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Research paper

Analysis of steel industrial portal frame building subjected to loads resulting from land surface uplift following the closure of underground mines

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Abstract: The liquidation of underground mines by the flooding leads to movements of the rock mass and land surface as a result of pressure changes in the flooded zones. The changes resulting from the rising water table caused by the changes in the stress and strain state, as well as the physical and mechanical properties of rock layers, can lead to damage to building structures and environmental changes, such as chemical pollution of the surface water. For this reason, the ability to predict the movements of rock masses generated as a result of mine closure by flooding serves a key function in relation to the protection of the land surface and buildings present thereon.
This paper presents an analysis of a steel industrial portal-frame structure under loading generated by the liquidation of a mine by flooding. The authors obtained land surface uplift results for the liquidated mine and used them in a numerical simulation for the example building. Calculations were performed for different cases, and the results were compared to determine whether limit states may be exceeded. A comparison was made between the cases for the design state and for additional loading caused by the uplift of the subsurface layer of the rock mass.

Keywords: mine closure; mine flooding; uplift; numerical modelling; industrial portal frame hall; mining damages

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1. Introduction

The impact of underground mining activity on deformation of the land surface and stresses in buildings structures has been the subject of much scientific research since the late 19th century [1]–[5]. This research has shown that mining activity has an adverse effect on the building infrastructure lying within its zone of impact [6]–[9]. It leads to deformation of building foundations, causes additional stresses in structures, and affects their stability. Buildings structures may be subject to tilting, fractures, cracking, or ultimately failure [8]–[10]. Each of the aforementioned causes may pose a risk to the safety of use of buildings. However, the degree of damage to a building subject to mining-related deformations is largely dependent on its flexibility with respect to deformations of its base. The flexibility of a superstructure is a significant factor, dependent on the interaction between the building and the base that is subject to mining-related impact. Depending on the building's flexibility, the structure adapts to a greater or lesser degree to the kinematic conditions generated by the deforming base. On the other hand, a structure that has been protected against the effects of mining will have greater rigidity in the plane of potential displacements generated by land surface deformations. It is assumed that a properly protected buildings will be capable of transferring additional loads without posing a safety risk. Determination of the additional loads resulting from deformation of the rock mass due to mining activity is one of the basic issues to be addressed during the design of structures located within the impact zone of mining operations.

Unfortunately, the increased rate of closure of European mines in recent years has entailed changes to the impact zones defined for particular mining operations [11]–[13]. This is due to the nature of the mine closure process, which involves flooding of the mining excavations [14]–[17]. This leads to secondary deformations of the rock mass [13], [18]–[20], characterised by uplift of the land surface [21]–[25], a relatively low value of deformation and, importantly, a much larger impact zone. The uplift itself is not very significant: it reaches values of approximately 5–8% of the measured subsidence resulting from the former mining activity. However, a significant change in the radius of impact of land surface deformation means that buildings structures which lack protection, because at the time of mining activity they were outside the impact zone[5], will be subject to additional loads resulting from the liquidation of the mines.

[5] In Poland, a mining area is defined as the space subject to predicted adverse effects of mining works (Article 6(1)(15) of the Act of 9 June 2011 titled Geological and Mining Law; Dz.U. 2020/1064). The boundaries of the area are defined in the concession granted to conduct mining operations. Within the mining area, so-called mining damage may occur.

In the international literature we can find descriptions of cases of rock mass movement in the form of land surface uplift, sometimes accompanied by damage to buildings ~~and~~ structures, especially in the neighbourhood of fault regions (Fig. 1) [26].

Fig. 1. Examples of damage to buildings subject to additional loads resulting from land surface uplift, analogous to those described in [26]

The impact of the process of mine flooding on the land surface is a problem that has become increasingly significant in recent years. There has not yet been any research into the impact of such processes on unprotected buildings located outside the mining area, which – due to changes in processes in the rock mass – may become subject to the effects of secondary deformations related to the flooding of the mines. Structural analyses to date have been limited to identifying the occurrence of damage (mainly related to discontinuous linear deformation of the base). In the present work, the authors performed calculations of changes of stress state in structural elements of a steel industrial hall building that was not protected against the effects of uplift. This is a field that has not been the subject of research to date.

2. Design requirements for structures subject to the effects of mining activity

All types of impact generated by mining operations must be taken into account either at the stage of the design of new buildings structures, or at the stage of their use (in the case of existing objects). In both cases, it is necessary to make suitable adaptations to the structure to enable it to withstand the additional load resulting from the effects of mining activity [9]. The division into new and existing buildings is a basis for differentiation both in the technological solutions used to provide protective measures, and in the way of determining the potential loads generated by underground activity and manifested on the surface of the mining area [1], [2], [27].

