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COMPUTER SIMULATION USAGE FOR VERIFICATION OF DEEPENED SHAFT ARTIFICIAL BOTTOM CONSTRUCTION

WYKORZYSTANIE SYMULACJI KOMPUTEROWEJ DO WERYFIKACJI KONSTRUKCJI SZTUCZNEGO DNA DLA POGŁĘBIANEGO SZYBU

The paper presents the design verification methodology for so called artificial bottom of the mining shaft using computer simulation. Artificial bottom serves as the protection of the lower part of the shaft, in which works related to shaft deepening are carried out, against falling to the bottom of the shaft elements transported in its upper, active part. Model describing the phenomenon of artificial bottom stress is complex. In presented case it is a process of collision between object with a mass of 18 Mg model, falling into the shaft from a height of 800 m, and artificial bottom construction and inducted phenomenon of stress and strain wave propagation in various elements of construction. In this case load receiving elements are heavily deformed and many of them has to be destroyed. Therefore for construction verification computer simulation method has been chosen, conducted on the basis of subsequent crash tests, using the LS-DYNA program. The object of the research was an innovative solution of artificial bottom, developed by Central Mining Institute. A series of falling mass impact tests were performed, which had to prove the usefulness of applied solutions, as well as determine the influence of selected construction geometric parameters to effectiveness of transferring the impact load. This way, using the successive approximations method, the assumptions about the number of artificial bottom platforms and plate thickness used for additional coverage of one of the platforms were verified.

Keywords: finite element method, shaft artificial bottom, string characteristics identification, destruction simulation

W artykule przedstawiono metodykę weryfikacji konstrukcji tzw. sztucznego dna szybu z wykorzystaniem symulacji komputerowej. Sztuczne dno szybu spełnia funkcję zabezpieczenia dolnej części szybu, w której prowadzone są roboty związane z pogłębianiem, przed spadaniem na dno szybu elementów transportowanych w jego górnej czynnej części. Model opisujący zjawisko obciążenia sztucznego dna jest złożony. W analizowanym przypadku jest to proces zderzenia modelu przedmiotu o masie 18 Mg, spadającego w głąb szybu z wysokości 800 m, z konstrukcją sztucznego dna i wywołanego tym zjawiska propagacji fali odkształceń i naprężeń w poszczególnych elementach konstrukcji. W takim przypadku elementy przejmujące obciążenie są silnie odkształcane, a wiele z nich musi ulec zniszczeniu. Dlatego dla

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weryfikacji konstrukcji wybrano metodę symulacji komputerowej, prowadzonej na zasadzie kolejnych testów zderzeniowych z wykorzystaniem programu LS DYNA. Przedmiotem badań było innowacyjne rozwiązanie sztucznego dna opracowane w Głównym Instytucie Górnictwa. Przeprowadzono szereg testów obciążenia upadającą masą, które miały wykazać przydatność zastosowanych rozwiązań, a także określić wpływ wybranych parametrów geometrycznych konstrukcji na skuteczność przenoszenia przez nią zadanych obciążeń. W ten sposób metodą kolejnych przybliżeń zweryfikowano wstępnie przyjęte założenia co do liczby pomostów sztucznego dna i grubości blachy służącej do dodatkowego pokrycia jednego z pomostów.

Słowa kluczowe: metoda elementów skończonych, sztuczne dno szybu, identyfikacja charakterystyk strun, symulacja zniszczenia

