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Research paper

Numerical modeling of transport roads in open pit mines

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ABSTRACT

Transport of overburden and mineral raw materials in surface mining is one of the most complex and costly processes today. Good transport roads are essential for successful transportation by trucks in open pit mines. Poor design, and maintenance of the roads has the greatest impact on the high transport costs and possible risks in terms of security. Numerical modeling was performed to analyze the effects of the properties of the built-in materials used in the construction of roads, the thickness of the layers and the interaction of tires with the road surface. The distribution of stress and strain determined in the construction of a road depends on the characteristics of the road and the structure and mass of the truck. For this reason, numerical modeling and computer simulation is considered a very suitable method in the design of roads, because in a short period of time and at a lower cost calculations for the construction of a large number of models can be implemented and the best model available will be chosen. The most favorable construction will be considered to be the one that will, at minimum construction costs and with low costs of maintenance, enable the efficient use of transport equipment for a longer period of exploitation.

1. Introduction

1.1. Introducing the problem

The occurrence of many accidents due to incidents on the roads in mines is noticeable. In the goal to increase productivity larger capacity truck are used. But, to use trucks of larger capacity haul roads must be adapted/improved to avoid and reduce the occurrence of accidents (Ding-Bang, Chuan-Bo, Yang-Bo, & Jian-Yi, 2014; Hustrulid & Kuchta, 2009; Nuric, 2009; Nuric, Nuric, Kricak, & Husagic, 2013). That is why the improvement of the structure of transport roads is essential because it would lead to increased effectiveness of trucks, increased productivity, reduced maintenance costs and also important increases in the safety of truck operators and other employees of the mine. Haul road design consists of two main aspects, these being structural and geometric design. The structural design of roads refers to determining the thickness of the various layers of the haul road, special combinations of structural materials and the configurations of load. Geometric design of the transport roads refers to physical dimensions, such as width, cross-sections of slopes, the height of channels and the height of safety berms.

1.2. Exploring the importance of the problem

Empirical methods of road design with the usage of previously acquired experience are commonly used in mines, but this approach does not always result in the optimum design of roads (Hustrulid & Kuchta, 2009; Nuric, 2009; Thompson, 2009; Milne & Jenkins, 2005; Yukio, 2007; Hadjigeorgiou, Kyriakou, & Papanastasiou, 2006; Nawar et al., 2009; Behbahani, 2004; Tannont & Regensburg, 2001; Kumar, 2000). It is therefore necessary to explore the possibility of including information technology in the decision-making process and the choosing of an optimal project solution for opening and developing a surface mine. Numerical modeling and computer simulation is a well-researched methodology in various fields and has specificities in each discipline. In this case, the application of the finite element method for the simulation of the construction of transport roads on surface mines will be investigated because of the previously stated assertion that transport makes up the largest share of the total cost of exploitation. Reduction in the cost of the exploitation of minerals and satisfying the basic conditions of human and ecological environmental safety is the primary task of any mining company. Determining the optimal road construction will certainly go a long way to achieving such a goal. Efficient use of all available simulation software will help to make road construction decisions easier. In combination with previous research on this subject, consideration will be given to the general problems of the construction

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of transport roads, not only in surface mines but also for other uses.

1.3. Literature review

Many authors have written about the importance of the correct construction of transport roads in the surface exploitation of ore and its impact on the total cost of ore extraction. The geometric parameters of haul roads and the selection of material with specific characteristics and properties in the layers of the road construction were considered by Hustrulid and Kuchta (2009), Nuric (2009), Thompson (2009), Milne and Jenkins (2005), Behbahani (2004), Tannont and Regensburg (2001), Kumar (2000), Zheng, Xu, Li, and Dong Xiang (2005), Saravut (2003), Hadjigeorgiou et al. (2006). Detailed elaboration about the theoretical bases of numerical methods, the finite element method (FEM) and its engineering application for determining optimal road construction using numerical methods and simulation techniques was considered by Ding-Bang, Chuan-Bo,Yang-Bo, and Jian-Yi (2014), Nuric et al. (2013), Yukio (2007), Nawar et al. (2009), Grujicic, Marv, Arakere, and Haque (2010), Nuric, Nuric, Kricak, Lapandic, and Husagic (2012), Ninouh and Guenfoud (2008), Salehabadi (2012), Nuric, Nuric, Hercegovac, and Lapandic (2009), Namjoo and Golbakhshi (2014). Hartmann and Katz (2007), Hunter and Pullan (2001), Liu and Quek (2003), Zienkiewich and Taylor (2000). They gave an overview of the theoretical basis and the application of numerical methods, as well as the methodology of analysis and the interpretation of the results obtained, taking into account in-situ measurements and experimental data for the verification of numerical models.

