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IMPACT OF GEOTECHNICAL BARRIER MODELLED IN THE VICINITY OF A BUILDING STRUCTURES LOCATED IN MINING AREA

WPŁYW ZAMODELOWANEGO WOKÓŁ BUDYNKU ROWU GEOTECHNICZNEGO NA OGRANICZENIE NIEKORZYSTNYCH SKUTKÓW EKSPLOATACJI GÓRNICZEJ

The paper presents a new geotechnical solution indicating a possibility of effective building structures protection. The presented solutions enable minimization of negative effects of underground mining operations. Results of numerical modelling have been presented for an example of design of preventive ditches reducing the influence of mining operations on the ground surface. To minimize the mining damage or to reduce its reach it is reasonable to look for technical solutions, which would enable effective protection of building structures. So far authors concentrated primarily on the development of building structure protection methods to minimize the damage caused by the underground mining. The application of geotechnical methods, which could protect building structures against the mining damage, was not considered so far in scientific papers. It should be noticed that relatively few publications are directly related to those issues and there are no practical examples of effective geotechnical protection. This paper presents a geotechnical solution indicating a possibility of effective protection of building structures. The presented solutions enable minimization of negative effects of underground mining operations. Results of numerical modelling have been presented for an example of design of preventive ditches reducing the influence of mining operations on the ground surface. The calculations were carried out in the Abaqus software, based on the finite element method.

Keywords: FEM (Finite Element Method); geotechnical methods of building protection; decompression ditch; ground surface deformation

W celu minimalizacji szkód górniczych lub ograniczenia ich zasięgu, rozsądnym jest poszukiwanie rozwiązań technicznych, które umożliwiałyby skuteczną ochronę obiektów budowlanych. Dotychczas autorzy skupiali się przede wszystkim na opracowywaniu metod zabezpieczenia obiektów budowlanych, aby zminimalizować szkody spowodowane podziemną eksploatacją. Zastosowanie metod geotechnicznych, które mogą chronić obiekty budowlane przed szkodami górniczymi nie było do tej pory poruszane w artykułach naukowych. Należy zauważyć, że stosunkowo mało publikacji bezpośrednio związanych

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jest z tą tematyką i brakuje praktycznych przykładów skutecznej ochrony geotechnicznej. W niniejszym artykule przedstawiono rozwiązanie geotechniczne wskazujące na możliwość skutecznego zabezpieczenia konstrukcji budowlanych. Prezentowane rozwiązania umożliwiają minimalizację negatywnych skutków podziemnej eksploatacji górniczej. Przedstawiono wyniki modelowania numerycznego dla przykładowej konstrukcji prewencyjnych rowów zmniejszających wpływ działalności górniczej na powierzchnię terenu. Obliczenia przeprowadzono w programie Abaqus opierającym się na metodzie elementów skończonych.

Słowa kluczowe: analiza numeryczna, MES (metoda elementów skończonych), ochrona budynku poprzez zastosowanie geotechnicznego rozwiązania, rów geotechniczny, przemieszczenie powierzchni terenu

1. Introduction

Each case of underground mining is related to the disturbance of the rock mass structure, which could result in heavy deformations of the subsoil and in the ground surface degradation (e.g. Siriwardane & Amanat, 1984; Najjar & Zaman, 1993; Deck & Singh, 2012; Kowalski & Polanin, 2015). This is a major problem in the urbanized Europe, where the repair of mining damage or a likely payment of compensations is a significant percentage of the production costs for a ton of coal. For example, the expenditure to cover the cost of mining damage in Germany in 2010 was circa €12 per ton of extracted coal, where the cost of mining damage in buildings was circa 7 €/ton (Sroka et al., 2012). Any engineering intervention reducing the negative effect of underground mining and allowing to reduce the costs related to the mining damage is positive and brings not only measurable benefits. Such profits work first of all for the mining companies, but also make that the mining operations are incomparably more accepted by local communities.

Analysing the hitherto solutions it is possible to notice that authors focused mainly on the development of methods for structural protection of facilities to minimize the damage (e.g. Kwiatek, 1997; Malinowska & Hejmanowski, 2010; Malinowska, 2011; Rusek & Firek, 2016). The issue of geotechnical methods for building structures protection against the mining damage was in the background of the aforementioned interests (e.g. Hashash et al., 2004; Javadi & Rezania, 2009; Zhang et al., 2014). Despite that, practical examples of geotechnical methods application to protect building structures exist worldwide, e.g. in Germany (Sroka, Protective trenches – results of in situ measurements in the Ruhr Area, unpublished report, 1994), in USA (Luo & Peng, 1991), and in the United Kingdom (National Coal Board, 1975) or in China (Huang et al., 1996; Dai et al., 1997). Some of them have already been successfully applied in Poland and the obtained results of the ground surface deformation and of the mining damage reduction are more than satisfactory (Florkowska, 2013; Misa et al., 2014).