With the introduction of Eurocodes, requirements for the determination of combinations of loads for buildings structures in mining areas were made uniform. Cholewicki et al. [28] adapted the loads generated by continuous and discontinuous mining-related deformations and shocks to the load combinations defined by the PN-EN 1990:2004 standard [29].

To determine the limit states – the *ultimate limit state* (ULS) and *serviceability limit state* (SLS) – account must be taken of the additional load on the building structure resulting from mining activity in the combinations defined by PN-EN 1990:2004. When considering the ULS, two combinations are used:

- the basic combination, consisting of constant and variable impacts, which takes the form

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\gamma_g Q_{g,k}+\sum_{i>1}\gamma_{Q,i}\Psi_{0,i}Q_{k,i} \tag{1.1}$$

where:
$\gamma_{G,j}$ – the partial safety coefficient for the j-th constant impact,
$G_{k,j}$ – the characteristic value for the j-th constant impact,
γ_g – the partial safety coefficient for mining impacts,
$Q_{g,k}$ – the characteristic value for the mining impact caused by continuous deformations,
$\gamma_{Q,i}$ – the partial safety coefficient for the i-th variable impact,
$\Psi_{0,i}$ – the coefficient for the combination value of the i-th variable impact,
$Q_{k,i}$ – the characteristic value for the i-th variable impact;

- an exceptional combination, consisting of constant impacts, some variable impacts, and one exceptional load (in justified cases more than one exceptional load may be included), which takes the form

$$\begin{gathered}\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+0.8\cdot\gamma_g Q_{g,k}+0.8\cdot\sum_{i>1}\gamma_{Q,i}Q_{k,i}+A_w\\ \sum_{j\geq 1}\gamma_{G,j}G_{k,j}+0.8\cdot\sum_{i>1}\gamma_{Q,i}Q_{k,i}+\left(A_w\ or\ A_g\right)\end{gathered} \tag{1.2}$$

where:
A_w – denotes impacts caused by mining shocks,
A_g – denotes impacts caused by discontinuous deformations of the land.

In analysis of the serviceability limit state (SLS), two combinations are used for calculations, of which:

- the first is the basic combination consisting of constant loads and the one most unfavourable variable load

$$\sum_{j} G_{k,j} + Q_{g,k} + \sum_{i>1} \Psi_{0,i} Q_{k,j} \tag{1.3}$$

- the second is a combination referring to long-term impacts, consisting of constant loads and a part of the long-term variable loads

$$\sum_{i=1}^{m} \gamma_{fi} G_{ki} + 0.8 \sum_{i=1}^{m} \Psi_{0i} \gamma_{fi} Q_{ki} + A_w \tag{1.4}$$

These combinations are used at the stage of verification of ultimate limit states, according to the following criteria:

- EQU: due to loss of the static equilibrium of building structure or of any part thereof regarded as a rigid body;
- STR: due to internal failure or excessive deformation of the building structure (or its elements) where the strength of the structural materials is of key importance;
- GEO: due to failure or excessive stress of the ground base having significant importance for the load-bearing capacity of the structure, or when deformation of the base has significant importance for the load-bearing capacity of the building.

Proceeding in accordance with the ITB (Building Research Institute) instructions [28], continuous deformations of the surface being the result of mining activity are to be classed as exclusively short-term variable loads, and discontinuous deformations and vibrations of the surface as the effect of shocks and as exceptional loads.

3. Analysis of an steel industrial hall subject to the impact of uplift of the ground surface layer

3.1. Geological conditions

For the analysis, the authors chose the example of the Ostfeld section of the German Ibbenbüren mine, which is currently undergoing flooding. Mining activity in this area began in 1800, with mining of coal from the Glücksburg seam. Extraction operations ended in late 2018. The last worked coal seam was Flöz 78. During the lifetime of the Ibbenbüren mine, coal was extracted from 22 seams in the Ostfeld section, at depths of up to 1600 m below the ground surface (Fig. 2). With the decision to discontinue mining operations in this part of the mine, steps were taken to begin the process of its liquidation. The maximum permissible level of the underground water table was determined at approximately 65 m above sea level.

