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Simulation of Rock Mass Stress-Strain Behavior Using the Method of Equivalent Materials During Ore Deposit Open-Pit Mining

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Abstract: This study contains the results of simulation the slopes deformation process with equivalent materials. It provides basic areas of mass deformation and fracture, identifies empirical dependence of the deformation value on the pit depth and these results are compared to earlier obtained results of the numerical simulation. The objective of this simulation is improving the accuracy of the information about deformation processes by ensuring rock mass fall parameters management. The concept of this method is described below. Rock in the open-pit side is modeled from synthetic materials which are choosing in such a way that physical and mechanical properties of these materials would in a certain way, correlate to the physical and mechanical constants of simulated rock. The obtained information about rock mass stress-strain behavior will provide a possibility to predict the state of rock mass slope and reduce the risk of technogenic accidents occurrence.

Key words: Simulation, method of equivalent materials, stress-strain behavior, rock mass, continuous medium, deformation, stability factor, pit depth

INTRODUCTION

Simulation is currently one of the most popular experimental methods. It allows studying the object of research within a wide range of preset parameters and properties. In the course of studying the large objects that are commonly encountered when investigating the geotechnical situation, simulation helps to minimize costs and obtain optimal solutions (Argimbaev and Kholodjakov, 2015; Argimbaev *et al*., 2015).

In the situation under consideration, it is advisable to carry out research using models by means of scientific object geometric dimensions reduction by several times (Eshiett and Udosen, 2009).

The method of equivalent materials allows to study the mechanism of development of various geological and geotechnical processes visually (Argimbaev *et al*., 2015). The method demonstrates the maximum efficiency in the course of detailed geotechnical investigations when representative data on the structure, properties and state of the object are available. The method is promising for the creation of geological bodies' 3D models (Argimbaev and Kholodnyakov, 2014).

The photoelastic method (or the methods of stress optical measurement) was developed in the late 19th century. However, it became popular over the past 20 year in studying rock mass stress state (Behim *et al*., 2007).

The method is based on the ability of some transparent materials to decompose polarized light into components which direction coincides with the direction of the principal normal stresses; the rate of light transmission is proportional to the stress values. If values of principal stresses differ from each other, the path-length difference of polarized beams is proportional to the difference and to the thickness of the object under consideration. When a loaded model made from photoelastic materials is illuminated with white light, a picture consisting of colored bands is displayed on the screen (Argimbaev and Yakubovskiy, 2014; Eyo and Abasiekwere, 2009).

A number of factors affect the stress-strain behavior of mass near-edge zone. They are as follows: geological and hydro geological structure of the deposit and pit wall parameters-depth, pit slope angle (Argimbaev and Yakubovskiy, 2014). Rock mass is a very complex medium in which deformation processes of different nature occur simultaneously during mining (Kholodjakov and Argimbaev, 2014). It is very difficult to track the slope deformation process due to the fact that field observations are characterized by considerable labor intensity, high cost and require a lot of time. However, it becomes possible to study geomechanical processes by means of simulation. No other methods, either analytical methods or observations or measurements in natural conditions, can provide such opportunities (Argimbaev and Kholodjakov, 2013; Balaji *et al*., 2013). The object of the deformation processes study is a homogenous slope from equivalent materials and stage-by-stage model simulation.

MATERIALS AND METHODS

The deformations measurements of a model from equivalent materials were carried out using, primarily, sensors of different designs embedded into the model. Dynamometers are quite simple and reliable. Electrical resistance transducers are rigidly pasted on elastic elements in them. In the course of the experiment their resistances proportional to the deformation values were measured at specific time intervals using a bridge circuit. The obtained strain values included some inaccuracy as the rigidness of the sensors was different from the rigidness of the model material. Therefore, we used non-intrusive methods of deformation measurement by optomechanical instruments. We also monitored movement of datum points located on the surface of the model. Datum point displacement was recorded by photographing the model by ground photogrammetric cameras and dial indicators. In addition, mechanical properties of the mixture used to simulate slopes were investigated in detail.