1. Introduction

The paper presents the design verification methodology for so called artificial bottom of the mining shaft using computer simulation. Artificial bottom is created in shaft deepening process in case when it is assumed that during the deepening works shaft will still be actively working and operate existing exploitation levels of the mine. Therefore it is very responsible construction, which task is to protect the lower part of the shaft, where the deepening work are being carried out, from falling on the bottom of the shaft elements transported in its upper, active part. Such accidents during transport works often occur and despite of usage of various types of technical and organizational protection this kind of risk should be taken into consideration during the planning of existing shaft deepening process. This risk include the possibility of falling into deepening works area an element with even 20 Mg of mass, from the height of 1000 m. To effectively protect the excavation in the bottom of the shaft the artificial bottom should dissipate the falling mass kinetic energy and hold it firmly on specified height until removing the threat of further slipping and falling of the object laying on the artificial bottom, which itself may or even should be seriously damaged. The design verification of artificial bottom should be based on the collision models of heavy mass rigid body moving with high velocity with artificial bottom construction, which collision causes large deformations, exceeding the linear range of stress-strain characteristics for materials used in construction and leads to partial destruction. Additionally it should be taken into account that heavy mass element with relatively small contact surface during impact with respect to artificial bottom area could collide not necessary centrally, but in various locations of the bottom, which fundamentally changes the construction load state.

Model which describes the phenomenon of artificial bottom load application is therefore so complex, that any attempts of its construction verification on the basis of currently used analytical computational methods are insufficient and significantly restrict the design process.

In this situation, a useful verification method is collision computer process simulation, which contains the collision of falling object model and artificial bottom construction, as well as generated stress and strain wave in each part of construction, which are highly deformable and many of them has to be destroyed.

In the article a possible way of artificial bottom construction verification, carried on a basis of subsequent crash tests using LS DYNA program was presented. The object of the research was an innovative solution of artificial bottom, developed by Central Mining Institute (Szot at al. 2011). A series of falling mass impact tests were performed, which had to prove the usefulness of applied solutions, as well as determine the influence of selected construction geometric parameters to effectiveness of transferring the impact load. This way, using the successive approximations method, the assumptions about the number of artificial bottom platforms and plate thickness used for additional coverage of one of the platforms were verified.

2. Description of artificial bottom construction as the subject of the research

On Fig. 1 the solution of artificial bottom construction for the mining shaft was presented. This solution was further investigated in computer simulation tests.

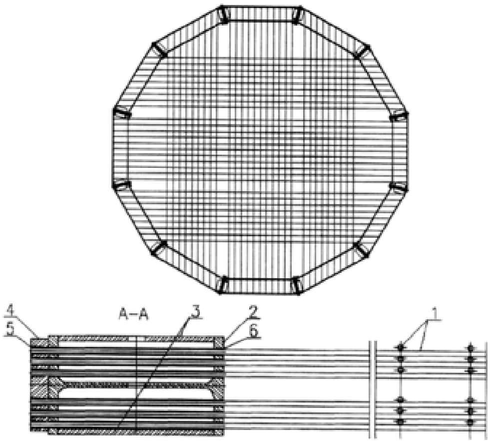

Fig. 1. Design solution of shaft artificial bottom

According to this solution, artificial bottom is a multilayered steel string membrane, composed of seven-wire steel strings 1 with increased strength. These strings are the essential energy suppressing elements; they are stretched in horizontal layers, crossing vertically with the next row of strings. The composition of twelve string layers is divided into two parts called the upper and lower deck. Supporting structure of shaft artificial bottom consists of HEB profile beams 2, which are connected by screws through metal plates, and then are placed in shaft housing. Connection between strings and supporting structure is realized with self-locking heads 5, suspended over each other according to the solution from MK4 Company. Strings are carried by the construction by guide bushings 6, which facilitates the correct placement of the strings; guide bushings are also protecting the strings from negative aspect of their bending on sharp edges of construction. Upper and lower plates 3 are designed to fit the construction into shaft housing. The main purpose of this assembly is to transfer load energy resulting from the collapse of the object with a mass of 18 Mg from a height of 800 m, wherein is possible to change a number of vertical layers, according to falling object mass variations and initial falling height. In design project an assumption was made that upper deck, as well as partially lower deck could be destroyed in such collision, however the falling object should stop on three bottom layers of lower deck, which layers shouldn't be destroyed. These assumptions were made on the basis of energy balance for falling object kinetic energy change into braking work of the supporting strings.