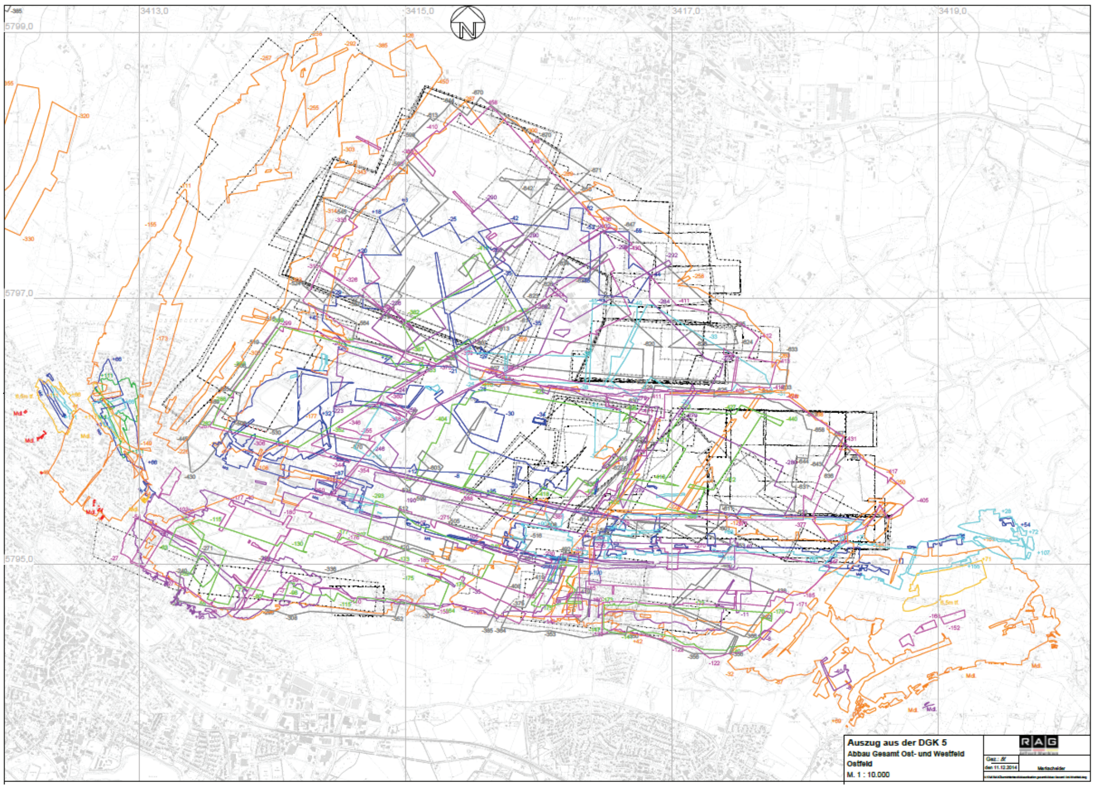


Fig. 2. Map showing areas of coal extraction [RAG Antrazit]

As a result of a prediction made by a research group [21] it was determined that the rock mass in the region of the Ibbenbüren-Ostfeld mine would be subject to uplift reaching a maximum value of 384 mm, located in the centre of the former extraction area. Because, in principle, buildings and structures within the mining area are protected to withstand significantly higher land deformations, the projected maximum uplift is not expected to have any adverse effect on their stresses and stability. However, a much more significant indicator for the current research is the radius of the main influence, which is much greater in the case of mine flooding than in the case of active mining work (Fig. 3).