RESULTS AND DISCUSSION

Studying of the slopes deformation process by the method of equivalent materials was carried out at the Mining University under supervision of G.A. Holodnyakov on a flat stand 250×50×150 cm. Model simulation and slope formation were carried out at the rate of sinking corresponding to a decrease in the design coefficient of stability margin by 0.1 (Table 1). The slope was maintained till the end of deformations stabilization in each new position.

The mixture of composed of white sand (37% of the total volume), cast iron shot (60%) and spindle oil (3%). Physical and mechanical characteristics of the mixture for simulation: the angle of internal friction $\varphi = 30°$, density $\rho = 3340$ kg m^{-3}, adhesion C = 585 Pa, deformation modulus $E = 2.10^6$ Pa and poisson's ratio $\nu = 0.3$.

Simulation by the method of equivalent materials is based on replacement of natural rocks by such artificial materials in the model which physical and mechanical properties are in certain relationships with the same properties of natural rocks (June and Khalaf, 2009; Argimbaev and Kholodjakov, 2016; Pikalov *et al*., 2016).

These relationships are determined based on the general provisions of the theory of mechanical similarity and ensure achievement of a close analogy in the course of geomechanical processes occurring in nature and in the model under the influence of gravitational forces (Sarma, 1979). The model from equivalent materials was built by

Table 1: Design coefficients of stability margin for each stage of model simulation

Slope height (cm)	Slope angle (degrees)	Design coefficient of stability margin
21.5	45	1.50
30.5	45	1.30
39.0	45	1.20
44.5	45	1.15
47.5	45	1.13
52.0	45	1.08
57.5	45	1.02

analogy with the homogeneous near-edge zone rock mass. A grain in the model corresponded to a life-size average rock block. The dimension scale of the model is 500 and the dimensions of a life-size pit wall are as follows: pit depth H = 287.5 m, pit slope angle $\alpha = 45°$. Physical and mechanical properties of life-size rocks are determined according to the following equation:

$$C^M = \alpha_l^{-1}\alpha_\gamma^{-1}C^H; tg\phi^M = tg\phi^H; \quad E^M = \alpha_l^{-1}\alpha_\gamma^{-1}E^H \tag{1}$$

Where:

α_l = Dimension scale of the model ($\alpha = 500$)
γ_γ = Ratio of life-size rock bulk density to the bulk density of material in the model (α_γ)
E^M = Modulus of material elasticity in the model
E^H = Modulus of elasticity of actual material
C^M = Material adhesion in the model
C^H = Actual material adhesion
φ^M = Angle of internal friction of material in the model
φ^H = Angle of internal friction of actual material.

So, the physical and mechanical properties of actual rock are as follows: angle of internal friction $\varphi = 30°$, density $\rho = 3340$ kg m^{-3}, adhesion, C = 585 Pa, modulus of deformation $E = 2.10^6$ Pa and Poisson's ratio $\nu = 0.3$. In Fig. 1-3 present the results of research.

The results of the studies of slope deformation carried out on models (Fig. 1-3) are as follows: as far as the height of the slope increases, deformations increasing in dimensions spread across the surface of the slope top and from the surface of the slope deeper into the mass and after a certain moment (when the height of the slope corresponds to the stability coefficient equal to 1.10) as far as the stability coefficient decreases, the maximum values of relative deformations (shifts and horizontal deformations) in the upper part of the slope are accumulated at a certain constant distance from the edge of the slope and they move to the slope surface in the bottom part.

Analysis of the data presented in Fig. 3 shows that the maximum relative deformations in a homogenous pit slope are associated to the central part of the near-slope

