Mining Science, vol. 23, 2016, 203−214

www.miningscience.pwr.edu.pl

Mining Science
(previously Prace Naukowe Instytutu Gornictwa
Politechniki Wroclawskiej, ISSN 0370-0798 in polish)

ISSN 2300-9586
previously 0370-0798

Received June 8, 2016; reviewed; accepted October 1, 2016

THE EFFECTIVENESS OF EARTH STRUCTURES REINFORCEMENT ON MINING AREAS: NUMERICAL ANALYSIS

Michał PACHNICZ*, Magdalena RAJCZAKOWSKA, Damian STEFANIUK

Wroclaw University of Science and Technology, Faculty of Civil Engineering

Abstract: This paper presents a numerical analysis of a Multi-layer soil structure improved with the use of geosynthetics. Numerical calculations using the finite element method (FEM) in ZSoil program were performed to determine the effectiveness of the applied reinforcement. In the solution of the problem, different boundary conditions were modeled to analyze the influence of several technologies on the construction of a rail road embankment, subjected to the effect of mining works. In the analysis, the applied loads correspond to the II category of the mining area. Mainly, the different load conditions reflect the intensity of the subsidence of the ground surface due to mining. The effectiveness of the soil reinforcement was determined using the comparison of the numerical calculations of displacements and strains for different scenarios. The reinforcement conditions were always contrasted among them and against the rail road embankment without any improvement. The displacements were measured at the surface of the rail road embankment. The slope stability of the embankment was measured using the soil shear strength reduction method (SSR). The obtained results show, that applying the appropriate reinforcement to the soil, the load/bearing capacity and the stability of the earth structure located in a zone of mining influence can be improved considerably.

Keywords: *mining deformations, embankment reinforcement, geosynthetics*

INTRODUCTION

If it is necessary to locate a structure on an area affected by mining activity, it will be required to provide the adequate strength to the structure due to the "extra" loads associated with the effects of the mining works. Negative effects affecting the structures are caused by (Gruchlik & Kowalski, 2012):

---

* Corresponding authors: michal.pachnicz@pwr.edu.pl (M. Pachnicz)

doi: 10.5277/msc162317

1. Subsidence: in the range of constant deformations and described by the adequate deformation indicators, i.e. lowering or tilting of the terrain surface (*T*), curve and the radius of the hollow (*R*) and the horizontal strains (*ε*), see Fig. 1.
2. Dynamic shocks: expressed with their energy level caused by the rapid movement (e.g. along the planes of tectonic dislocation) or cracking of rock layers.
3. Variations of ground and surface water level, i.e. lowering and raising of the ground water level.

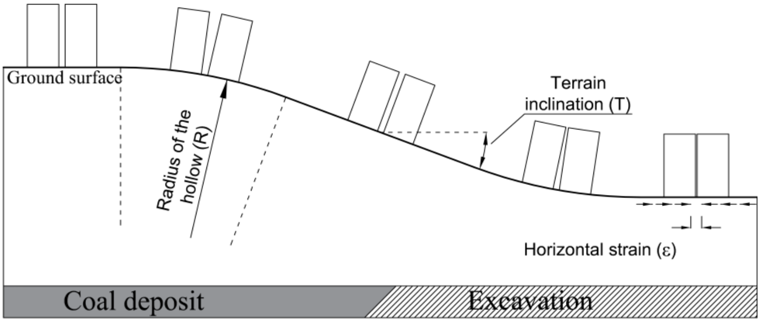

Fig. 1. The sketch of tilting of the terrain surface (*T*), the radius of the hollow (*R*) and the horizontal strains (*ε*)

In the presented study authors analyze the ground surface displacement and deformation influence on the horizontal strains and displacements in a road embankment. Mining influence on the building structures can be classified into one of five categories (see Table 1).