2. 3D numerical analysis of geotechnical protection in the form of destressing ditches

A numerical model was developed to determine the effectiveness of geotechnical protections application, which would reduce the ground surface deformation resulting from the underground mining operations. The calculations were carried out using the Abaqus Standard module (Simulia, 2013), to which a subroutine was added, enabling the simulation of mining deformations of the subsoil. The model consisted of a building structure and part of the subsoil (rock mass), which was subject to deformation processes caused by the deposit extraction. The existence of so-called destressing/expansion ditch made around the building to reduce the mining deformation influence was an additional element. The ditch was filled with a flexible material, creating the area, where the deformation concentrated. This way it worked as a 'shock absorber' protecting the immediate subsoil of the building against excessive deformations. The presented modelling was aimed at the determination of the impact of expansion ditches presence on the reduction of adverse effects of underground mining operations on the building's structure. To this end numerical computations were carried out for a few dozen situations differing in geometrical parameters and mechanical properties of the adopted soil medium. The computations were qualitative, the selected parameters were taken from the available literature and materials made available by Polish hard coal mines (Tajduś, 2009).

Because of the extensiveness of the obtained results the paper presents only selected results, the most interesting ones and also those, which show in the most obvious way the evident impact of geotechnical structures on the minimization of the soil medium displacements and deformations as well as the decrease of stresses in the foundations of building in the area of the distressing ditch application.

2.1. Geometry of the model, including the boundary conditions

The geometrical space of the problem consisted of a section of subsurface rock mass layer including a building founded there. The theoretical layout of the building – the subsoil, subjected to static and continuous mining interactions was analysed. The building was 10×10 m large in the horizontal plane and 6 m high (the ceiling slab was modelled as ferroconcrete floor and the structure of the walls as solid masonry), the foundations (reinforced concrete foundation footings) were 2 m deep. At a distance of 5 m from the building a ditch was modelled, filled with a flexible material (peat may be an example of such material), 30 cm wide and with a depth reaching below the level of the building foundation. In the analysis, it was assumed that at the moment of two surfaces contact (at a zero distance between them) full interactions in the normal direction to these surfaces take place, in turn, interactions in the tangent direction are transmitted through friction. During the calculations, cases were analysed when the coefficient of friction *f* was 0 then 0.1; 0.3; 0.5 and 0.7. All data presented below assumed friction coefficient *f* equal 0. The paper presents the results of numerical simulations for two ditch depths: 3m and 5m (Fig. 1).

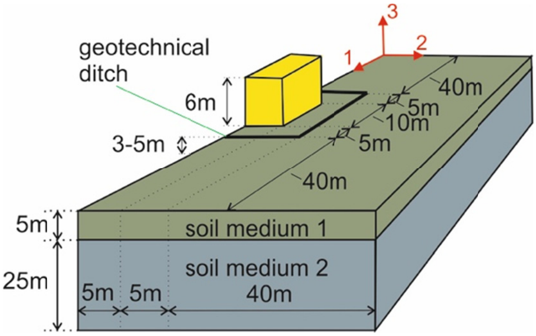


Fig. 1. General diagram of the computational model

To reduce the problem's size the system symmetry with respect to the vertical plane 1-3 was applied. Dimensions of the subsoil body were selected in such a way as to eliminate the influence of the boundary conditions on the stress and deformation state in the building and the protecting ditch surroundings.

An assumption was made that the building was affected by longwall mining carried out at a depth of approx. 455 m, at a rate of 2.4 m/day. The longwall extraction starts at a distance of 450 m from the building axis and proceeds along direction 1 of the system of coordinates, as shown in Fig. 2. The thickness of the mined seam was taken as 1.5 m. Displacement vectors, calculated in the prepared subroutine based on the Knothe geometrical-integral theory (Knothe, 1951) for the aforementioned mining situation, were assigned to the lower surface in the model. The calculated maximum deformation coefficients for this mining situation are:

- maximum ground subsidence: $w_{\max} = 1.2$ m,
- radius of main influences range on the surface: $r = 250$ m,
- maximum horizontal displacement: $u_{1\max} = 0.38$ m,
- extreme linear horizontal deformation: $\varepsilon_{\max/\min} = \pm 2.3$ mm/m.