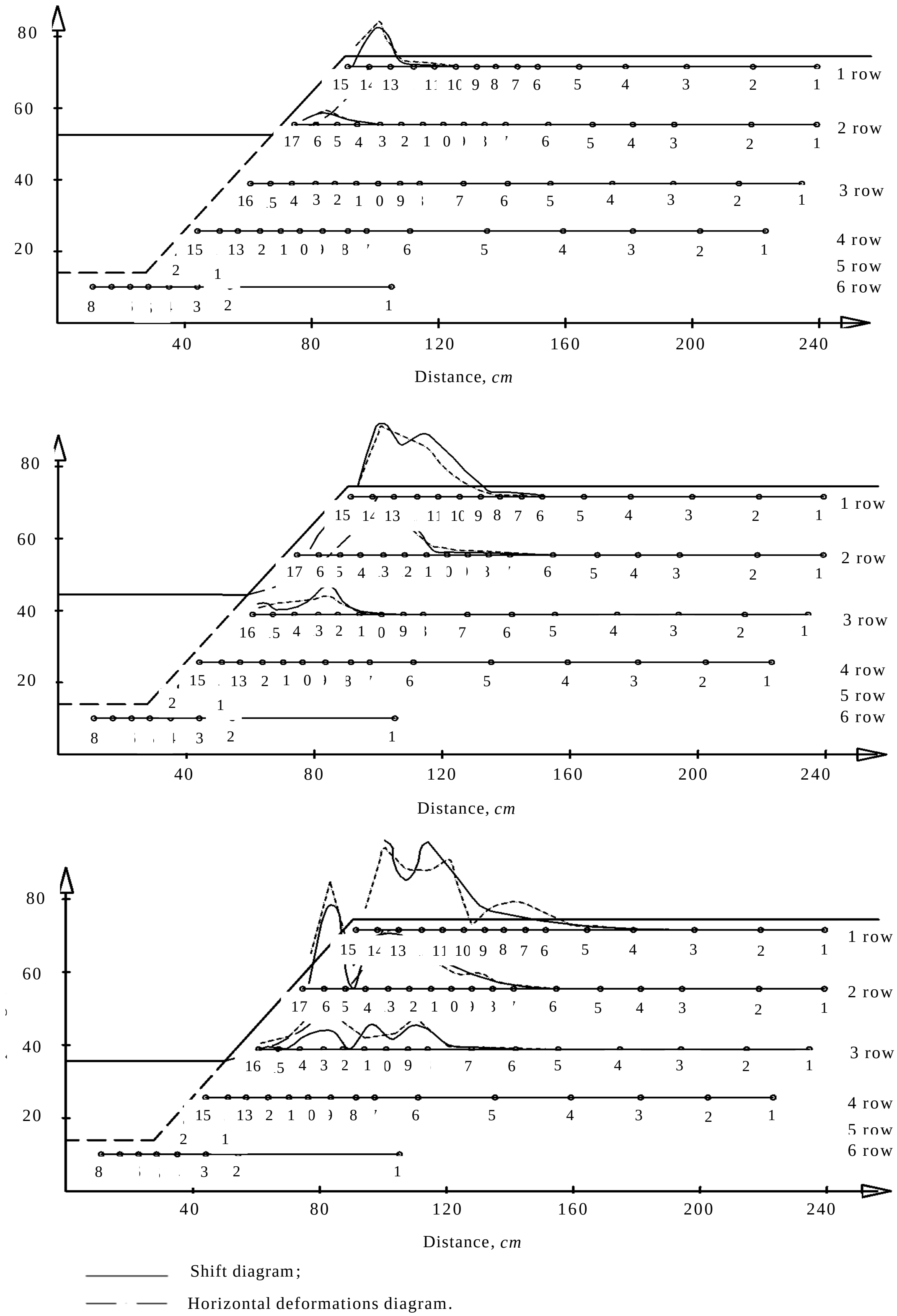

Fig. 1: Development of deformations across a homogenous medium slope in the course of stage-by-stage model simulation