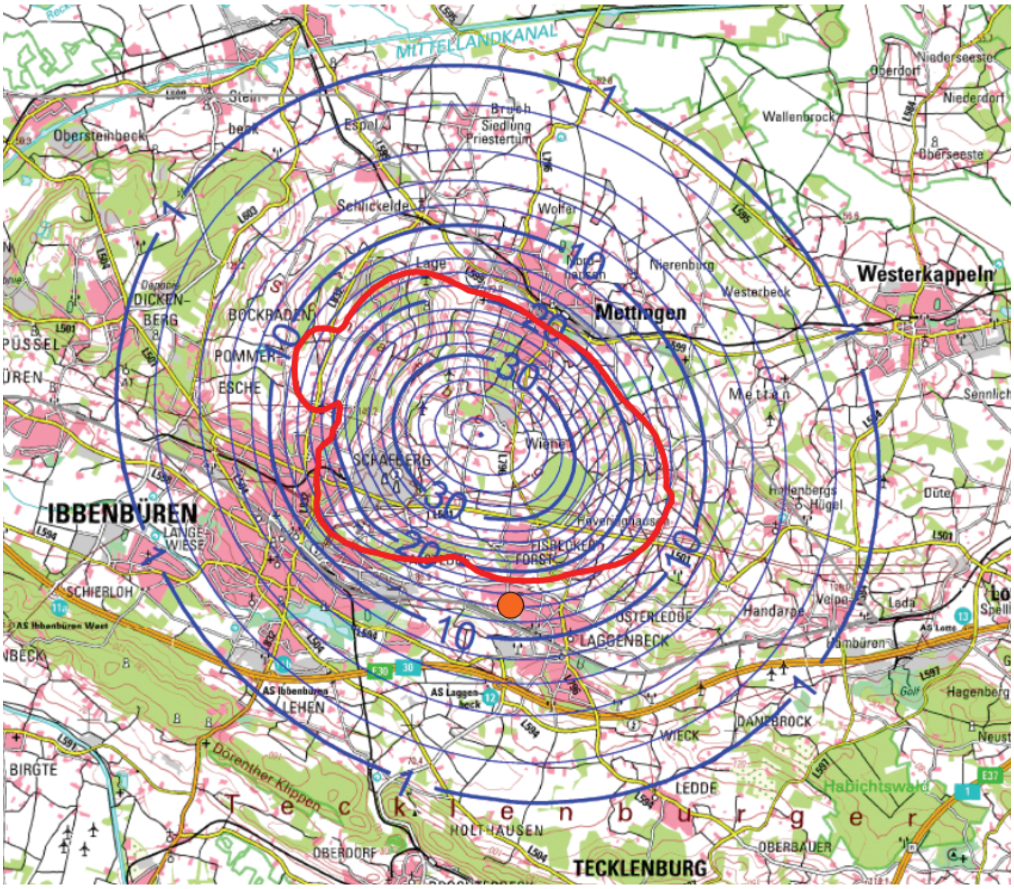


Fig. 3. Predicted values of land surface uplift (blue: uplift in cm; red: maximum extent of subsidence; orange spot: location of warehouse)

3.2. Characteristics of the studied steel industrial hall

The example building that is the subject of the present analysis of the effect of surface deformation due to uplift of the ground surface layer is an industrial portal frame made of steel. This building is not protected against possible mining damage. It is located outside the influence zone of the former mining operations (Fig 3 – red zone); however, due to the decision to flood the mine, it is currently within the influence zone of continuous surface deformations in the form of uplift (Fig. 3 – blue zone).

In view of its geometry and construction technology, the analysed construction is unsusceptible to non-uniform displacements of the base [27]. The building is shown in Figure 4. Its horizontal dimensions are 35.0×24.0 m, and its height is 7.0 m. The steel hall has three bays, with a construction based on columns and beams. The analysed structure is a hall industrial building. The superstructure in the lateral plane is a rigid steel frame fixed in the ground. It consists of steel columns of I-sections (HEB 300) and a connected steel girder of the same section but the different types (IPE 270). The subject hall consists of three naves: the main nave and two side naves. The girders of the side naves were connected to the columns of the main nave by a hinge. The outer columns of the side naves (HEB 200) were connected rigidly to the girders (IPE 200) and jointed to the ground. The building has 7 frames at intervals of 5.0 meters. Thus the total length of the structure in this direction is 35.0 m. The lateral dimension of the main nave is 12.0 m, while that of the side naves is 6.0 m. In the longitudinal direction, the system is braced in the wall and roof plane with "X" and "V" type bracing. In addition, longitudinal steel beams from rolled I-sections IPE profiles were used in the ridge of the main nave and at the edges of the hall in the floor plate area.