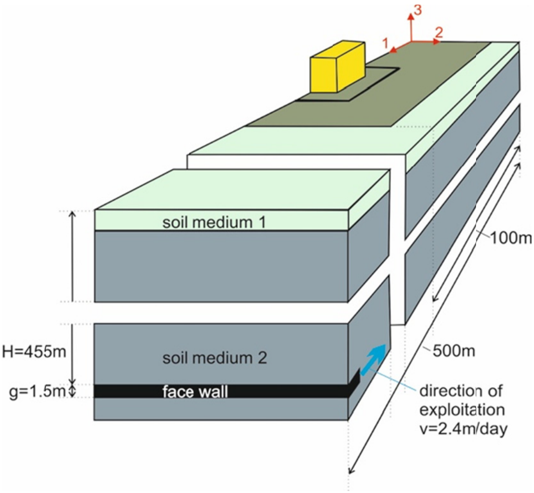


Fig. 2. Diagram of mining impact

Two models were adopted in the computations: linear-elastic and Coulomb-Mohr model. To simplify the considerations an assumption was made that the building and the material filling the ditch work within the elastic range and that this is linear elasticity. Instead, the Coulomb-Mohr material model was adopted for the modelled soil medium (the top and bottom geotechnical layer). In accordance with Fig. 1 two geotechnical layers were distinguished in the subsoil body:

- the top layer representing the soil medium 1 behaviour, 5 m thick,
- the bottom layer representing the soil medium 2 behaviour, 25 m thick.

In the building's area also two substitute material models were defined:

- model representing the masonry medium properties, and
- model representing the ferroconcrete floor properties.

The parameters adopted for individual materials are specified in Table 1.

TABLE 1

Values of parameters taken for 3D numerical calculations

Material of the rock mass / building	**Adopted model**	***E* (GPa)**	***ν* (-)**	***ρ* (kg/m^3)**	***φ* (°)**	***c* (kPa)**
top geotechnical layer (soil medium 1)	Coulomb-Mohr	0.40	0.38	1800	30	0
bottom geotechnical layer (soil medium 2)	Coulomb-Mohr	3.00	0.25	2400	34	0
masonry	linear-elastic	1.0	0.25	1600	—	—
ferroconcrete floor	linear-elastic	20.0	0.28	2500	—	—
material filling the ditch	linear-elastic	88.0E-06	0.33	1200	—	—

2.2. Back analysis

A discrete model, being a system of equations with a finite number of degrees of freedom, was created through processes of spatial and time discretization. Cubic, eight-node, linear finite elements with reduced integration points were used both for the building and for the rock mass. The analysed numerical model comprised nearly 500,000 finite elements. Fig. 3 presents the adopted grid of elements.

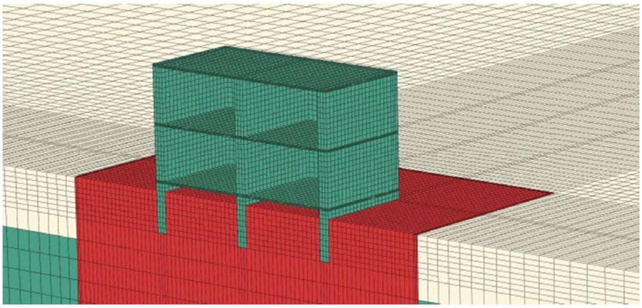
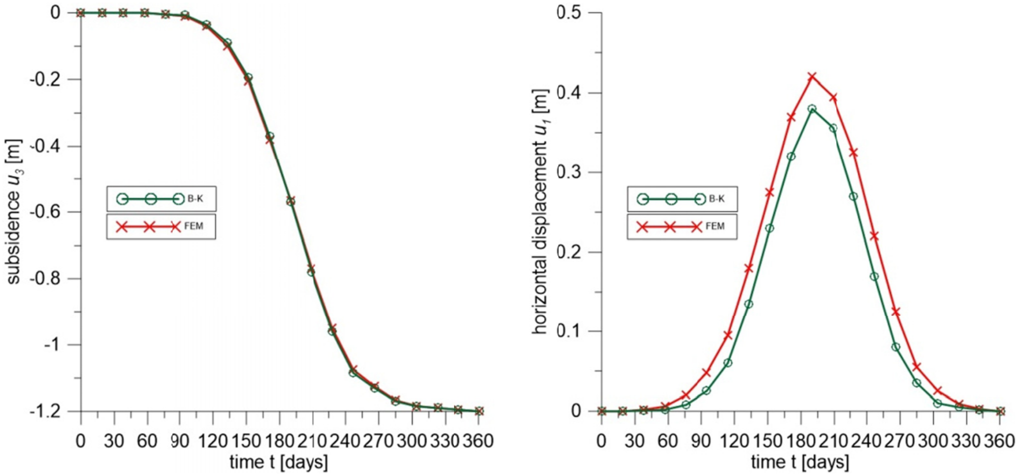