Tab. 1. Categories of the mining area per the values of indicators of the deformation (Gruchlik and Kowalski, 2012)

Category of the mining area	Indicators of the deformation		
	Terrain inclination *T*	Radius of the hollow *R*	Horizontal strain *ε*
	[mm/m]	[km]	[mm/m]
0	T≤0.5	40≤|R|	|ε|≤0.3
I	0.5<T≤2.5	20≤|R|<40	0.3<|ε|≤1.5
II	2.5<T≤5.0	12≤|R|<20	1.5<|ε|≤3.0
III	5.0<T≤10.0	6≤|R|<12	3.0<|ε|≤6.0
IV	10.0<T≤15.0	4≤|R|<6	6.0<|ε|≤9.0
V	15.0<T	|R|<4	9.0<|ε|

Requirements for safety and comfort of structures under use can be provided by: separating the structure from the mining impacts, locating it outside the area of the mining influence, modifying the structural shape by applying expansion joints, or through additional reinforcement, i.e. applying correctly selected materials.

In this paper, a road embankment was analyzed under the influence of subsidence, with the deformation indicator values corresponding to the II mining area category, i.e. $R = 19$ km and $|\varepsilon| = 3$ mm/m. Road embankments are large, linear objects, so the complete elimination of the negative mining influences, like enforced horizontal strains of the ground surface or increased and uneven settlements, is practically impossible. In addition, their location is often imposed by logistic aspects. Therefore, the ideal solution for the problems might be the application of structural reinforcement.

In this paper, authors analyze the influence of the type, geometry and parameters of reinforcement on the reduction of the surface deformation. At first, methods of the counteraction to mining influence are presented. Solutions like geo-mattress (Chu & Yan, 2011) and sand bed (Liu and others, 2008), which are then used in the numerical analysis, are characterized. Secondly, parameters and the method of creating the numerical model are described. The analysis of embankment core reinforcement considers 6 different combinations of strengthening elements. In addition, the interaction between the modeled materials is considered by implementing the contact elements on the joints of the subdomain layers.

PREVENTING NEGATIVE MINING INFLUENCE

There are many methods of reinforcing the soil structure. One way is to improve the foundation of the structure (subsoil parameters). A series of technologies can be used for that purpose, i.e. upgrade of the subgrade soil (mechanically or chemically), increasing soil compaction along with the consolidation (if needed) or the use of deep foundations. Unfortunately, these solutions are indirect and increase the amount of work and costs. A different approach is to change the parameters of the earth structure itself. To enhance an earth structure, different types of reinforcement can be utilized, i.e. metal bars, geosynthetic materials and even leaves of plants (Nicholson, 2014). The variety of additional structural layer applications seems to be interesting, when it comes to optimization. Therefore, the authors focus on finding the optimum (as far as stability and load capacity are criteria) solution for reinforcing the road embankment core with the use of additional layers of sand-bed and geo-mattress.

STRENGTHENING LAYER (GEO-MATTRESS)

Strengthening layer is a stiff structure composed of aggregate reinforced with synthetic geogrids. The most essential component of the geo-mattress is chipping. The aggregate built into the geo-mattress works as a warp (matrix) and the geogrid works as the reinforcement. For the construction of the mattress, coarse-grained soil of the natural origin is most commonly used, including sand, gravel, crushed stone and slag.

Main parameter of the aggregate is its gradation (particle size distribution of a granular material), i.e. the grain size distribution index ($1 \leq C_c \leq 3$ is required for geo-mattress) (Sękowski, 2002). For coarse aggregates the volume fraction of fractured particles is also very important. Geogrid's role is stabilization and strengthening unbound chippings as well as enlarging carrying capacity and durability of the aggregate layer. Due to the stiff knots, geogrid carries tensile stresses and it also stabilizes aggregate during the soil compaction. Because the great stiffness of geo-mattress, the ground layered above does not undergo exaggerated deformations (Łupieżowiec, 2012). Geo-mattress deals with normal and shear stresses which are then transferred to the subgrade. Shear strength, driven mainly by a high internal friction angle of material (used as aggregate), is crucial when it comes to evaluating the reinforcement layer strength (Łupieżowiec, 2012).