1.4. Hypotheses and their correspondence to research design

The primary hypothesis of this article is: Carefully selected material types be used in layers of the transport road significantly affect its quality, strength and durability.

The secondary hypothesis is: Displacements, deformations, and stresses in road construction are reduced with the installation of materials with better properties of the Young modulus of elasticity and the Poisson coefficient as well as the density of the materials used.

2. Methods

2.1. In-situ investigations

Good transport roads are essential for successful transport by trucks in the open pit mines. Poorly designed and maintained roads have the greatest impact on high transport costs and create possible risks in terms of security. Fig. 1 shows the cross-section of a typical road for transportation by trucks with four different layers: base, lower base course, binder course, wearing course (Nuric, 2009; Milne & Jenkins, 2005; Hadjigeorgiou et al., 2006; Salehabadi, 2012; Zheng et al., 2005; Saravut, 2003). A base layer has to receive all of the burden that falls onto the wearing course. In some cases, this layer will simply be the natural surface of the earth; in others it will be rock or material that is excavated as overburden. The upper wearing course enables the execution of the transport process, reduces traction, reduces the shear of the upper layer, transfers the load from the tires in the ground and prevents the penetration of surface water in to the inner layers of the road. This surface can be concrete or paved, but most often it is a crushed rock material with satisfactory physical and mechanical properties. Binder course is a layer of very high stability and density. Its main purpose is to distribute stresses caused by the action of the load from the wheels in the wearing course, so that there is no deformation or displacement of lower layers in the construction of the road. The lower course is "located" between the binder and the base surface (Behbahani, 2004; Tannont & Regensburg, 2001; Kumar, 2000; Nuric et al., 2009).

2.2. Numerical modeling using the finite element method

The basic concept of modeling for engineering design is the process of solving physical problems through the appropriate simplification of reality. Modeling can be presented as two major parts: physical and theoretical. Through physical modeling useful information for developing empirical algorithms for analysis is obtained. Theoretical modeling usually consists of four steps:

1. Construction of a mathematical model for a corresponding physical problem with appropriate assumptions (differential or algebraic equations).
2. Development of an appropriate numerical model.
3. Implementation of the numerical model to obtain solutions.
4. Interpretation of the numerical results in graphs, charts, tables, etc.

Numerical models are mathematical models that use some sort of numerical time-stepping procedure to obtain the model's behavior over time. With the increase in computational technology, many numerical models and software programs have been developed for different engineering problems. It is important o use an appropriate level of simplification, in order to distinguish important features from those that are unimportant during modeling. Additionally, there are difficulties in obtaining accurate material properties of in situ earth materials and construction materials for correct and accurate results (Hartmann & Katz, 2007; Hunter & Pullan, 2001; Liu & Quek, 2003; Milne & Jenkins, 2005; Ninouh & Guenfoud, 2008; Nuric et al., 2013; Yukio, 2007; Zienkiewich & Taylor, 2000).

Numerical modeling and computer simulations for building transport roads in open pit mines are the main theme of the paper. In order to select two final variants of models for presentation, several different models were made which were related to different thicknesses of layer materials, different characteristics of the material in the layers, different types of loading equipment that can move along the transport road, and also the dimensions of the transport road The width of the transport road in surface mines is conditioned by the dimensions of the largest truck that will be used along this route, as well as its load

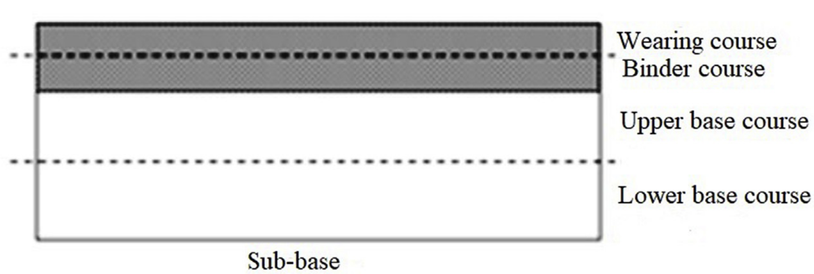

Fig. 1. Cross-section of road construction.