3. Methodology and models of falling object and artificial bottom used in simulation tests

Object of seemingly simple construction, which is string artificial bottom of mining shaft according to presented structure, is by no means simple when it comes to modeling the phenomenon of destruction in dynamic deformation an generation of complex string stress state process. Occurring phenomena are among the rapidly changing and nonlinear plastic deformations with cohesion loss as a result of exceeding the criterion value of deformation. It should be added that so far conducted attempts of describing the dynamic processes occurring in steel ropes were limited only to the cases of simple stretching. Moreover, the results of laboratory tests of dynamic loading of lines in axial direction confirms the difficulties of recognition unequivocal characteristics of this process nature and identification of its basic parameters (Wolny, 2006, 2009). According to this, the only method that could be reasonably used for study of string artificial bottom behavior subjected to impact loads is computer simulation.

One of the most important factor for this kind of tests is appropriate choice of application i.e. a computer program, because the phenomenon description models are quite complicated, and their numerical solution requires to use explicit integration method (abbreviated as *explicite method)*. Model also requires to assume some simplifications, due to the complexity of object components construction, such as wire strings their mounting methods; these simplifications are mainly the result of the number of components and their dimensions. The shaft diameter is in general not smaller than 7.5 m. Wire strings, as energy dissipative elements, are relatively long, so their discretization, which can be used in finite element method (FEM), requires the element division into sufficiently large number of smaller elements; moreover, then number of strings is quite substantial. Thus, because of the calculation time and analysis results effectivity line model had to be chosen as the rod with adequate stress and strain characteristics.

Specialized computer program which was used in this case is the LS-Dyna, a program developed by the American company Livermore Software Technology Corporation (LSTC) from Livermore, California. This program is based on finite element method and incudes the implementation of explicit integration of differential motion equations, which allows for the analysis of short-term dynamic effects such as explosions, crash tests with consideration of element deformation, in particular the highly non-linear cases, leading to the destruction of the material ("LS-DYNA Theoretical Manual ", 2007).

The calculation algorithm uses the discrete form of the equations of motion:

$$m \cdot \ddot{x}(t) + c \cdot \dot{x}(t) + k \cdot x(t) = F(t) \tag{1}$$

Using the central finite difference method with frog-leap algorithm and variable integration step size, the program allows to find the solution of equation (1) in form of displacement and velocity of each model node for the moment $t_{n+1} = t_n + \Delta t_{n+1}$.

After calculation of nodes forces, the nodes acceleration is obtained according to the formula (2):

$$\ddot{x}_i = \frac{F_i}{m_i} + b_i \tag{2}$$

where:

m_i — mass concentrated in nodal point,
F_i — force acting on the nodal point,
b_i — body acceleration component.

In the next steps the information about nodes velocity and displacement is updated according to the following equations:

$$\dot{x}_i^{n+1/2} = \dot{x}_i^{n-1/2} + \ddot{x}_i^n \Delta t^n \tag{3}$$

$$x_i^{n+1} = x_i^n + \dot{x}_i^{n+1/2} \Delta t^{n+1/2} \tag{4}$$

The general form of calculation procedure for solving dynamics issues with explicit finite element method is shown on following figure 2.