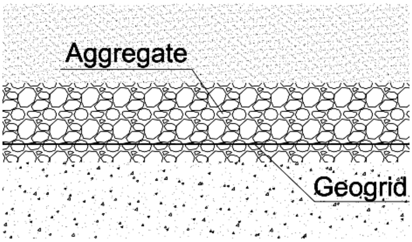

Fig. 2. Geo-mattress conformation

SLIDING LAYER (SAND-BED/ FRICTION LAYER)

The basic task of the sand bed is to provide the possibility of mutual displacement between the base and the core of the embankment. It is often adapted to structures being built in the areas of earthquake influences, as the isolator and energy dissipater (Zhou, 1996). Coarse-grained soil, e.g. coarse/medium sand, can be used as a sliding layer material. This layer is usually embedded with appropriate compaction, specified by index $I_s = 0.95–0.97$.

CASE STUDY

In this paper, an earth structure reinforced with the geo-mattress and the sliding layer is studied. The analyzed case study corresponds to the road embankment within S-3 railway. The size of the model is carefully selected, to eliminate the effects of the boundaries influence. In the model, a division of subsoil into layers of different parameters is considered. The geometry of the area along with the system of layers is showed in Fig. 3. Mechanical parameters of the adopted materials are summarized in Table 2.

Tab. 2. Materials' parameters for numerical model

Layer name	Material formulation	Thickness	Parameters						
			Elastic		Non-linear			Unit weights	
			E	ν	c	φ	ψ	γ	γ_d
		m	kN/m^2	–	kN/m^2	deg	deg	kN/m^3	kN/m^3
Railway embankment	M-C*	7.05	80000	0.30	24.00	20.50	0.00	20.00	20.00
Subgrade (layer 3)	M-C*	1.60	80000	0.25	2.00	28.40	0.00	18.00	18.00
Subgrade (layer 2)	M-C*	2.40	30000	0.30	22.40	13.70	0.00	20.00	20.00
Subgrade (layer 1)	M-C*	19.0–23.0	100000	0.25	3.00	30.20	1.00	18.00	18.00
Road foundation	M-C*	0.50	120000	0.20	80.00	29.30	5.00	20.00	20.00
Bituminous layer	Elastic	0.25	11000000	0.20	–	–	–	20.00	20.00
Road base	Elastic	0.25	500000	0.20	–	–	–	20.00	20.00

*M-C-Mohr-Coulomb failure criteria for material.

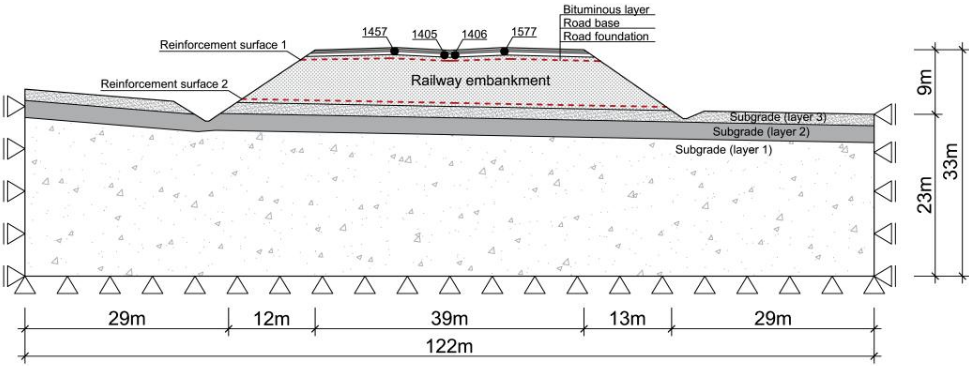

Fig. 3. Scheme geometry, boundary conditions and selected points of road foundation layer

The type of assumed boundary condition has a significant effect on the deformations of the domain, especially in the case of mining deformation influence. Therefore, authors decided to adopt the boundary condition presented in Fig. 3. According to (Kowalski, 2006) it matches the deformations of the area that is associated with the effects of mining in an optimal way.

Fig. 3 shows two surfaces of probable reinforcement structural layers. In the optimization process 6 different cases are investigated. In each case, the geometry or the type of the applied reinforcement differs from the previous ones. All cases/instances are summarized in Table 3.

Comparison between individual cases of the reinforcement and the reference state (embankment without reinforcements) constitutes grounds for determining which, from the analyzed configurations is the most effective one.