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capacity, which will in turn affect the load on the road. This paper considers two variants of road construction in terms of the use of machinery with a maximum mass, capacity and dimensions. For each variant, a geometry model with material properties, loading conditions as well as boundary conditions is created. Different types of material applied in the construction of the road will be added to each variant of the model. Computer simulations will provide a range of results (stresses, displacements, strains, etc.), and after the analysis the selection of the optimal model of road construction will be possible. The methodology proposed will be able to prove or disprove the primary and secondary hypotheses of this piece of work and provide essential information for making decisions in the design process of open pits.

2.2.1. Pre-processing with the finite element method

Pre-processing involves creating a geometric model and adding material characteristics. Geometry includes a selection of elements that will create a mesh. In these calculations, ADINA (Automatic Dynamic Incremental Nonlinear Analysis), which is the main program of finite elements for high-nonlinear structural analysis of bodies and structures, was used. For all steps of the analysis and all types of material plane strain state is used. In the analysis, 2D (two dimensional) iso-parametric finite elements with numerical Gaussian integration points were used. Formulation of the model is performed use the geotechnical Mohr-Coulomb material model, which was used to define small and large displacements and in both cases small stresses are assumed. This model used the first class of boundary conditions defined through nodal degrees of freedom (Ding-Bang et al., 2014; Nawar et al., 2009; Hartmann & Katz, 2007; Salehabadi, 2012; Nuric et al., 2009).

2.2.2. Processing with the finite element method

This analysis applied the “mass proportional” load, which is typically used to load models with gravity with uniform acceleration of the soil. In nonlinear static analysis the non-linear response during a gravitational load is calculated and then other loads are taken into account, if there are any. The main purpose of the applied time function is to control the variation of loads over time (in time step 0 it was 0% of the load which increased linearly to time step 10 with 100% of the load). In addition to the above steps, an important segment can be extracted and the time step that controls the increment time/loading during analysis can be defined (Namjoo & Golbakhshi, 2014; Nawar et al., 2009; Nuric et al., 2013). As previously mentioned, nonlinear static analysis was performed because of material properties, kinematic assumptions and the use of special features such as the option “death/birth” elements. Static equations were solved using the Full Newton iteration, with a maximum of 15 iterations. The appropriate characteristics of the material obtained in laboratory and in-situ research are associated to geometric models (Table 1).

2.2.3. Specific control parameters used for processing with the finite element method

Since the analysis is performed for a longer period of time, restarting the analysis was introduced to increase the accuracy of the calculations. The computer can, at a certain time step, stop the calculation and allow the user to make some permitted changes to the input data, such as: the number of steps in the calculation, the time function that describes the changes in the load, the change from static to dynamic analysis, iterative methods, tolerance, automatic steps of time, new entry for external load, new material constants in the types of materials that must remain the same, as well as groups of elements and changes in boundary conditions. In addition to the aforementioned capabilities of the software, it is possible to use the “death/birth” elements when adding or removing elements from the structure. If the “birth” option is used on an element, the element is added to the overall system of the finite element at the time which the ‘birth’ option is used. If the “death” option is used on an element, the element is taken from the total system of finite element for the time after the usage of the death option. If the birth and then the death option is used, the element is added to the system of the finite element at the time which the birth option is used and remains in the overall system until the time of the usage of the death option. Time of death must be greater than the time of birth (ADINA R&D, 2003).

Table 1
Geo-technical data for binder materials.

