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EVALUATION OF THE ELASTIC MODEL OF A BUILDING ON A CURVED MINING GROUND BASED ON THE RESULTS OF GEODETIC MONITORING

This article presents a comparison of the real amount of structural bending of a traditional residential building on curved mining ground with the bending results from an elastic model of the system: building + ground. Thanks to surveying measurements conducted during the exploitation front, the relationship between the curvature of the building and the curvature of the area in its direct vicinity was determined. The measurement work lasted one and a half years. Observation results collected in nature verify the deformation results of the modelled structure in the approach proposed by the guidelines for designing buildings in mining areas in Poland. Building Research Institute Instructions, Guidelines, Guidance 416 (2006) allows the adoption of an elastic model for the structure, and for the ground, it allows the adoption of linear elastic features characteristic of Winkler elastic ground. The main purpose of the work was to determine the overestimation of stress in the modelled building resulting from the use of a simplified, computational engineering approach.

Keywords: mining subsidence, ground curvature, numerical analysis, masonry structures

1. Introduction

The curvature of a mining area in tandem with horizontal deformations is one of the biggest threats to the construction of buildings on a deforming ground (Kwiatek et al., 1997; Kwiatek 2007; Szojda, 2009). For these reasons, several thousand such objects are damaged every year as a result of mining operations (Kulczycki & Piątkowski, 2010). The estimation of internal forces in a building on a deforming ground is both difficult and necessary for the effective implementation of appropriate building damage prevention (Kwiatek et al., 1997; Kwiatek, 2007;

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Szojda, 2009; Mrozek et al., 2017). The above-mentioned methods were focused on building protection and prevention against mining influence. An interesting method for decreasing mining influences on construction was presented by Misa et al. (2018), where a significant lowering of these influences was achieved by digging a trench around the building foundation. A different approach for a building analysis under mining deformation was considered by Deck et al. (2003) and Saeidi et al. (2009). They described the structure vulnerability according to materials use and building geometry, depending on the predicted mining subsidence. Finite element method (FEM) software was used to model the curvature and horizontal ground deformations. Due to the high degree of difficulty in describing the phenomenon of the interaction of a building with a mining ground, simplified models for both the building and the ground are usually used in an engineering approach. The simplest ones proposed by the Building Research Institute (2006) are a substitute beam layout or substitute beam grillage. Thanks to the development of information systems, structures in mining areas are more often analysed with the help of widely available programs based on FEM (Hughes, 2012). In such a computing environment, buildings are most often represented by spatial shell models of a structure close to the actual object. The problem of modelling the ground is usually reduced to a typical linear elastic Winkler analogue (Fedorowicz, 2006; 2008). This article compares the dependence of the actual building and mining ground curvatures with the same dependences obtained in the calculation model: building + ground.

The analysed building was presented as a spatial shell model located on a curved Winkler ground. The results of geodetic monitoring allowed evaluating the deformation of the object obtained in the modelling.

2. Description of analysed construction and operating data

The analysis was based on a three-storey building from the 1920s, erected using a traditional brick technology. The ceilings over the basement were made using Klein technology; the others are wooden. Photo 1 shows the southern elevation of the building.

This is a typical example of residential construction from the turn of the 19th and 20th century in Silesia. The overall dimensions are length 44.3 m and width 11.8 m. The building was

Photo 1. Southern facade of the analyzed building

made as one piece, without dilatation. The wall of the exploitation front that runs directly under the object is perpendicular to its long edge. The location of the analysed building relative to the exploited field and operational progress over time are shown in Fig. 1.

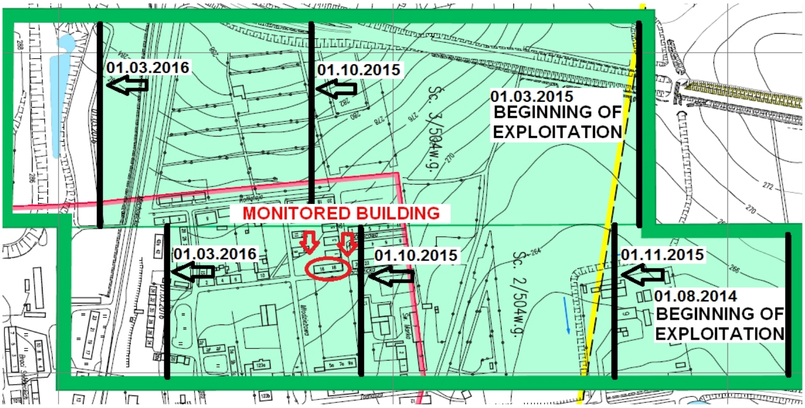

Fig. 1. Location of the building relative to the field of exploitation and operational progress in time
Source: Kapusta (2017) based on materials from Bobrek-Centrum Coal Mine

During the transition of the exploitation front, cyclical geodetic measurements of the ground curvature and curvature of the building were carried out simultaneously. The curvature of the ground was measured on a field line located parallel to the longer (44 m) building wall. The curvature of the building was measured on the southern external wall, parallel to the field line. The results of the measurements are described in detail in Kapusta (2017). Selected results are shown in Fig. 2.