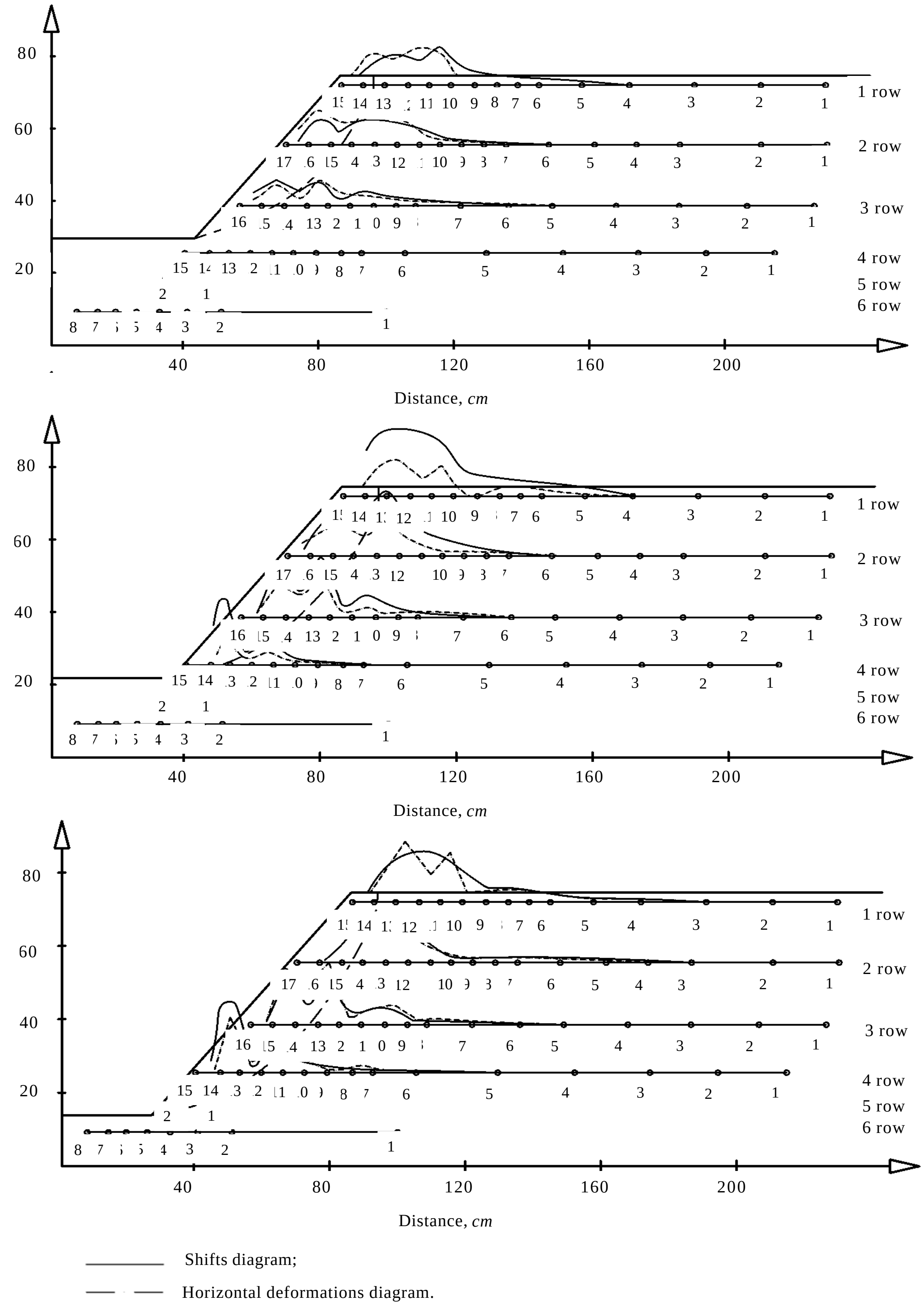

Fig. 2: Development of deformations across a homogenous medium slope in the course of stage-by-stage model simulation