	Base	Clayey sandstone	Sand	Hugely crushed material	Finely crushed material
E [MN/m^2]	100	50	30	20	10
ν	0.3	0.3	0.4	0.4	0.4
γ [MN/m^3]	0.0022	0.002	0.0019	0.0018	0.0018
φ [°]	33	30	28	23	22
c [MN/m^2]	10	7	3	3	3

2.2.4. Post-processing with the finite element method

Post-processing with the finite element method and ADINA software is enabled through the creation of bitmaps, contour maps, diagrams, video and numeric files. As it is the simplest methods, display of output values (displacements, stresses and deformations) through the creation of bitmaps or videos is most commonly used. Both methods include an efficient legend that describes the output and allows for easier interpretation. This paper used the display of calculated values through bitmaps and diagrams.

2.2.5. Research design

Research design has gone through several standard phases of scientific research. The investigation of different constructions of haul roads with different types of materials for layers and for the same conditions of use was performed. The selected location was researched and all necessary input parameters for that location were collected, such as the geo-mechanical properties of the surface material of the mine, as well as characteristics of the largest equipment that moves on the transport roads to the pit. For the given location, a geometric and numerical model was prepared. The simulation was performed using the finite element method with the specific requirements described in the previous subchapter. The results obtained are presented through graphical and tabular displays. The ultimate goal is to get displacement that cannot cause strains and cracks in transport roads.

3. Results

For all models, the calculation of output parameters in the form of displacements, stresses and strains of all the elements, nodes, and time (0–10) were carried out. The presented values are displacements in the direction of the z and y axis. The stresses in the direction of the y axis and the shear stress in the direction of the y axis for time step 10 with 100% load were then simulated on the road, i.e. the assumption that the road is loaded with the largest truck, Terex MT3600B.

3.1. Modeling and computer simulation for model 1

Model 1 was prepared for profile 2-2 and includes 15,624 elements and 15,898 nodes (Fig. 2). 2D squares and triangular elements were used in order to approximate the description of the actual state of the profile. If the movement of equipment with half the weight is observed, the values for displacement on the y axis in time step 5 are a maximum of +0.101 and a minimum of −0.113 m. The maximum value of horizontal displacement for the same model in time step 10, when it is assumed that the largest equipment is moving on the road, is +0.1004 and the minimum is −0.1125 m. The values of vertical displacements in step 10, with a minimum value of −1.333 m, are shown in Fig. 2.

Shear stress (Fig. 3) under the wheels of trucks in the direction of *y*

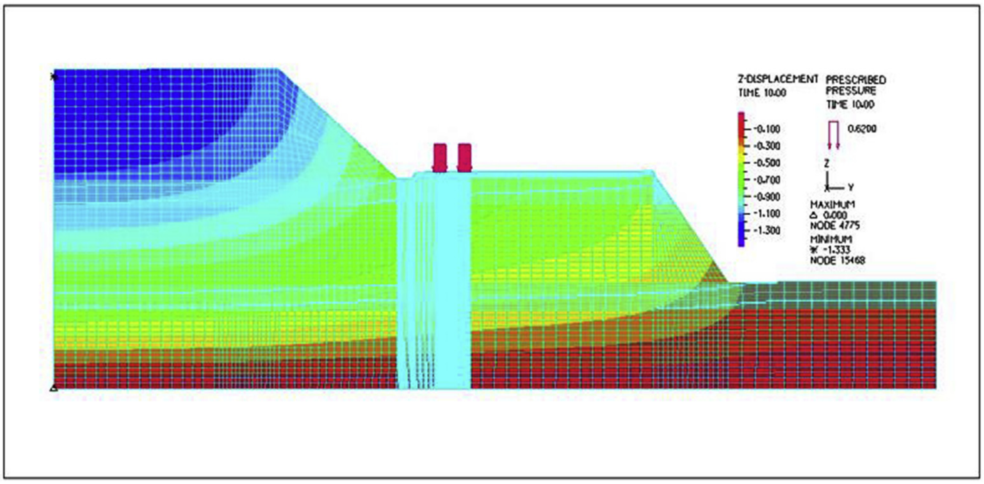

Fig. 2. Distribution of the displacements-z in time step 10 for model 1.

shows the minimum value $-0.0866\ \text{MN/m}^2$ for step 5 and in step 10, in the same position, the minimum value is $-0.1614\ \text{MN/m}^2$. The maximum value of this stress is in the legs of the lower bench and is $1.833\ \text{MN/m}^2$ for each time step. This indicates that there is a defect in the road and instability of the lower bench.