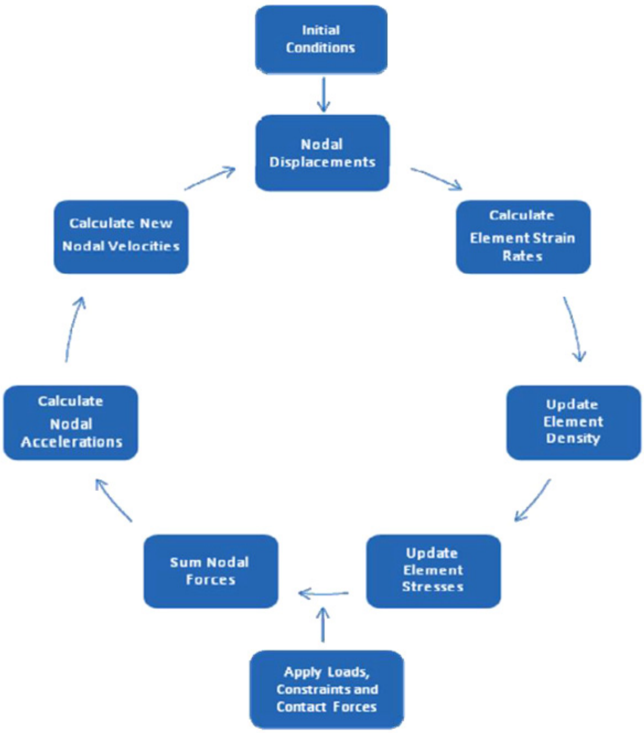

Fig. 2. Computation procedure scheme used in LS-DYNA computer program. (*Explicit Dynamics Theory Guide*, 2010)

The usefulness of the program for modeling dynamic phenomena is documented from its foundation, for which is considered the development of the program DYNA3D by Dr. John O. Hallquist in 1976, intended for modeling the explosions of nuclear bombs (*LS-DYNA Theoretical Manual*,

2007) until now, when the program is used in the automotive industry for modeling crash tests and in the aerospace industry for, among others, modeling collisions of birds with wings of airplanes. In military applications, package LS-DYNA was, inter alia, used by the United States Army for modeling threats for helicopters to improve machine survival chance on the battlefield (Friedmann 2006). It has been also used by NASA for computer simulations creation during the examination of the space shuttle "Columbia" crash (Gabrys et al., 2004). Simulation studies of road barriers made of ropes and wires, supported by experimental verification, have shown adequacy of this kind of virtual experiments in relation to the actual conditions. (Stolle & Reid, 2010).

The unquestionable references of the LS-Dyna program mentioned above, as well as its functional features such as possibility of CAD models import from wide range of CAD modelers, multitude of base element types, which constitute the basis for the development of more complex virtual models and effectivity of solvers computational algorithms the makes the program ideal for usage as a computer simulation verification tool of other types of structures, such as artificial bottom wells.

In this particular case, by introducing new construction elements and using the successive approximations method the number of artificial bottom platforms and thickness of plate for additional coverage of one of the platforms were verified (Gospodarczyk at al., 2012). Additionally, the usage of substitutive string models as beams implied to determine the characteristics of these elements in experimental tests as well as their adequacy verification by conducting the computer simulations of individual strings stand tests using Autodesk Simulation Mechanical.

On figure 3 was shown the single platform geometrical model of artificial bottom, consisted of string membrane and cover plate (Gospodarczyk & Stopka, 2012). The 18 Mg impact weight was assumed as cuboid with 2.5 × 1.5 m base dimensions. Analytical calculation of falling object velocity during the impact allowed to reduce the simulation time interval to 0.1 s. It was determined that the test should have been made for two impact locations, namely in the middle of the platform (the center of falling object mass lies in the axis of the shaft) and at the edge of the platform, which allows to determine the effect of the impact position for final construction structural damage.

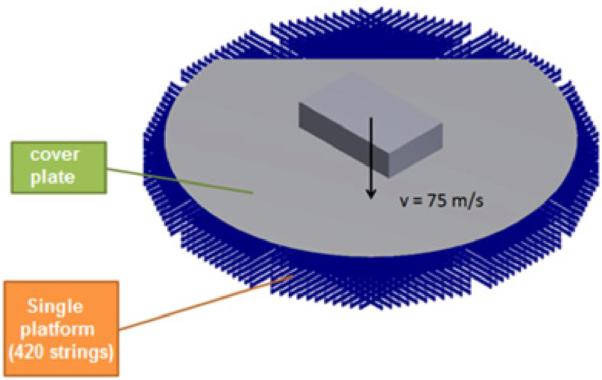

Fig. 3. Geometrical model of shaft artificial bottom with impact weight

The basis for determining the geometric and material model parameters of individual beams were the results of laboratory tests of static string stretching and attempts to destroy strings using transverse force. Figure 4 shows an example of the stress – strain characteristics of one of the strings subjected to the tests in the Central Mining Institute laboratory.