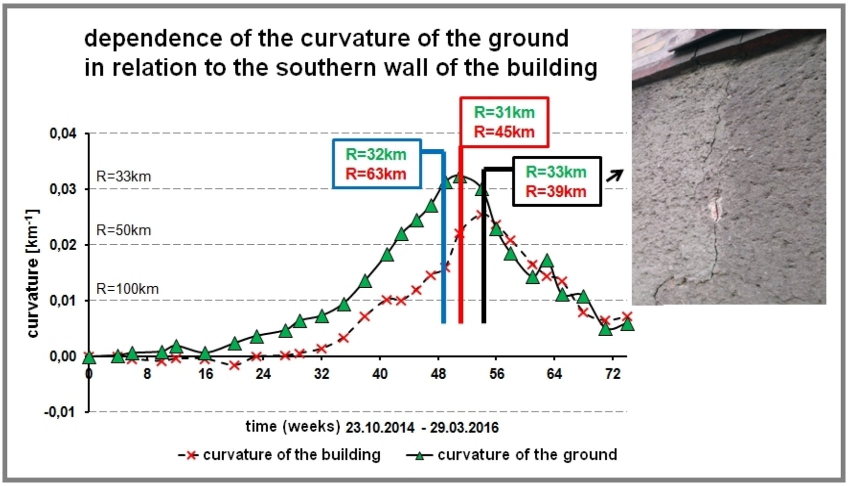

Fig. 2. Variability of the curvature dependence of the building in relation to the curvature of the area during the passage of the exploitation front under the building. *Source:* Kapusta (2017)

The curvature increase was determined on tilt changes for two adjacent measuring sections. Sections 4-5 and 5-6, with length about 25 m each, were considered. The location of the measurement line in relation to the long-wall of the building is presented in Fig. 3.

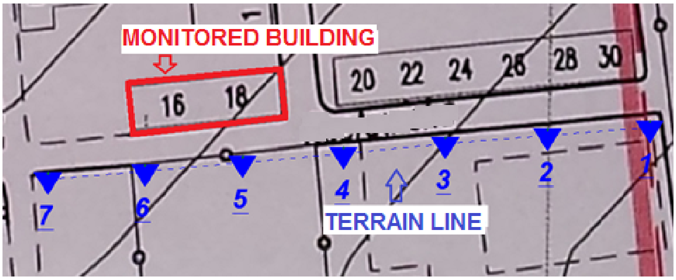

Fig. 3. Location of the measurement line with benchmark points in relations to the monitored building
Source: Kapusta (2017)

The tilt changes for measurement line Sections 4-5 and 5-6 in relation to time are presented in Fig. 4.

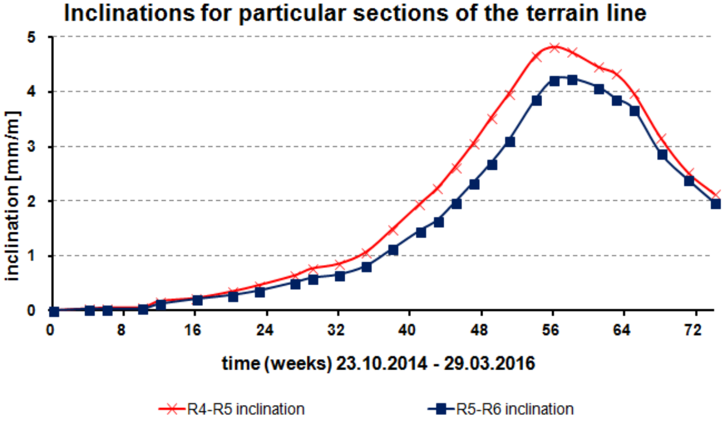

Fig. 4. Tilt changes for measurement line Sections 4-5 and 5-6. *Source:* Kapusta (2017)

3. The model of the building

The field observation results show that in the initial phase, the curvature of the building is smaller than the curvature of the terrain. Then, both curvatures take similar values. In modelling the problem, the moment of maximum terrain curvature (51st week of observation), causing the creation of maximum internal forces in the building structure, was selected as the main point on the timeline. After 51 weeks of observations, when the curvature of the terrain reached the maximum value ($R_{\max\ TERRAIN}$ = 30.8 km), the curvature of the building was even higher and, in the 54th week of observation, was greater than 3 weeks earlier despite the already decreasing curvature of the terrain. This phenomenon may be related to the occurrence of a crack in the wall of the building monitored during this period. Until the 51st week, the construction of the object did not lose its continuity; hence, the last moment on the time axis was adopted for modelling, when the building was not damaged – the point marked with a red vertical line (Fig. 2).