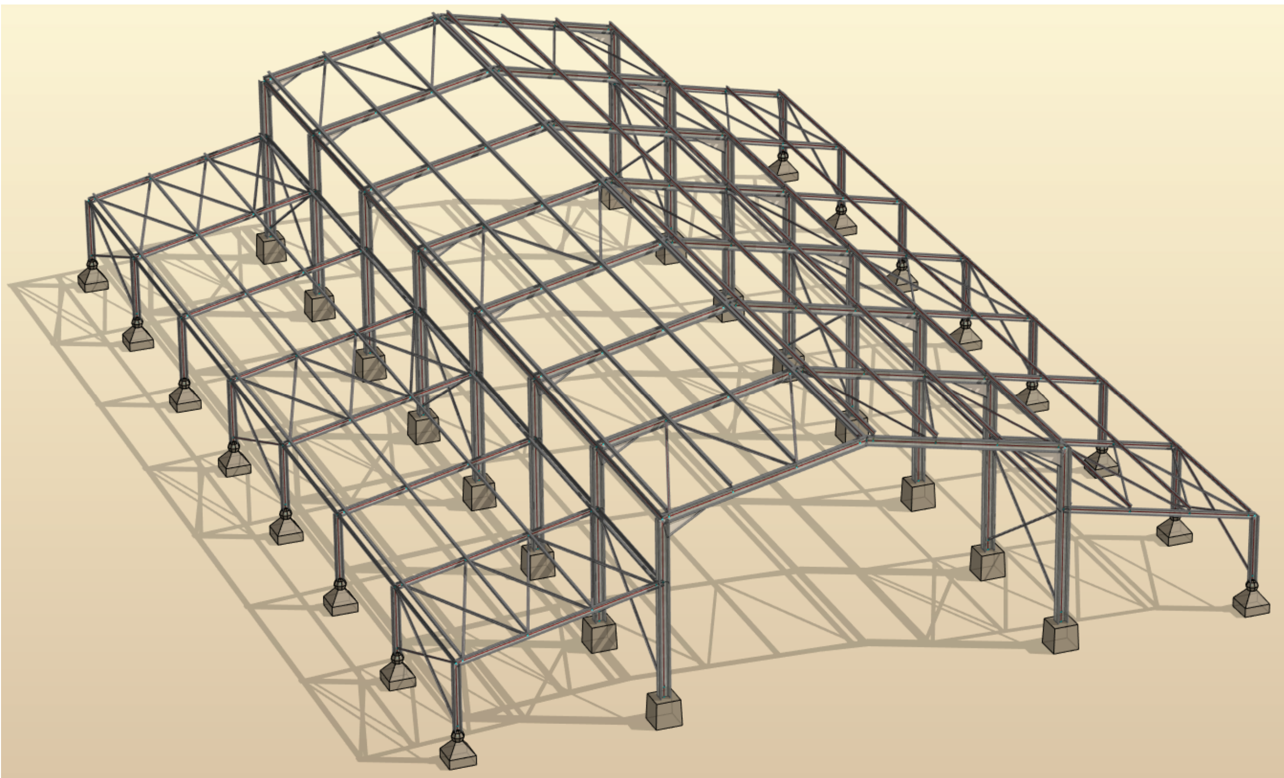


Fig. 4. Numerical model of the analysed structure, created using the Autodesk Robot Structural Analysis Professional [30]

3.3. Numerical computations

For the purpose of further analysis, a numerical model of the structure was created, which is shown in Fig. 4. The finite element method (FEM) and Autodesk Robot Structural Analysis Professional [30] software were used to create the model.

The created model was loaded with the following sets of loads:

- Load under the construction's own weight;
- Snow load in accordance with the standard PN-EN 1991-1-3. Eurocode 1: Impact on constructions. Part 1–3: General impacts – Snow load;
- Wind load in accordance with the standard PN-EN 1991-1-4. Eurocode 1: Impact on constructions. Part 1–4: General impacts – Wind impacts;
- Load resulting from displacements of the ground surface layer arising during flooding of the underground excavations (uplift).

In accordance with the PN-EN 1991-1-3 standard relating to snow load, analysis was made of cases of uniform and non-uniform loads on the roof, where the load was determined for both persistent and temporary situations. Three load cases were obtained for the part between the bays (ridge roof) and two each for the roofs of the side bays.

Wind load cases were determined based on the standard PN-EN 1991-1-3. To determine the loads, it was assumed that the building is located within a type I wind impact zone and on category III land. Ultimately, two cases each were obtained for loads in the X direction (transverse) and in the Y direction (lengthwise) of the structure.

The analysed building was also subjected to loads resulting from displacements caused by deformations of the ground surface layer, arising as a consequence of the flooding of disused underground excavations. The values of the displacements are tabularised for each of the supports (table 1).

The calculations were carried out within the ultimate limit state (ULS), and more precisely within the structural failure state (STR) which means internal failure or excessive deformation of the structure or structural elements). The calculations were carried out in order to refer to the effect of other loads, which are usually dimensioning in this type of objects (wind, snow, self-weight). The work focuses on the comparison of these effects with the results of calculations after the structure is loaded with an additional effect from soil uplift. Within the analyzed limit state, 138 load combinations have been obtained.

Tab. 1. Projected values of land surface displacements for the supports of the analysed warehouse (U1 – horizontal displacement in the X direction; U2 – horizontal displacement in the Y direction; U3 – vertical displacement)

Support no.	X [m]	Y [m]	U1 [mm]	U2 [mm]	U3[mm]
1	0	0	–8.0	9.5	180.1
2	0	5	–7.8	10.4	180.0
3	0	10	–7.5	11.3	180.0
4	0	15	–7.2	12.2	179.9
5	0	20	–6.9	13.1	179.8
6	0	25	–6.6	14.0	179.7
7	0	30	–6.4	14.9	179.5
8	0	35	–6.1	15.8	179.4
9	6	0	–7.4	9.80	180.0
10	6	5	–7.1	10.7	180.0
11	6	10	–6.8	11.6	179.9
12	6	15	–6.6	12.4	179.8
13	6	20	–6.3	13.3	179.7
14	6	25	–6.0	14.2	179.6
15	6	30	–5.7	15.1	179.4
16	6	35	–5.4	16.0	179.3
17	18	0	–6.1	10.4	180.0
18	18	5	–5.9	11.2	179.9
19	18	10	–5.6	12.1	179.8
20	18	15	–5.3	13.0	179.7
21	18	20	–5.0	13.9	179.6
22	18	25	–4.7	14.8	179.5
23	18	30	–4.4	15.7	179.3
24	18	35	–4.1	16.6	179.2
25	24	0	–5.5	10.6	179.9
26	24	5	–5.2	11.5	179.9
27	24	10	–4.9	12.4	179.8
28	24	15	–4.6	13.3	179.7
29	24	20	–4.4	14.2	179.6
30	24	25	–4.1	15.1	179.4
31	24	30	–3.8	16.0	179.3
32	24	35	–3.5	16.9	179.1

Computations of the deformation of the building were performed by applying the obtained land surface displacements directly to the foundations of the structure model, simulating the "worst case" and assuming that the deformation is fully transferred from the ground to the building foundations. For the model constructed in this way, subjected to standard loads and the effects resulting from deformation of the ground surface layer, a comparative analysis was made for two cases:

- W1: Model subjected to dead weight, wind, and snow loads;
- W2: Model subjected to loading only to the effect of surface deformation from mine flooding.