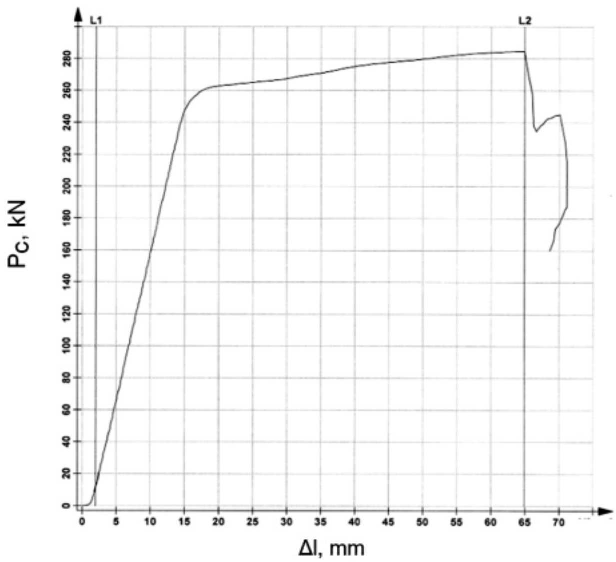

Fig. 4. Stress – strain characteristics for one of the tested strings

Empirical characteristics were the basis for establishing analogous characteristics of string model used in simulation tests. This model was being verified for subsequent approximations, which were based on static stretching process numerical simulations in Autodesk Simulation Multiphysics program. In case of the selection of appropriate string material destruction model, the results of dynamic string breaking tests were used. Similarly as for the static tests, a series of simulation tests were conducted to reproduce the physical experiment, providing as the result the requested string material destruction criteria (Fig. 5).

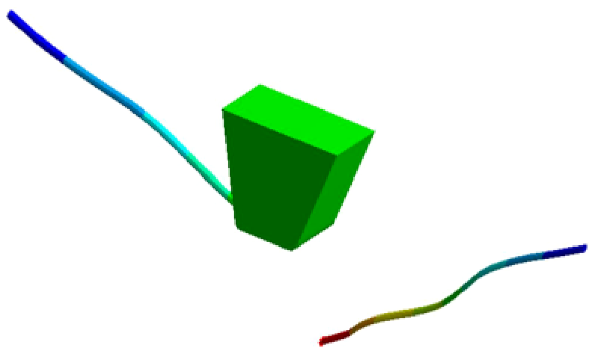

Fig. 5. Load impact test for 1 m long steel rope. Load mass m = 20 Mg, falling velocity v =1.24 m/s (t = 0.18 s)

4. Simulation tests course and results

Due to time consuming calculations of complete artificial bottom simulation, in first instance simplified trial tests were conducted – test object was composed of one string platform, which means 420 wire ropes, with including steel cover plate. Tests included the cases of symmetric and asymmetric impact. The exemplary result of one of conducted simulations is presented on Fig. 6.

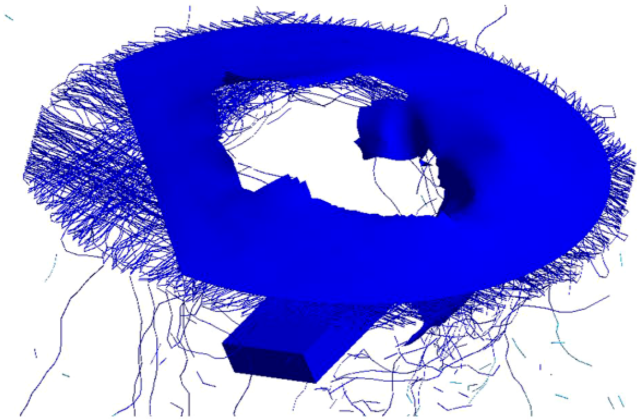

Fig. 6. Simulation of load impact one artificial bottom platform. Final load velocity $v = 48$ m/s