Changes in the value of displacements and stresses in surface nodes are visible in the diagram presented in Fig. 4. Displacements-*z* have expressed values which indicate that there are strains in the construction of the road, while changes in the orientation of the stresses-*yz* confirms the above assumption, especially in knots under numbers 3, 18, 33 and 47, which coincide with the line of contact of tires with the ground. Displacements in the *y* axis do not change to a significant extent their values and may be ignored in detailed analysis.

3.2. Modeling and computer simulation for model 2

Model 2 was also created for the profile 2-2, but with changed characteristics of the material in the construction of the road. It was assumed that the installation of binders and wearing course made out of stronger material characteristics in terms of carrying capacity is carried out. The maximum and minimum value of displacement *y* in step 5 is + 0.01007 m and −0.01128 m and in step 10 is + 0.01002 m and −0.01122 m respectively. The minimum value of displacement *z* in steps 5 and 10 is −0.1333 m (Fig. 5).

On the basis of information about the displacements of surface nodes and stresses-*yz*, a diagram of the changes of displacements in the direction of the *z* and *y* axis and stresses-*yz* at nodes on the surface of the route in which the truck is moving was created (Fig. 7). It can be seen in the diagram that the values of the displacements are considerably smaller compared to the previous model (in a range from −0.07 to −0.09 m) and displacements were expressed below the tires. Stresses have critical changes at the same nodal point as the model with lower performance, but the value is much lower than in the previous case, by up to 10%.

4. Discussions

Numerical modeling and computer simulation can be an extremely appealing method for the design of haul roads because it can, in a period of short time and at a lower cost, implement calculations for a large number of models and choose the most convenient. In addition to all of the above, as outlined in the available literature, significant savings in the production process are visible because, in the simulation process, shortcomings and mistakes can be revealed that in the later stages of the simulation can be checked and eliminated (Yukio, 2007; Nawar et al., 2009; Behbahani, 2004; Nuric et al., 2009). The analysis of a series of results (stresses, displacements, strains, etc.) obtained by this computer simulation enables an optimal model for road construction to be selected.

For Model 1 it can be concluded that the displacements-*z* have

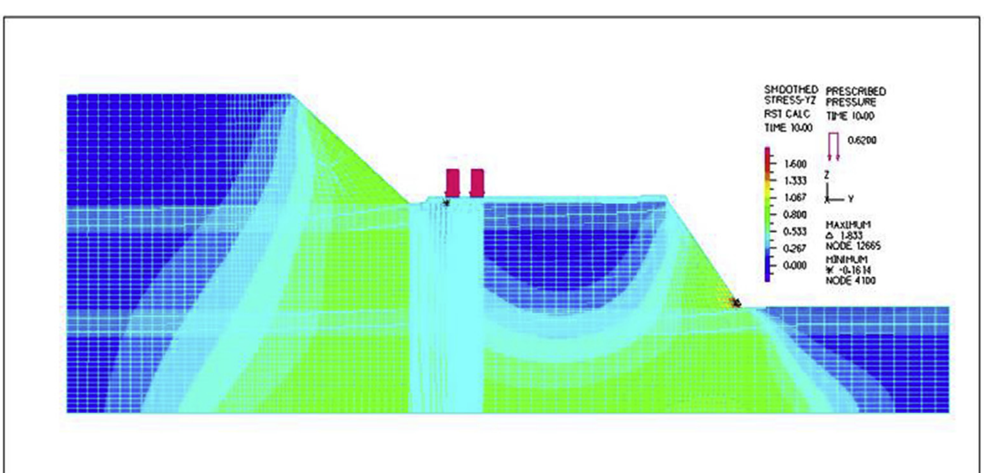

Fig. 3. Distribution of the stresses-yz in time step 10 for model 1.