By adopting these loading schemes, it has been possible to identify those elements of the superstructure which are most likely to be at risk as a result of additional soil excitation. To keep the results clear and interpretable, reference was made to the combinations from the design stage (W1), generating all possible load combinations. The values of the relevant cross-sectional forces (longitudinal forces, transverse forces, and bending moments) were therefore compared. However, for the case of W1, all values were given in the form of an envelope. It should be recalled that the GEO state, due to failure or excessive stress of the ground base, was not considered in the analysis, because the analysis concerned only the possible effect of constant deformation (ground uplift) on structural elements of the building and their possible failure. Figures 5 and 6, for cases W1 and W2, show the bending moments distributions in two planes (transverse and longitudinal). For both cases (W1 and W2), the values of internal forces for representative groups of structural members are summarised in table 2.

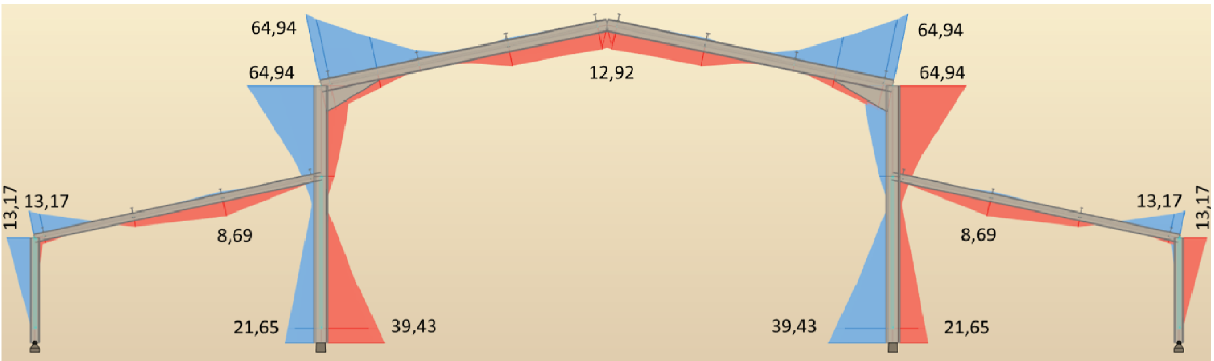
Tab. 2. Comparison of extremal values for internal forces in building elements for cases W1 and W2 (N – normal force; Q – shear forces (associated with the bending plane); M_x – bending moment in lateral plane, M_y – bending moment in longitudinal plane)

	W1					W2					W1/W2·100%				
	N [kN]	Q_y [kN]	M_x [kNm]	Q_x [kN]	M_y [kNm]	N [kN]	Q_y [kN]	M_x [kNm]	Q_x [kN]	M_y [kNm]	N [kN]	Q_y [kN]	M_x [kNm]	Q_x [kN]	M_y [kNm]
Columns main nave HEB 300	60,0	27,1	39,4	16,8	11,2	3,0	0,8	3,0	18,7	11,8	5,0	3,0	7,6	111,3	105,4
Columns sides naves HEB 200	27,3	12,1	13,2	5,9	2,9	11,7	0,2	0,6	22,0	5,6	42,9	1,7	4,5	372,9	193,1
Girders Main nave IPE 270	–	32,5	64,9	–	–	–	0,1	0,6	–	–	–	0,3	0,9	–	–
Wall braces main nave	8,9	–	–	–	–	24,6	–	–	–	–	276,4	–	–	–	–
Wall braces sides naves	3,5	–	–	–	–	23,3	–	–	–	–	665,7	–	–	–	–

Analysing the results obtained, which are presented in Table 2, it can be stated that the longitudinal component related to ground uplift has the greatest influence on the additional strain on the structure. This is manifested by the fact that, in comparison with the design situation (W1), the effect of ground uplift in the longitudinal plane (M_y, Q_x) definitely exceeds the level obtained taking into account the influence of the internal load, wind, and snow (the uplift here is respectively: 111,3÷372,9% for shear forces in columns and 105,4÷193,1% for bending moments in columns in the longitudinal direction). In addition, a group of the most sensitive structural members became apparent, which in this case are the bracings (276,4÷665,7% exceedance of the stress level from the design stage W1). In this case, the stresses caused by ground uplift are up to 6 times higher than the effects of the loads included in the combinations for case W1.