Tab. 3. Summary of study cases

Case	Reinforcement surface	Applied solution	
		Geo-mattress	Sand-bed
A	1	+	
	2		
B	1		
	2	+	
C	1	+	
	2	+	
D	1	+	+
	2	+	
E	1	+	
	2	+	+
F	1	+	+
	2	+	+

Symbol + means that in that case addressed reinforcement type is applied.

PROBLEM SOLUTION

The defined model is a plain strain boundary problem with elasto-plastic soil behaviour. Series of finite element (FE) analysis, using ZSoil, are performed (Zimmermann *et al.*, 2010). The flow of the groundwater is not taken into consideration. To create the numerical model, the dimensions described in Chapter 3 are used. At first, the quantity of nodes sufficient for calculations is examined by testing the sensitivity of the model to the mesh density. For that purpose, a safety factor (FOS) of embankment slope is calculated for the D case (with 3 different densities of model mesh each time). FOS values are computed using shear strength reduction method (SSR). The SSR method is a numerical solution consisting of gradually reducing the value of mechanical parameters of the soil, until the moment of exceeding the steady-state condition. In the presented study, the internal friction angle ($tg\ \varphi$) and the cohesion (c) are reduced. The calculated critical slip surfaces are introduced in the Fig. 4.

The obtained results (Table 4) show, that 2416 is the sufficient number of nodes in the model, since further mesh refinement does not improve the accuracy of the safety factor value.

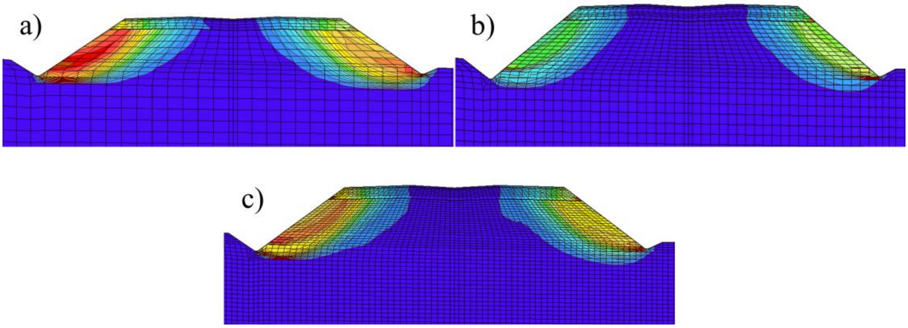

Fig. 4. Critical slip surface (case D) for different scheme discretization:
a) 1070 nodes, b) 2416 nodes, c) 6171nodes

Tab. 4. Factor of safety for case D

Number of nodes	FOS
1070	1.62
2416	1.48
6171	1.48

To reflect the real state of primary geostatic stress in the soil and in the core of the embankment, all stages of constructing and loading of the embankment are considered. Kinematic boundary conditions are being imposed after all previous loads. Deformations of mining origin are taken into account by setting appropriate values of displacement on the succeeding fixed nodes. Bending of the surface is included in vertical displacements, however the creeping of the ground is being reflected by horizontal transfers of supports.

The deformations of the subgrade under the embankment, increasing in the opposite directions, create the most unfavorable situation, leading to the loosening of the embankment soil material. It results in faster degradation/destruction of the road layers and often causes uneven settlements of the whole structure. Thus, the line of zero horizontal transfers is assumed to be in the symmetry axis of the considered road, to reflect the most unfavorable case (see Fig. 5). Away from this axis a linear increase in values of the horizontal (UX) and the vertical (UY) transfer is modeled. Displacements of the supports correspond to the radius of the assumed hollow. Maximum values of imposed displacements on the region boundaries are as follows: on the right boundary edge UX = 0,187 m, on the left boundary edge UX = –0,179 m and on the bottom boundary edge UY = –0,104 m.