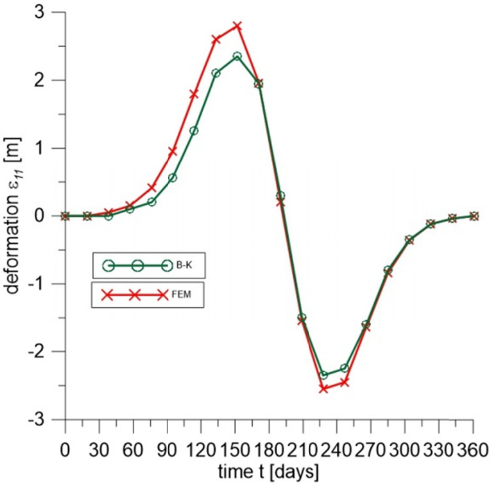
Fig. 3. Adopted grid of finite elements

To check the correctness of assumptions made for numerical FEM modelling, comparative computations were carried out for the deformation results for the Budryk-Knothe theory and for numerical modelling computation results. The computations were performed changing parameters of the modelled rock mass (soil medium) and then the results obtained from carried out numerical computations were compared with results calculated acc. to the Budryk-Knothe theory (Knothe, 1951; 1953) in accordance with the back analysis method. Computations were carried out until matching the subsidence trough u_3, horizontal displacements u_1, and deformations (horizontal strain) ε_{11}. This method was used to analyse a dozen or so areas of Polish hard coal mines (Tajduś, 2010).

Fig. 4 presents comparison of subsidence u_3, horizontal displacements u_1, and deformations ε_{11} at point P (50, 0, 0), i.e. at the building's axis.



(a) subsidence u_3 (b) horizontal displacements u_1



(c) deformations ε_{11}

Fig. 4. Comparison of theoretical course of (a) subsidence u_3, (b) horizontal displacements u_1, and (c) deformations ε_{11} for point P(50, 0, 0) over time acc. to the Budryk-Knothe theory (line with a circle – B-K trough) and obtained from numerical computations (line with a dagger – FEM trough)

3. Modelling the deformation course within the soil for models with and without the geotechnical protection

A series of numerical computations was carried out to evaluate the influence of geotechnical ditch on the reduction of adverse effects of underground mining operations in the building's structure and in the immediate vicinity of protected building. Numerical simulations comprising a full process of mining deformations trough development in the subsoil were carried out:

- for a building without protection,
- for a building protected with a ditch of depth reaching 1m below the foundation level (ditch 3 m deep),
- for a building protected with a ditch of depth reaching 3 m below the foundation level (ditch 5 m deep).

The obtained results of numerical calculations confirm the nature of soil behaviour in the vicinity of soil gaps (e.g. natural faults), observed in reality (Grün, 1995; Sroka, 2008). The nature of results obtained in various variants is similar.

Fig. 5 presents distributions of horizontal displacements u_1 at a selected time moment, on day 186 from the mining start. Displacement maps are shown for the situation of unprotected building and for the building surrounded by a protecting ditch in two depth variants (ditches 3 and 5 m).

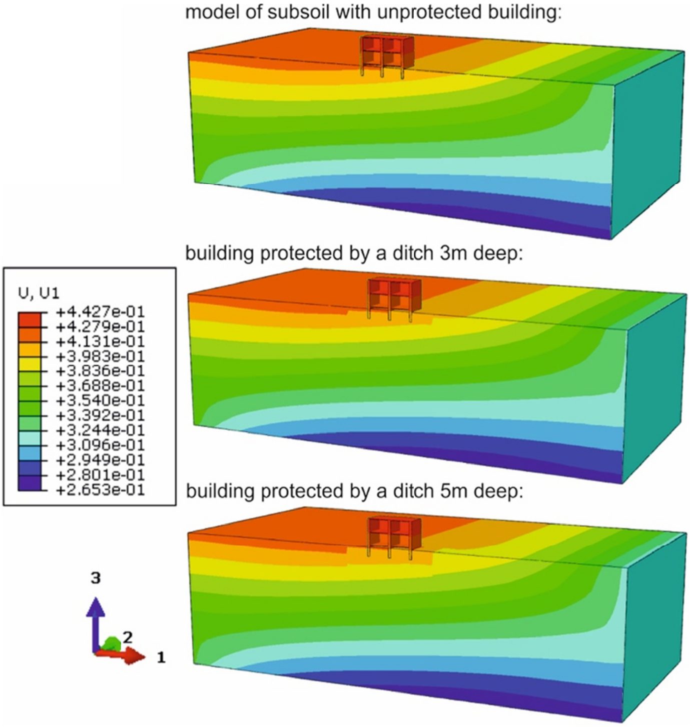


Fig. 5. Distributions of horizontal displacements u_1 for the model of subsoil with building unprotected by the expansion ditch and for the model with building protected by the expansion ditch 3 m and 5 m deep, for the time t = 186 days (0 m)

The comparison of displacement distributions at the same time moment for the variant with building unprotected and protected by ditches of various depth allows to distinguish a zone determined around the building by the existence of a gap in the soil. This zone is marked clearer in the case of the deeper ditch. The presented displacement maps show that the subsoil in the vicinity of the gap moves toward the gap and results in the ditch tightening. A zone of significant deformations originates around the ditch, reducing thereby the origination of large compressive deformations in the soil surrounding the foundation.