The above results show that in the case of existing building structures, especially those with a non-determinate static scheme, the overstressing of structural members must be taken into account. In limit situations, this may lead to exceeding the safety threshold of existing structures assumed at the design stage. In addition, with reference to the group of hall-type structures, it may be generalised that the most vulnerable elements are bracing.

a)



b)

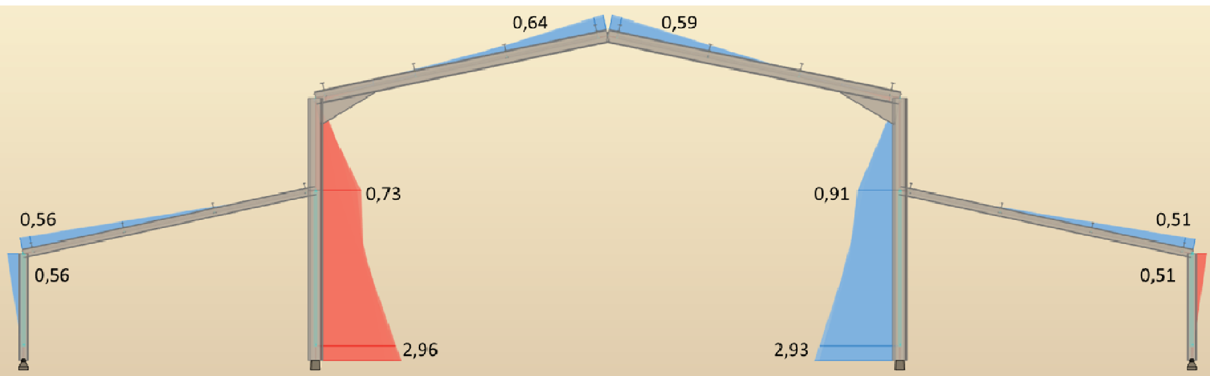


Fig. 5. M_x – bending moments in lateral plane for a) case W1 and b) case W2

a)

b)