According to the adopted assumptions, as well as result expectations, the falling mass has destroyed both cover plate and string membrane, penetrating them through. The load velocity loss after destruction was negligibly small and thus has shown that assumption of using at least two layer construction, from which the first one will be totally destroyed, was completely justified; although the possibility of transferring the load energy through the second same platform has become problematic.

Subsequently, in the next phase of the tests the construction consisted of two string platforms was examined. On Fig. 7 and Fig. 8 the results of conducted simulations are presented. In case of symmetrical load fall test the artificial bottom construction has stopped the falling mass, but the destruction of the second platform was to large. The load has destroyed the most layers of second platform and rested on the last wire rope layers. This case is unacceptable from safety requirements point of view. The asymmetrical test has clearly proven that two platform artificial bottom will be insufficient. In this case, the load has pierced both artificial bottom platforms, and its center of mass vertical velocity was still more than 10 m/s. These findings were also true for tests of double platform model with additional 6 cm steel plate cover mounted over the upper deck.

Negative results of studies involving the original solution of shaft artificial bottom led to the construction modification, to enhance the capability of energy dissipation by tested structure. According to this, the addition of third, middle platform between existing two was proposed. In case of symmetrical test the modified construction has successfully suppressed the impact energy and reflected the load mass into opposite direction. However, in case of asymmetrical test all

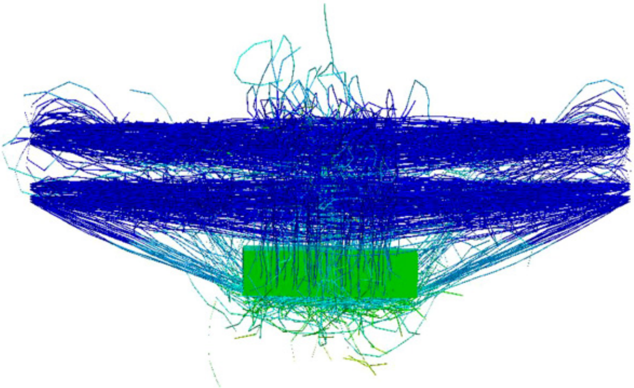

Fig. 7. Impact simulation of load mass with double platform construction – symmetrical test

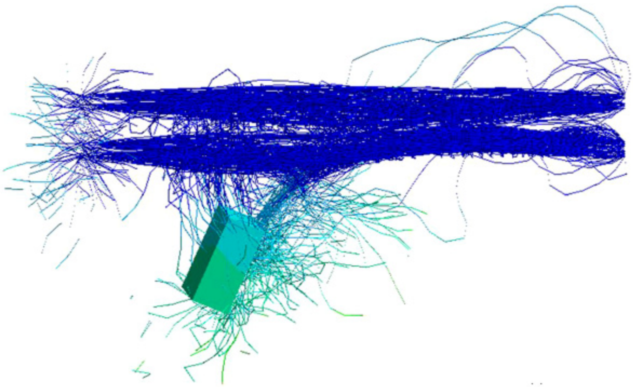

Fig. 8. Impact simulation of load mass with double platform construction – asymmetrical test

three string platforms were pierced and destroyed. In the consequence, additional plate elements mounted over the first and second platform were applied. A number of tests were conducted, which aim was to examine the effect of plate fixing method, their thickness and strength for artificial bottom energy dissipation properties. As a result, it was found that adding additional plate layers has significant and positive impact to reducing the destruction of the string platform. The most favorable results were obtained in the case of sheet thickness of 8 mm, high strength (*Re* = 780 MPa) and clamped at the edges (Fig. 9 and 10).