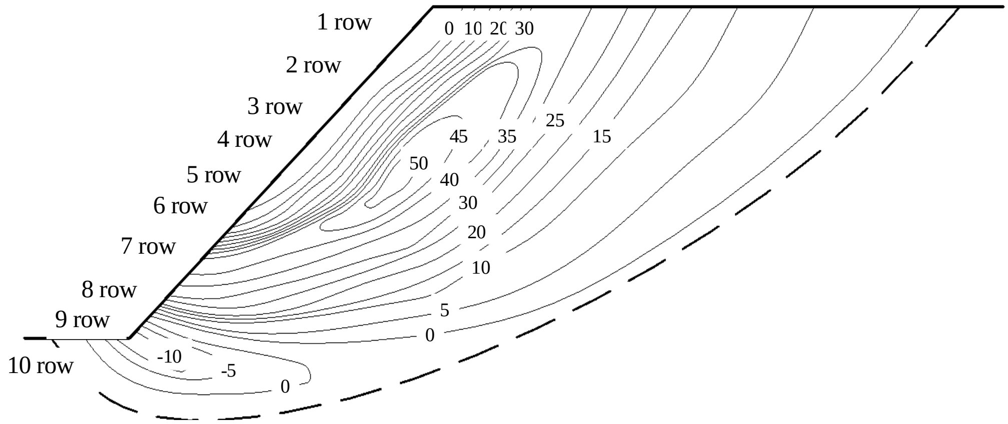

Fig. 3: Isolines of ultimate horizontal deformations of the slope model (deformation dimensions mm/m)

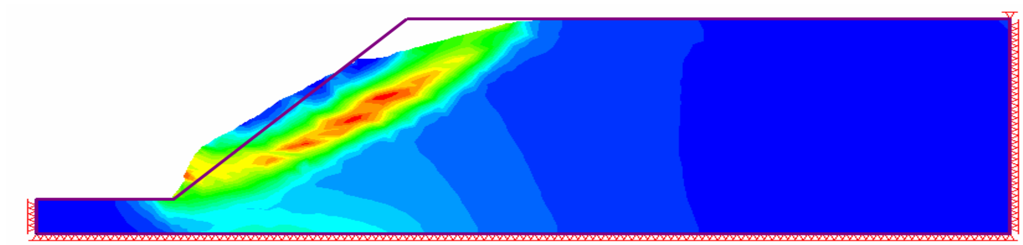

Fig. 4: Falling of a homogenous slope model

Table 2: Results of modeling by equivalent materials and the method of finite elements

Stages	Type of modeling	Design coefficient of stability margin	Maximum values of horizontal deformations across the surface of the model wall (mm/m)	Distance from the upper edge of pit slope to the maximum value of horizontal deformations across the surface (m)
1	By equivalent materials	1.50	0.0017	0.12
	Numerical	1.50	0.0017	0.23
2	By equivalent materials	1.30	0.0027	0.12
	Numerical	1.25	0.0021	0.15
3	By equivalent materials	1.20	0.0032	0.12
	Numerical	1.19	0.0021	0.15
4	By equivalent materials	1.15	0.0062	0.30
	Numerical	1.19	0.0032	0.22
5	By equivalent materials	1.13	0.0070	-
	Numerical	1.13	0.0034	0.19
6	By equivalent materials	1.08	0.0136	0.17
	Numerical	1.08	0.0025	0.20
7	By equivalent materials	1.02	0.0150	0.17
	Numerical	1.02	0.0100	0.24

zone across the line of an expectable sliding surface. So, by the example of simulation by equivalent materials it is possible to determine the qualitative picture of deformations development in a pit slope, identify the process of deformations development in the course of step-by-step pit simulation. Meanwhile, this method of evaluation of stress-strain behavior of the near-slope zone of rock mass is extremely labor intensive and requires a lot of time. The falling process was reproduced by means of computer simulation. It is shown in Fig. 4.

To provide a fuller picture of the formation process of a homogenous near-edge zone stress-strain model mass behavior in the course of stage-by-stage pit simulation, a comparison of horizontal deformations obtained by methods of equivalent materials and numerical modeling was carried out (Table 2). The results of numerical modeling were taken from the studies carried out earlier.

CONCLUSION

According to results of research conducted by the Mining University on models from equivalent materials and the results of numerical modeling based on the finite elements method, it was found that the sliding surface in a homogeneous near-edge zone mass does not overlap the bottom of the slope. On the contrary, the sliding surface along the slope line is located at a height of 0.2 H, where H is the height of the slope.

So, the results of a homogenous slope simulation by equivalent materials and numerical modeling based on the finite elements method in general, make it possible to trace the slope deformation process up to the limit state. Use of revealed patterns will allow avoiding formation of landslides in pits by preventing mass destruction. The results of simulation by equivalent materials and the results of numerical modeling are comparable. This leads to a conclusion that the software used for simulation can be successfully used for the evaluation of the stress-strain behavior of pit walls in natural conditions.

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