The time moment of 186 days (Fig. 6) is related to the building's location in the zone, in which compressive impacts occur for the building, much more adverse (the mining front existed at that time below the building's axis).

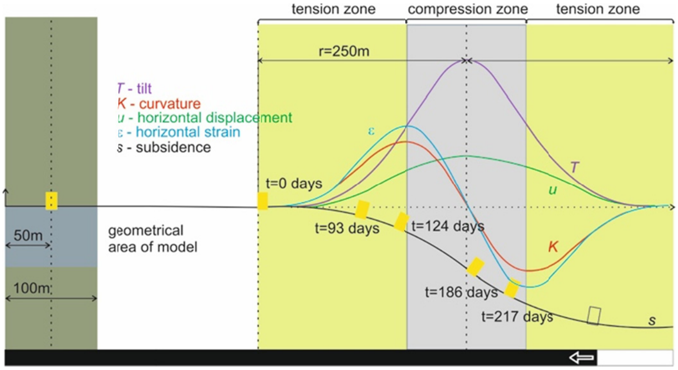


Fig. 6. Course of mining impacts in the analysed 3D problem

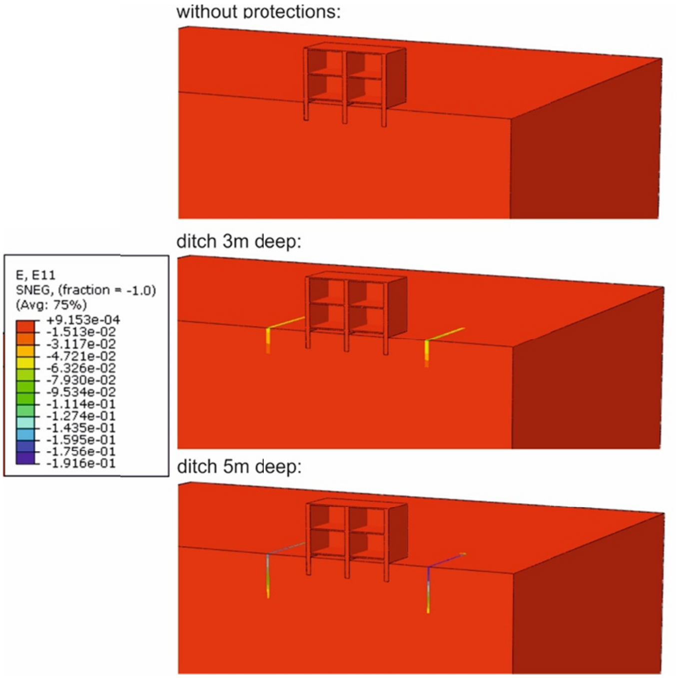


Fig. 7. Distribution of linear horizontal deformations ε_{11} for $t = 217$ days (80 m – extreme compressions)

4. The impact of excavated ditch in the vicinity of the building on the reduction of mining influence on the building's structure

The effect of deformations reduction is clearly visible in Figs. 7-8, which present distributions of deformations ε_{11} during the impact of extreme compressive deformations (for the time moment of 217 days, at a distance of mining front from the building's axis of approx. 80 m). The ditch tightening causes a local concentration of deformations inside it, as shown in Fig. 7. This zone fulfils the function of deformation shock absorber and causes that deformations are much lower in the area surrounded by the ditch.

This is well visible in Fig. 8, showing the deformation distributions, excluding the ditch area. A significant difference in the subsoil deformation values around the building can be easily noticed.