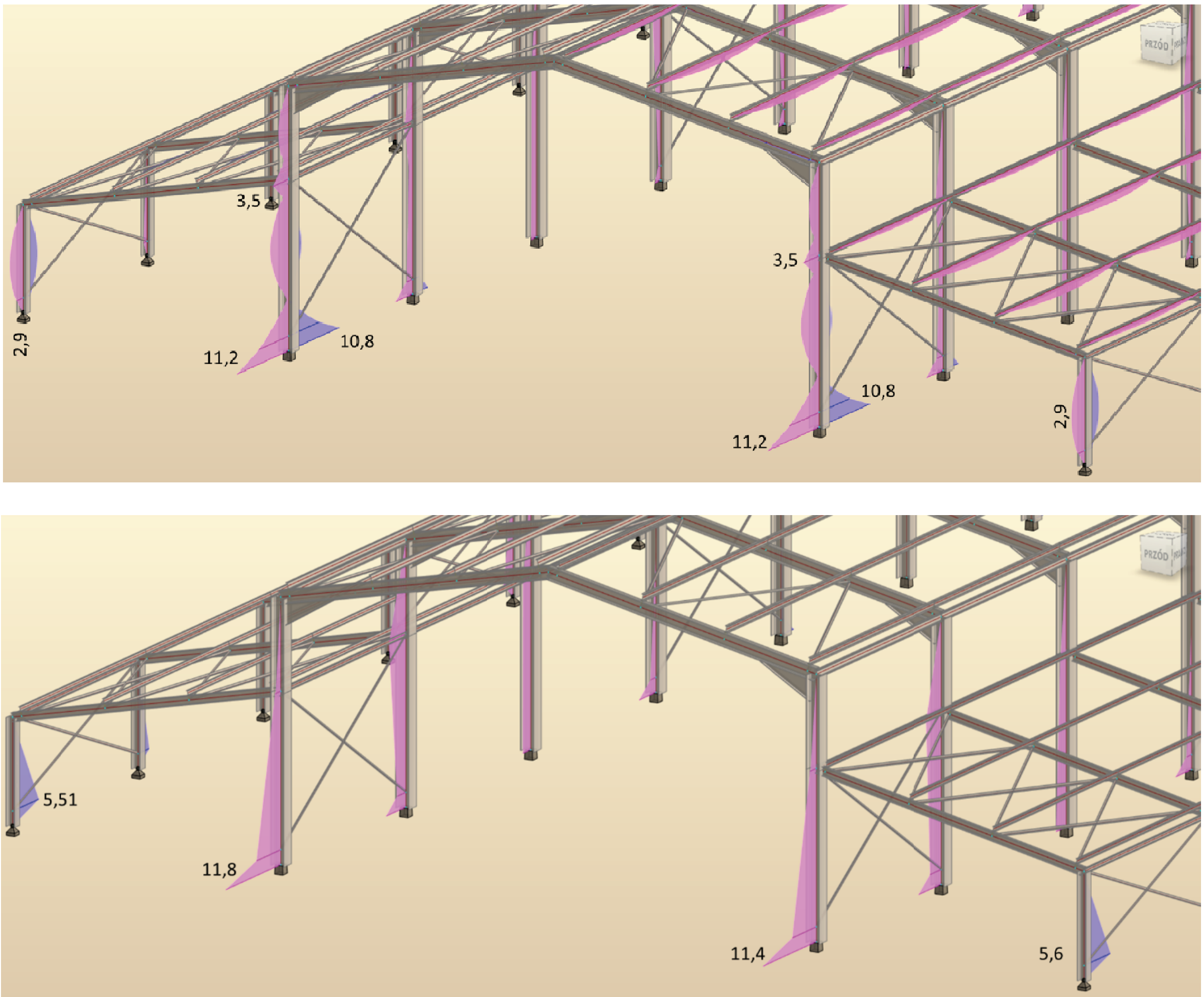


Fig. 6. M_y – bending moments in longitudinal plane for a) case W1 and b) case W2

4. Conclusions

This study has looked at the impact on buildings structures of surface deformations resulting from the flooding of underground mining excavations. Analysis was applied to an example building – a steel industrial portal frame hall structure – which is not protected against mining-related effects, but is located within the zone of rock mass uplift. Comparing the results obtained for the different analysed cases, it was found that the behaviour of the structure designed to transfer appropriate standard loads (produced by snow, wind, its own weight, and utilisation of the building) changes as a result of the additional load caused by the uplift of the ground surface layer. Loads obtained from the simulation generate additional strength of the structure which was not foreseen at the design stage, and which may cause limit states to be exceeded. Through a sensitivity analysis, the wall bracing was found to be the most sensitive of all load-bearing components. They may thus lead to structural damage, as is evidenced by numerous cases observed worldwide following the closure of many underground mines.

For newly designed buildings, given the results of the analyses obtained, it is necessary to take into account the loads from ground uplift in the load combinations already adopted at the design stage. For existing buildings, on the other hand, the analyses show that particular attention should be paid to the structural components carrying loads in the longitudinal direction, in particular bracing. In such cases, in order to adapt the structure to the new situation resulting from ground uplift, it is advisable to replace the cross-sections of the bracings so that they carry the additional loads efficiently. In conclusion, given the results obtained, it is advisable to inspect the load-bearing capacity of these elements and reinforce them if necessary.

In this work we have considered the impact exerted on buildings structures by continuous deformations only. The flooding of closed mines may also lead to the occurrence of discontinuous deformations. These will be the subject of further research.

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Analiza żelbetowej hali magazynowej poddanej obciążeniom pochodzącym od wypiętrzenia powierzchni terenu będących skutkiem likwidacji podziemnych kopalń przez zatapianie

Słowa kluczowe: likwidacja kopalń, zatapianie kopalń, modelowanie numeryczne, stalowa hala magazynowa, szkody górnicze

Streszczenie:

Likwidacja podziemnych kopalń przez zatapianie prowadzi do ruchów górotworu i powierzchni terenu w wyniku zmian ciśnienia w strefach zatapianych. Zmiany wynikające z podniesienia się zwierciadła wody podziemnej, spowodowane zmianami stanu naprężenia i odkształcenia oraz właściwości fizycznych i mechanicznych warstw skał mogą prowadzić do uszkodzeń powierzchniowych obiektów budowlanych oraz zmian środowiskowych, takich jak chemiczne

zanieczyszczenie wód przypowierzchniowych. Z tego względu możliwość przewidywania ruchów górotworu powstających w wyniku likwidacji kopalń przez zatapianie pełni kluczową funkcję w odniesieniu do ochrony powierzchni terenu i znajdujących się na nim budynków.

W artykule przedstawiono analizę przemysłowej stalowej hali magazynowej pod obciążeniem wynikającym z likwidacji kopalni w wyniku jej zatapiania. Autorzy uzyskali wyniki wypiętrzenia terenu zlikwidowanej kopalni i wykorzystali je w symulacji numerycznej przykładowego budynku. Obliczenia przeprowadzono dla różnych przypadków, a wyniki porównano w celu określenia, czy możliwe jest przekroczenie stanów granicznych. Dokonano porównania pomiędzy stanem projektowym i dla dodatkowego obciążenia spowodowanego wypiętrzeniem przypowierzchniowej warstwy gruntu.

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