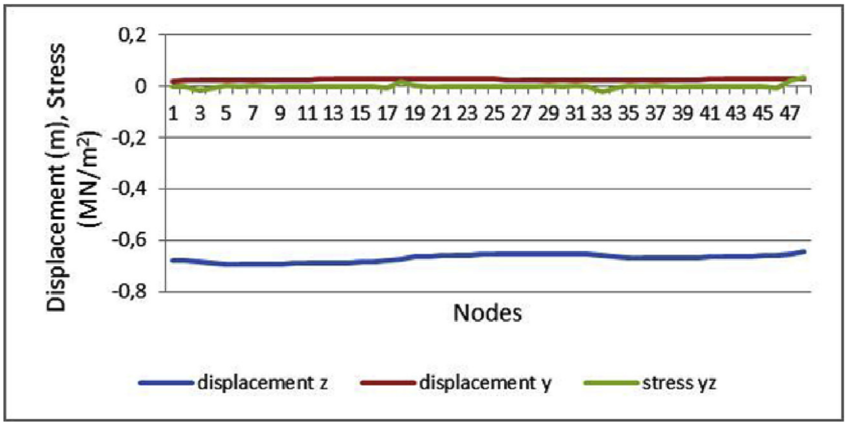

Fig. 4. Changes of displacements and stress for the surface nodes of the road in model 1.

expressed values, which indicate that there are deformations in the construction of the road and also instabilities in the lower bench below the road. The changes in stresses-*yz* coincide with the lines of contact of tires with the ground.

For Model 2, the values of displacements are much smaller when compared to the previous model which was positioned under the wheels of trucks. The stresses' extreme value was positioned in the same nodal point as the model with lower performance, but their value is considerably smaller than in the previous case (10% less). It is obvious that with leveling and filling material with favorable (stronger) geotechnical characteristics, improved driving conditions and maintenance of transport routes in the mine can be obtained.

5. Conclusion

Through analyzing the values obtained it is visible that the initial hypothesis has been proven and improvement of the characteristics of the materials in the layers of the road construction (materials of higher strength and less cohesion) leads to improvement of the general properties of the road in terms of its carrying capacity and durability, therefore reducing the need for maintenance.

The secondary hypothesis was also confirmed. With the use of materials in the layers of the construction of the path with higher values of Young module and density as input data, the displacements, stresses, and deformations as output data are reduced.

Comparison between research by other authors (Grujicic et al., 2010; Milne & Jenkins, 2005; Nawar et al., 2009; Ninouh & Guenfoud, 2008; Nuric et al., 2009; Salehabadi, 2012; Yukio, 2007) and the simulation results confirmed the impact of the characteristics of the material, the thickness of the layers themselves and their layout in the construction of the road. Further research in this area is advisable, for the current design of haul road as well as for the future new designs.

This piece of work presents answers to the hypothetical consideration of using different types of materials for binder course as well as for the wearing course in the construction of roads and proposes guidelines for further research. To continue the analysis, it would be necessary to conduct further detailed studies in order to define the geotechnical characteristics of the basic terrain, where there are plans to build transport routes, then to carry out additional laboratory tests of materials which are planned for use in the basic layer of the construction of the road (CBR – California Bearing Ratio tests, etc.). In addition, it is necessary to know whether there are discontinuities or other types of changes in the physical system of each element of the construction of the road, which should be adequately incorporated in estimation and analysis.

Declarations of interest

None.

Conflicts of interest

None declared.