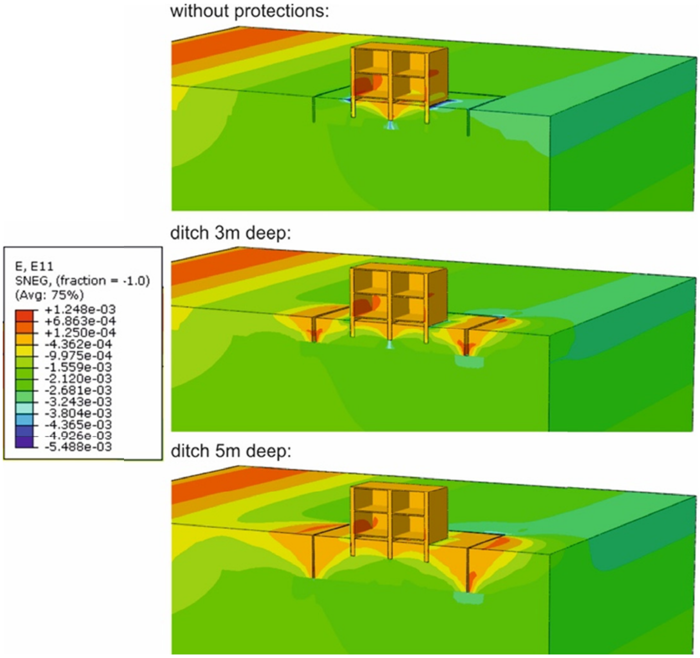


Fig. 8. Distribution of linear horizontal deformations ε_{11} for $t = 217$ days (80 m – extreme compressions) without taking into account deformations inside the expansion ditch

The possibility of soil movement to the inside of the geotechnical ditch results in a reduced level of compressive deformations in the mining subsoil. Fig. 9 presents the course of linear deformations ε_{11} drawn for the moment of extreme compressive deformations occurrence. A significant reduction of deformations due to the existence of the protecting ditch is visible. The reduction level grows with the increasing ditch depth. Assuming that for the unprotected building the deformation value is 100%, which has been denoted as $\varepsilon_{100\%}$, for the building protected by the ditch 3 m deep we obtain $0.52 \cdot \varepsilon_{100\%}$, i.e. a nearly twice smaller value. Instead, when the building is protected by the ditch 5m deep we obtain only $0.16 \cdot \varepsilon_{100\%}$, i.e. slightly more than 6-time reduced values.

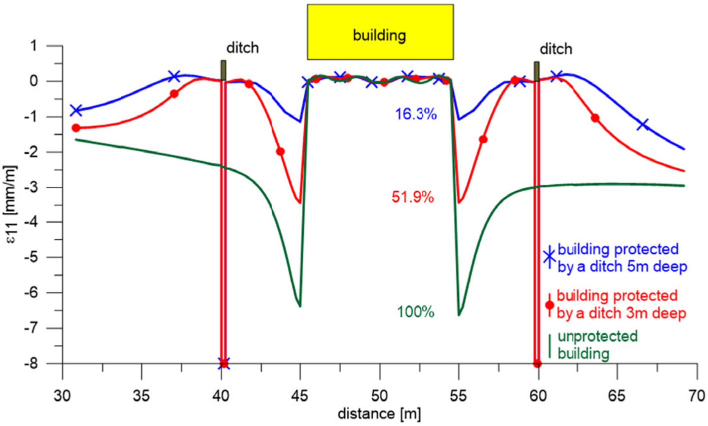


Fig. 9. Reduction of deformations ε_{11} at the building's foundation due to the existence of the expansion ditch. Distribution of deformations for $t = 217$ days (80 m – extreme compressions)

A similar analysis was carried out for stresses σ_{11} (Figs. 10-11) occurring in the zone of extreme (maximum) compressive deformations. In a similar way as at the reduction of deformations ε_{11} also significant reductions of the stress value are observed with the increasing depth of the building protection by a deeper ditch.

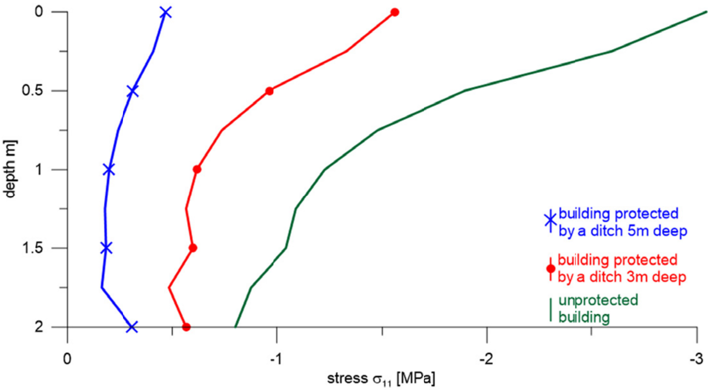


Fig. 10. Distribution of stresses σ_{11} acting on the building's foundation for $t = 217$ days (80 m)

Analysing these figures, it is possible to notice changes of distribution during the deformation and also the reduction of stress values caused by the modelling of expansion ditches in the vicinity of the building. A higher effectiveness of such solutions is obtained when a deeper ditch is excavated. Fig. 10 presents the situation at the moment of maximum compressive deformations occurring at the moment of $t = 217$ days affecting the building's foundations (at a distance of mining front from the building's axis of approx. 80 m).