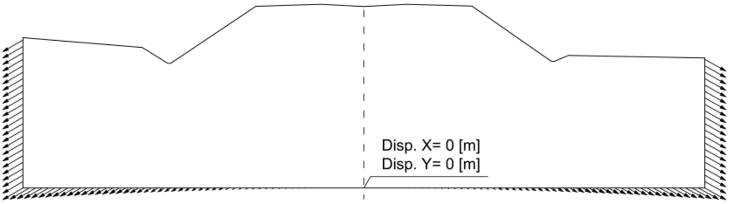

Fig. 5. Imposed displacements on the model boundaries

Geo-mattress is modeled as a separate layer of Mohr-Coulomb (M-C) material. The thickness of the layer is set to 0.5 m. It is strengthened in its bottom part with geosynthetic reinforcement. Geogrid is applied as an isotropic planar membrane element with the predefined elasticity parameters. Sand bed is introduced as 0.5 m layer of sand (M-C). Parameters of structural layers are listed in Table 5.

Tab. 5. Material parameters for reinforcement layers

Reinforcement element	Material formulation	Parameters						
		Elastic		Non-linear			Unit weights	
		E	ν	c	φ	ψ	γ	γ_d
		kN/m^2	–	kN/m^2	deg	deg	kN/m^3	kN/m^3
Geogrid	Isotropic membrane	2000	0.2	0	0	–	–	–
Aggregate	M-C	120000	0.25	18	18	4	32	5
Sand bed	M-C	50000	0.25	18	18	2	20.5	5

In addition, on the bottom surface of implemented elements of the reinforcement, a possibility of the mutual skid is taken into account. To satisfy that condition, contact elements are added. Their parameters result from the reduction of the internal friction angle derived from neighboring layers. The parameters are reduced by 40%.

RESULTS AND DISCUSSION

The presented results show the state of the horizontal deformation, the displacements in the core of the embankment and in the road surface. The reference state demonstrates the transfers and deformations caused by static load and a dead weight of the soil. The changes of displacements and strains are derived only from the influence of the mining area. The Figures 6–12 show the results for all the analyzed cases (Table 3).