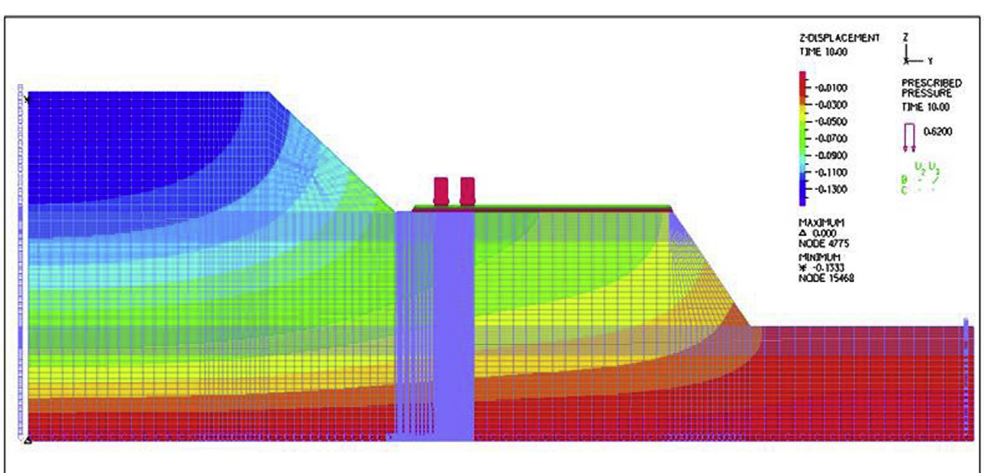

Fig. 5. Distribution of the displacements-z in time step 10 for model 2. The maximum and minimum value of stress-*yz* in step 5 is + 1.839 MN/m^2 and −0.08622 MN/m^2, and in time step 10 is + 1.839 MN/m^2 and −0.157 MN/m^2, respectively (Fig. 6).

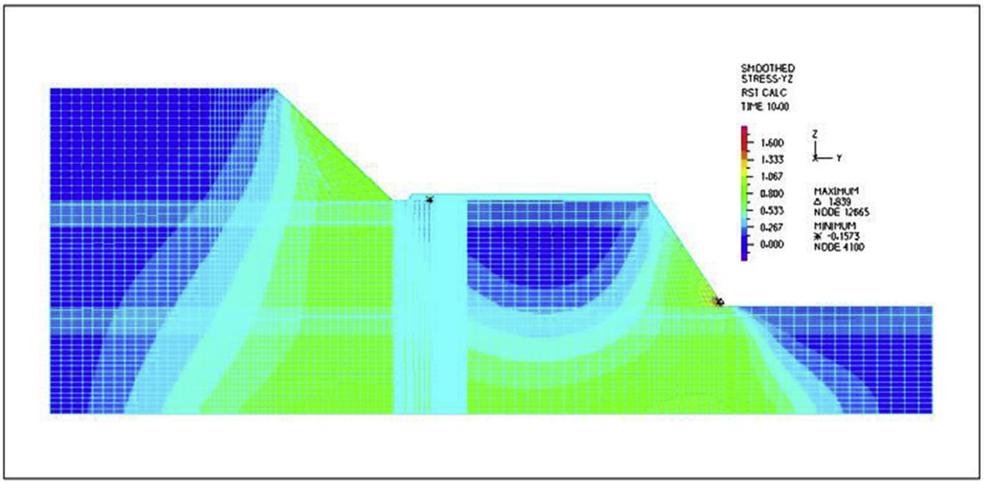

Fig. 6. Distribution of the stresses-yz in time step 10 for model 2.

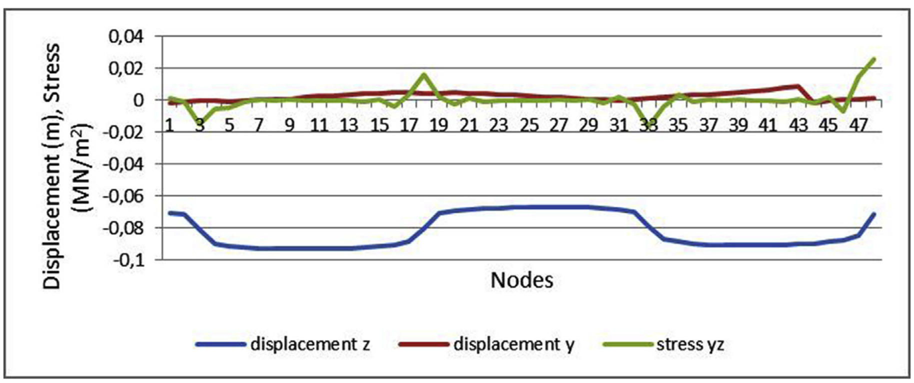

Fig. 7. Changes of displacements and stresses for surface nodes of the road in model 2.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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None.

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