Model Autodesk Robot Structural Analysis Professional 2019 was used to model the building on a curved bed. The building model geometry was adopted based on an inventory.

Following the Building Research Institute guidelines, the building was modelled as a spatial shell object resting on a flexible ground. The wall thicknesses were assumed according to real measurements based on taking stock of the structure. Depending on the position, the thickness of the basement walls was 52 cm and the walls above were 38 cm. Material features, as is usually the case at the engineering level, were assumed as linear elastic. The brick wall material was assumed to be homogeneous. The material parameters adopted for the analyses were determined based on macroscopic studies:

- compressive strength of the wall $f_k = 2.2$ MPa,
- volumetric weight of the wall $\gamma = 18$ kN/m^3,
- long-lasting modulus of elasticity of the wall $E = 900$ MPa.

The analysis does not take into account wooden ceilings and roof constructions due to their insignificant stiffness; they do not constitute stiffeners for the bent building.

After making the outcrop of foundations in the foundation level, clay was found in the hard-plastic state with the following parameters:

- the degree of plasticity $I_L = 0.2$,
- internal friction angle $\phi = 18°$,
- cohesion $c = 32$ kPa.

The terrain curvature model was made according to the Building Research Institute guidelines, in the form of vertical forced displacements set in elastic support nodes imitating the ground. The value of the terrain curvature radius was taken based on field measurements, $R_{TERRAIN} = 30.8$ km. Vertical displacement vectors were determined graphically (Fig. 5).

The elasticity coefficient for Winkler theory was assumed according to Businesque theory. This solution was implemented in the geotechnical part of the engineering software package

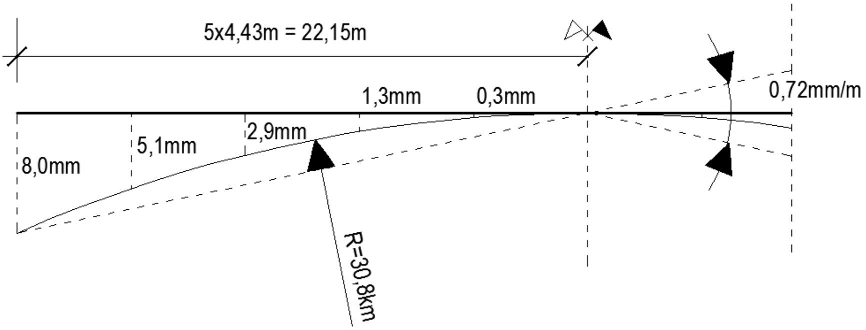

Fig. 5. Displacements of elastic supports in accordance with the curvature of the area with a radius of $R = 30.8$ km, given in calculations

Autodesk ROBOT Structural Analysis. The coefficient of elasticity for the supports also depends on the width of the foundation bench. Finally, for internal foundation benches with 1.0 m width, the elasticity coefficient was assumed as $K_z = 28.3$ MN/m and, for external 0.8 m width, the coefficient was $K_z = 23.4$ MN/m. During the measurement work in the area, in addition to the curvature of the terrain and the building, a tacheometric measurement of the terrain surface horizontal deformations was also performed (Ostrowski 2015). In combination with the maximum curvature of the terrain, horizontal deformations of $\varepsilon_{\max} = 0.9$ mm/m in the direction parallel to the longer wall of the building were observed for measurement line Sections 4-5 and 5-6 (Fig. 3). The calculations included their occurrence by applying tangential stresses under the bases of the foundations according to Building Research Institute Instructions, Guidelines, Guidance 416/2006. In addition to accounting for mining influences, the building model was also subjected to a load resulting from its own and utility weight (Fig. 6).