Fig. 11 presents results for the time moment of $t = 124$ days (at a distance of mining front from the building's axis of approx. 160 m), i.e. for the situation, when the building was exposed to the maximum tensile deformations.

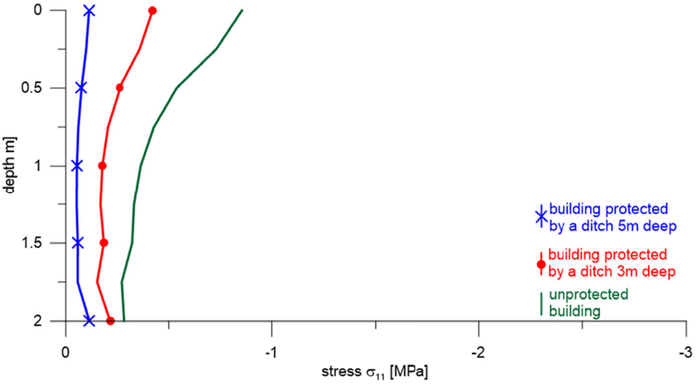


Fig. 11. Distribution of stresses σ_{11} acting on the building's foundation for $t = 124$ days (160 m)

Fig. 11 shows definitely smaller stress values as compared with the situation, where the building was situated in the maximum compression zone ($t = 217$ days, at a distance of mining front from the building's axis of approx. 80 m, Fig. 10). This situation confirms the fact showing a much bigger probability of hazardous damage to the building's structure occurrence in the situation, where the building is situated in the zone of maximum compressive deformations.

The reduction of acting compressive deformation values, obtained as a result of expansion ditches execution, causes reduction of stresses in the building's structure, originating from the mining operations. This effect is noticeable also in Figs. 12-13, showing distributions of maximum and minimum main stresses in the building for selected time moments.

The greatest reduction of maximum main stresses σ_{max} is observed in the zone of extreme compressive deformations ($t = 217$ days, the distance of mining front from the building's axis is 80 m), when the application of 3 m deep ditch causes that stresses amount then to approx. 72% of unprotected building stresses, and at a 5 m ditch the obtained maximum stress values are only 46% of unprotected building stresses (Fig. 12).

Similarly like at the distribution of maximum main stresses, also at the distribution of minimum main stresses (Fig. 13) for $t = 186$ days (the mining front was situated below the building's axis) the ditches influence is evident, when the application of a ditch 3 m deep causes that stresses amount then to approx. 66% of unprotected building stresses, and at a 5 m ditch the obtained minimum stress values are only approx. 38% of unprotected building stresses.

When analysing distributions of minimum main stresses, it is possible to notice a similar qualitative nature of changes occurring in the building as in the case of maximum stresses. With increasing ditch depth, the influence of the ditch on the decrease of stresses in the building's structure grows.

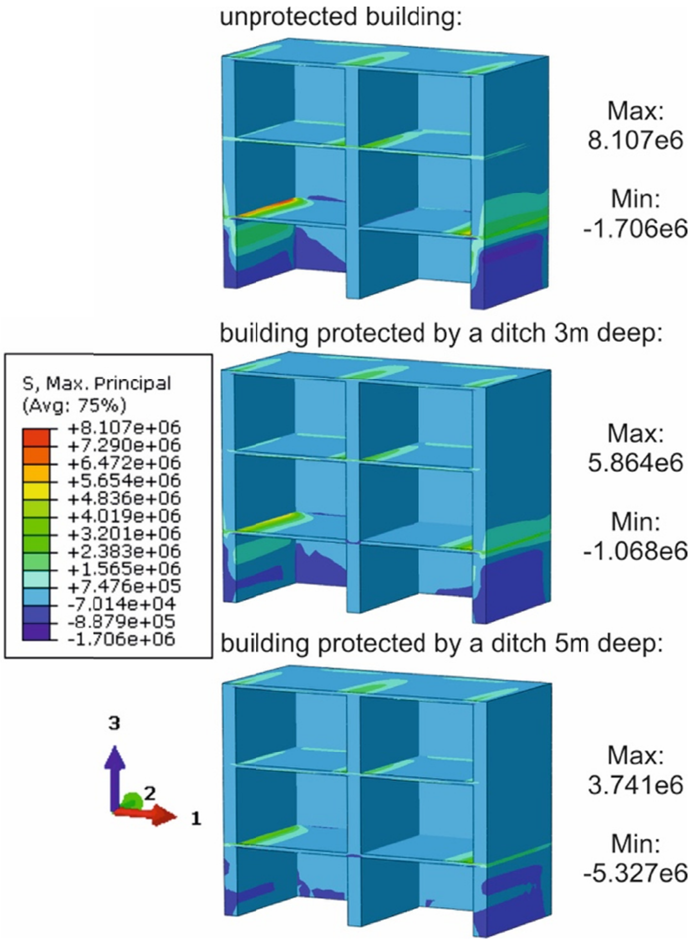


Fig. 12. Distributions of maximum main stresses $\sigma_{\max}$ [Pa] in the unprotected building and protected by a ditch 3 m and 5 m deep for the time moment of $t = 217$ days (80 m)

5. Discussion

Presented numerical analysis made it possible to get an answer to the question; to what extent and how geotechnical structures affect the results of surface deformation, and hence, the safety of a protected building.

