divide the sample space into areas, each of which has its own function. However, it is possible to note a number of little-studied questions connected with the division of the sample space into areas in which individual functions are built. The construction of particular models of selected areas also, in our opinion, does not completely solve the problem of identification.

Thus, the use of traditional methods for predicting the state of the filling shows low reliability due to ignoring the complexity of the object of study, which significantly narrows the scope of their use in practice.

We propose a procedure, as a result of which the obtained private models are combined into a single statistical model of the object (process).

The idea of the proposed method for predicting the state of the filling is to take into account the data structure, namely, the division of the space of features that characterize the state of the filling material at certain points in time into classes of similar objects in the feature space, each class has its own forecast function in these points in time. Building private models on selected areas makes it possible to combine partial forecast models into a single model for forecasting the state of the filling.

In other words, an attempt is made to take into account the structural inhomogeneity of the initial data on the states of the object of study in time, i.e. to approximate the real dependence of the state of the filling on the physical parameters of the stowing material with a function taking into account the time $t$ and its belonging to the class.

We present a regular formulation of the problem using the approach and symbols from the papers of Zhuravlev [4].

The set of trajectories of the hardening process, which are complex and time-developing systems of the same type, whose states are described in the attribute space, are considered.

There is a process of development of each object $S_v$, $v = 1, 2, ..., M$, on the interval $[t_0, t_T]$. The observation is carried out at discrete points of time interval $[t_0, t_T]$..

At every moment in time $t_k$. $k = 0, 1, ...,T$, any object from $\tilde{S}$ can be in one of its states, described using a set of $h(t_k)$ signs $x_1, x_2,..., x_h$.

The state of the object $S_V$ at time $t_k$ is described by the following vector

$$\overline{a}_v(t_k) = (\overline{a}_{v1}(t_k),...,\overline{a}_{vn}(t_k))$$
$$v = 1,..., M; \quad k = 0,1,..., T$$

Each of the signs $x_i$ takes values from a set $M_i, i = 1,..., h$ whose power depends on the time $t_k$. $K = 0, 1, ..., T$. We consider $M_i i = 1,..., n$ it to be a metric or semi metric space in which the triangle axiom does not hold.

States of dynamic objects $\tilde{S}$ at an arbitrary moment a time $t_k$.. are representatives of sometime-dependent sets $K_1,..., K_l$, hereinafter referred to as classes. We assume that $K_i \cap K_j = \varnothing, i \neq j, \quad i, j = 1,..., l \cdot$

We select a subset $\tilde{S}_0 = \{S_1,..., S_m\}$ of objects $\tilde{S}$ as a training set.

**The main task.** Let a trajectory S be given which belongs to one of the given trajectory classes $K_j, j = 1,2,..., l$ and be observed on the time interval. It is required to determine, by recognition procedures, that the trajectory *S* belongs to one of the specified trajectory classes.

The belonging of the trajectory *S* to one of the specified classes of trajectories is estimated by the measure of the correspondence of the trajectory *S* to the classes of the training set classes and is a function for determining the degree of readiness of the filling for operation.

A method that uses pattern recognition techniques can improve the accuracy of forecasts and get a model that more accurately expresses the predicted trajectory of changes in stowing material for a set of features of its state.

## 3. Conclusions

The problems of the complex use of pattern recognition methods, correlation and regression analysis, the theory of controlled random processes, the theory of optimization and others in constructing and solving mathematical models for predicting the technological process are considered. The considered approach makes it possible to impart to the statistical models the features of optimisability, controllability, and also to increase their adequacy to the chemical and technological processes under study.

Methods of pattern recognition and correlative-regressive analysis serve as a tool for studying statistical relationships and searching for empirical patterns. These methods are the main instrument for building statistical models of indicators. However, several conditions must be met in order for this analysis to find an adequate description of the studied phenomenon. Many of these conditions are unsatisfiable in reality, which significantly limited the scope of application for technical and statistical models. Exigent regression analysis requirements should include the "homogeneity" of the studied population, the possibility of describing the modelled dependency by a continuous function, restrictions imposed on the form of communication and inability to use discrete factors. At the same time, methods of pattern recognition do not impose the requirement of total homogeneity – they are designed to identify and describe structural patterns, and the development of homogeneous classes of objects. Discrete description character removes the limitations associated with the form of communication. At the same time, recognition procedures are often heuristic by nature; and the usage of discrete models for recognition is associated with an averaging and certain loss of information, in comparison with continuous regression models. Combined usage of both methods allows us to expand the scope of their application: pattern recognition ensures the conditions for adequate application or regression analysis.

The analysis of emerging problems of determining the readiness of the filling material is given. The disadvantages of traditional methods for determining the operational readiness of the stowing material are given.

A regular formulation of the problems of forecasting the state of the stowing material, used in mining, is proposed.

A methodology for determining the state of stowing material, which uses recognition methods based on the calculation of estimates, making it possible to identify the operational readiness of the filling has been developed.

The application of the developed methodology to solving specific problems allows to investigate in detail the state of the stowing material as it hardens, to establish the moment of operational readiness based on the application of recognition algorithms.

In other words, a technique using pattern recognition methods allows to increase the reliability of trajectory determination and to obtain a model that more accurately expresses the predicted trajectory of change of filling material according to a set of signs of its state on time interval.

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