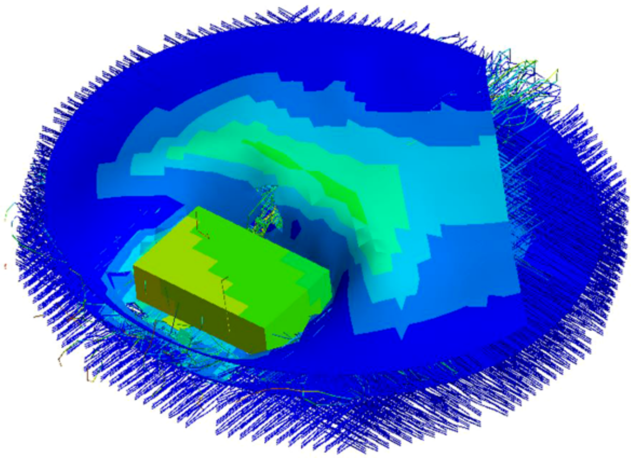

Fig. 9. Falling mass impact simulation for three platform artificial bottom with two additional cover plate layers – breaking of the first layer

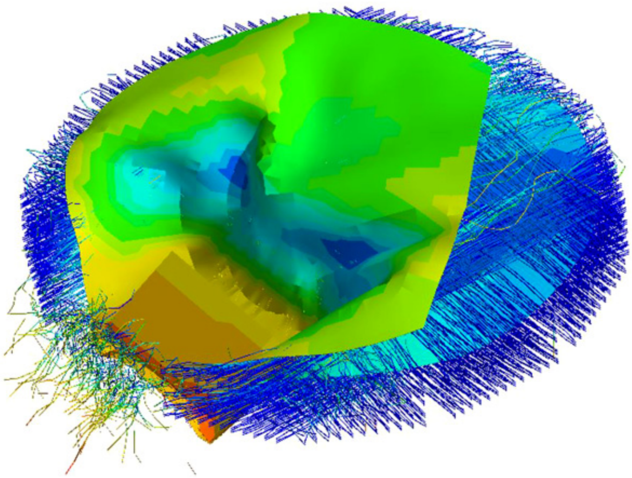

Fig. 10. Falling mass impact simulation for three platform artificial bottom with two additional cover plate layers – falling mass at rest

5. Summary and conclusions

The main objective of conducted studies, which was to verify the construction od shaft artificial bottom, has been successfully archived. As a result of simulation, using successive approximations, the most favorable parameters for artificial bottom with innovative membrane construction have been established. It was found that the best solution will be three platform structure, consisting of multilayered membranes, composed of steel wire ropes with additional plates rigidly mounted to carrier rings of first and second platform.

It was found that for initially assumed parameters the most preferred and guaranteeing a sufficient level of safety, and therefore adequate performance level of artificial bottom, will be usage of additional cover plates of 8 mm thickness each, made of steel with yield strength780 MPa.

From the national mining needs and expectations of view, the very important aspect of conducted studies was to confirm the efficacy of simulation tests for ensuring the safety of underground works connected with deepening the existing shafts. These tests concerns the impact of loads equivalent with masses and dimensions to real elements, which are able to create a serious risk of falling from high altitude, usually nowadays exceeding 1000 m, to shaft artificial bottom model, which shields the workplace of shaft deepening miners.

Presented method creates the possibility of virtual prototyping during the artificial bottom design process, which is especially important in case when due to economic, organizational and technical restrictions the experimental construction verification based on physical prototype test is not possible. Therefore, the only possible solution is to experimentally identify the construction elements characteristics, with determine the load capacity and its ability to dissipate the kinetic energy of falling object. Such type of verification was used in studies presented in this paper; it is the essential element of this kind of methodology.

Modeling studies of energy dissipation phenomena for selected constructions of shaft artificial bottoms are the subject of broader studies conducted within the research project led by Central Mining Institute from Katowice and Department of Mining, Dressing and Transport Machines from AGH University of Science and Technology in Krakow.

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