The values of determined stresses depend on the adopted material models and on their parameters. It is obvious that those values will change depending on the actual geological and structural conditions of a real system. However, the effect of the mining impact reduction obtained in the computations is evident. Numerical simulations have clearly shown a significant reduction of adverse impacts in the case of an expansion ditch existence.

The reduction effect for subsoil deformation values, which acted on the foundation, was more effective at the application of a deeper ditch. In the computations considering a ditch reaching

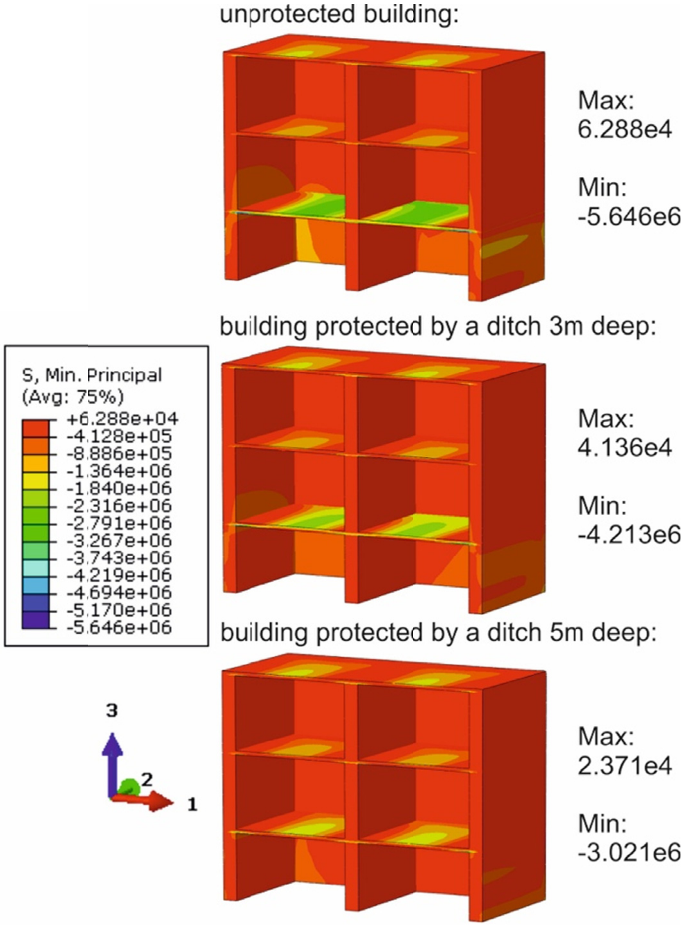


Fig. 13. Distributions of minimum main stresses $\sigma_{\min}$ [Pa] in the unprotected building and protected by a ditch 3 m and 5 m deep for the time moment of t = 186 days (0 m)

1 m below the building foundation level the value of deformations ε_{11} acting on the foundation was reduced nearly twice, while for a ditch reaching 3 m below the building foundation level the value of deformations was approx. 6 times lower as compared to the deformation values existing at the lack of protections. As a result of reduced values of adverse compressive deformations, the level of stresses originating in the building's foundations under the impact of mining was reduced.

At such analyses it is necessary to remember that the phenomenon of mining operations' (underground workings) impacts on the surface is very complicated, depending on many factors. In the numerical modelling it is impossible to take into account all factors because there is no accurate enough method to determine parameters, which would in detail and precisely characterize the considered rock mass. Hence it is practically impossible to determine qualitatively, but primarily quantitatively, the course of ground surface movements caused by the underground mining and by the 'surface' interference into the earth's crust (ditch execution). It seems justified to state, that under such conditions the obtained results should be required to provide sufficient data for practical objectives, which in turn would allow forecasting with some accuracy the surface deformation amount and would allow building engineers to apply appropriate methods preventing and minimizing the mining damage.

6. Conclusions

The performed numerical analyses have shown that the role of a protecting ditch (a vertical gap in the soil filled with a deformable material) is doubtless. Both the reduction of compressive and tensile stresses in the subsoil have been shown as well as resulting from this effect lowering of the level of stresses occurring in the building's structure.

Acknowledgments

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