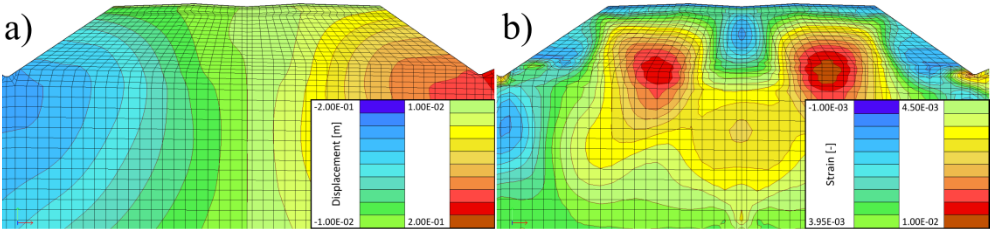

Fig. 6. Reference model: a) displacements X, b) strains XX

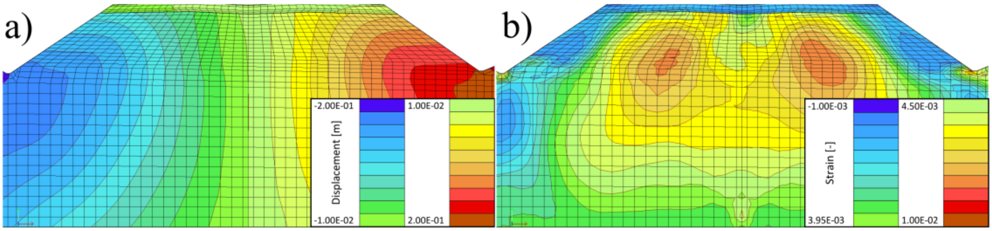

Fig. 7. Case A: a) displacements X, b) strains XX

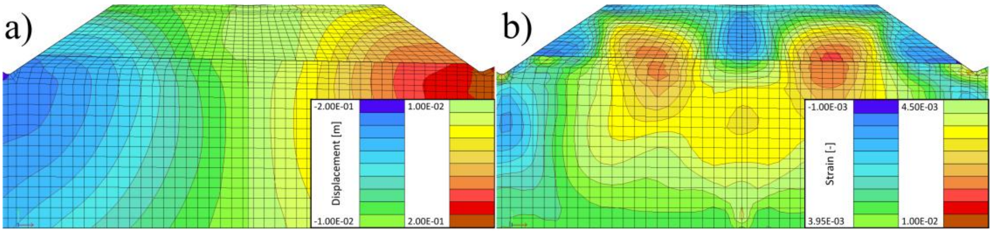

Fig. 8. Case B: a) displacements X, b) strains XX

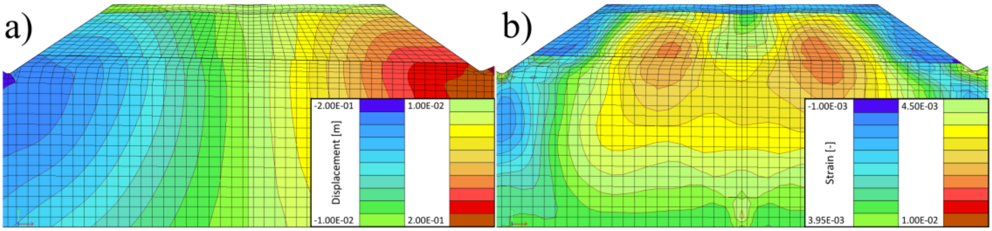

Fig. 9. Case C: a) displacements X, b) strains XX

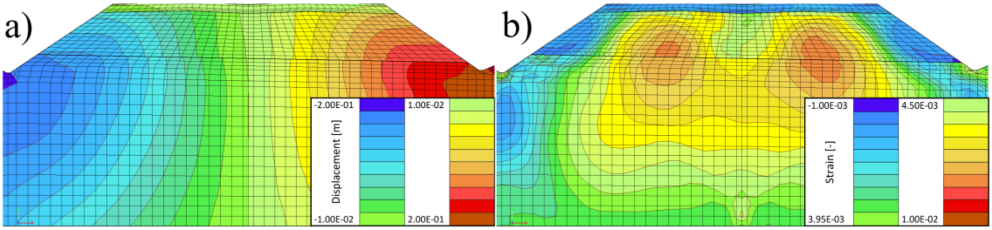

Fig. 10. Case D: a) displacements X, b) strains XX

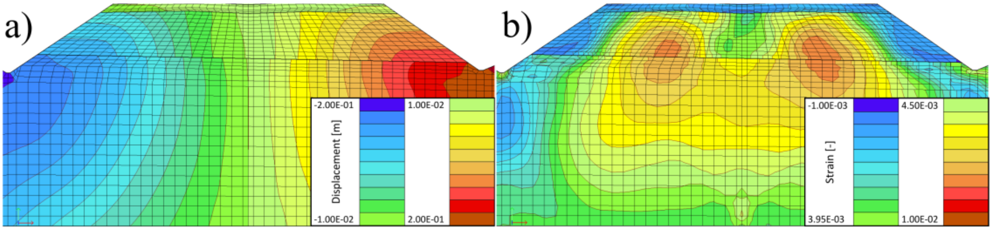

Fig. 11. Case E: a) displacements X, b) strains XX

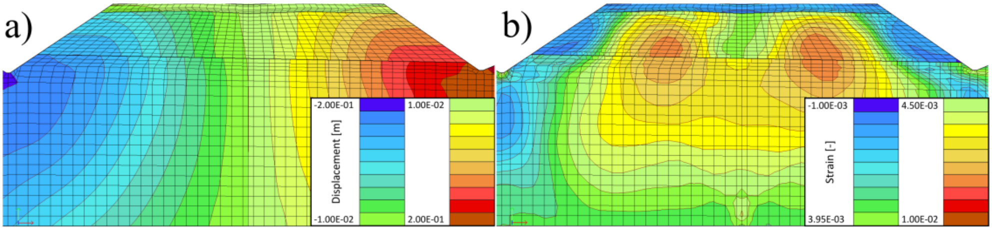

Fig. 12. Case F: a) displacements X, b) strains XX

The values of the horizontal strain deformation for selected finite elements (elements 1457, 1405, 1406 and 1577 in the road foundation layer pointed out in Fig. 3), are summarized in the Table 6.

Tab. 6. Selected finite element horizontal strain

Strain XX							
Selected element	Case						
	Reference	A	B	C	D	E	F
1577	205E-05	70.8E-05	212E-05	69.6E-05	64.9E-05	69.2E-05	64.4E-05
1405	169E-05	43.8E-05	170E-05	42.7E-05	38.0E-05	42.4E-05	37.4E-05
1406	168E-05	43.1E-05	170E-05	42.2E-05	37.4E-05	41.8E-05	36.6E-05
1457	204E-05	66.1E-05	210E-05	65.2E-05	59.8E-05	65.1E-05	59.5E-05

The obtained results show that strengthening the embankment with structural layers reduces deformations of the road surface. In the cases A, C, D, E and F horizontal strain was decreased by over 100%. However, in case B reinforcement did not improve the performance of the embankment. It might have been triggered by the fact that the application of the reinforcement in the bottom layer of the embankment is much less effective than in the top area due to the different values of frictional forces. Friction strongly depends on the value of the force normal to the displacement surface, so in the bottom part of the embankment, where high stress is generated, the friction resists relative lateral motion. Therefore, the sand-bed or even reinforcement layer does not compensate displacement caused by the mining surface deformation. For better results both reinforcement and sliding layer ought to have parameters associated with the loads they carry. Nevertheless, application of the reinforcement only directly below the road layers leads to large deformations of the embankment core.

Strain value in elements 1405 and 1406 is consequently smaller than the strain in elements 1577 and 1457. Thus, the horizontal deformation of the embankment is smaller in the area close to the axis of the road (in the case under investigation), than in the further areas.

CONCLUSIONS

Optimization of the earth structures reinforcement is a complex and difficult task. Variety of available solutions creates the alternative ways of constructing new structures and repairing the old ones. Unfortunately, there is not enough information about the way reinforcements should be modeled during the design process. The analyzed case study shows that basic conclusions about reinforcement effectiveness can be derived from numerical calculation results. However, the numerical model is responsive to the values of the input contact parameters that depend on many factors. Hence, the problem of defying mutual interaction between modeled structures should be the subject of further study.

REFERENCES

CHU J., YAN S., 2011. *Recent Development in the Construction of Coastal Protection Structures*, Geotechnics and Earthquake Geotechnics Towards Global Sustainability.

GRUCHLIK P., KOWALSKI A.,2012. *Metodyka identyfikacji i szacowania potencjalnych szkód ekologicznych na terenach górniczych dla potrzeb wspomagania zarządzania terenami przekształconymi antropogenicznie*, Zeszyty Naukowe Politechniki Śląskiej.

KOWALSKI M., 2006. *Wpływ przyjętych warunków brzegowych na odkształcenia modelu podłoża poddanego wpływom deformacji górniczych*, Geotechnika i Budownictwo Specjalne.

LIU J.L., LIU J.Q.,. Chen L.W, 2008. *Study on the mechanism of embankment reinforced with Geotextile by finite element method*, Proceedings of the 4th Asian Regional Conference on Geosynthetics, Shanghai, China.

ŁUPIEŻOWIEC M., 2012 *The influence of the rigid geomatrixes on stiffness of the ground under the road pavements*, Technical Transactions – Environment Engineering, Wydawnictwo Politechniki Krakowskiej.

NICHOLSON P.G., 2014. *Soil Improvement and Ground Modification Methods*, Elsevier Inc.

PN-EN 933-5:2000 *Badania geometrycznych właściwości kruszyw – Oznaczanie procentowej zawartości ziarn o powierzchniach powstałych w wyniku przekruszenia lub łamania kruszyw grubych*.

SĘKOWSKI J., 2002. *Podstawy wymiarowania poduszek wzmacniających*, Zeszyty Naukowe Politechniki Śląskiej.

ZHOU F.L., 1996. *Retrofit for Existing Buildings with Seismic Control of Structures, Post-Earthquake Rehabilitation and Reconstruction*.

ZIMMERMANN TH., TRUTY A., URBAŃSKI A., PODLEŚ K., 2010. Z_Soil.PC 2010, *3D user manual, Theory, Tutorials and Benchmarks, Data Preparation*, Elmepress International & Zace Services Ltd, Switzerland.