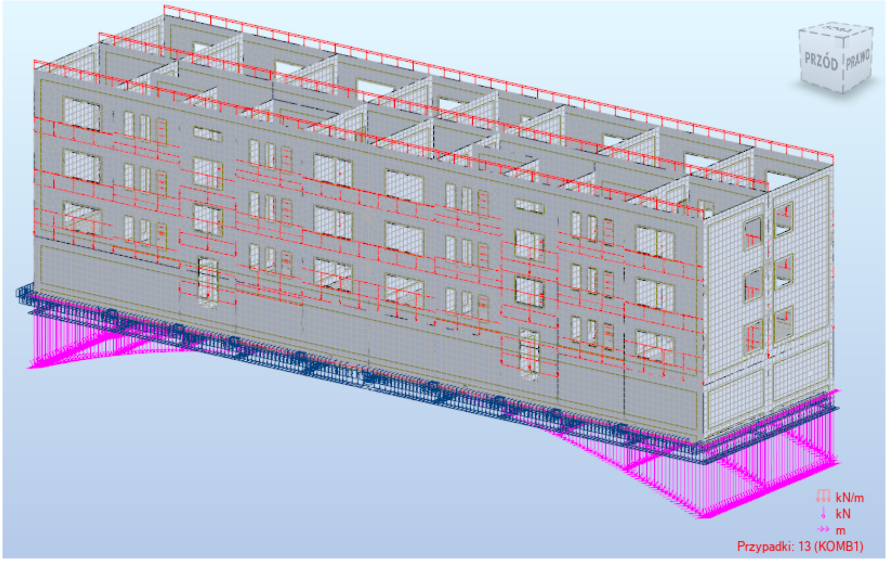

Fig. 6. The calculation model of the building + ground layout including all interactions

4. Results of numerical calculations

After applying loads and mining impacts, the building model underwent deformations. To compare the deformations of a real building with the model, vertical displacements in nodes located where wall repairs were installed on the actual structure were analysed (Fig. 7). True vertical displacements for these points are known. The results of comparing the model with the real condition are shown in Fig. 8.

Apart from the fact that the inclination of a building in nature is based on comparisons, it appears that the bending of the modelled structure is much larger than the real building. The radius of the model building curvature is $R_{Kmod} = 33.6$ km, whereas in reality, $R_{Kreal} = 45.0$ km. The difference is about 35%.

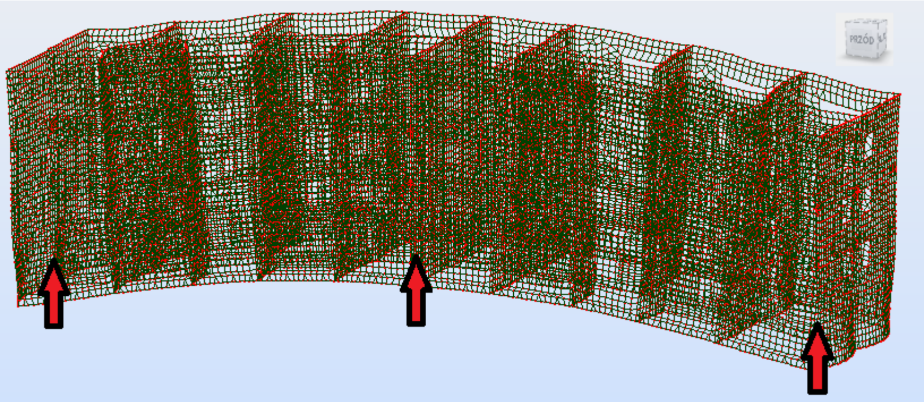

Fig. 7. Deformations of the calculation model

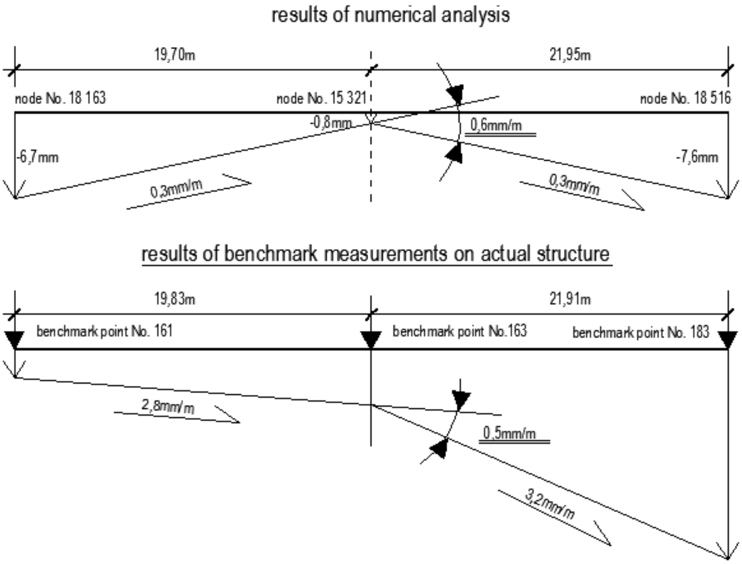

Fig. 8. Comparing bending results of the real building curvature with the modelled one

The bending of the modelled structure being larger than in nature suggests excessive stresses in the bent construction of the building, putting engineering considerations on the safe side. To estimate the differences in the amount of stress resulting from an overestimated model in relation to the actual curvature of the building, two systems have been modelled:

A) building + ground, in which the ground base represented by the parametric model was bent to the curvature of the area measured in the field measurements (Fig. 9A),
B) building resting on rigid supports on which forced displacements were applied in accordance with the real curvature of the building with radius $R_{Kreal} = 45.0$ km, measured in the field measurements (Fig. 9B).

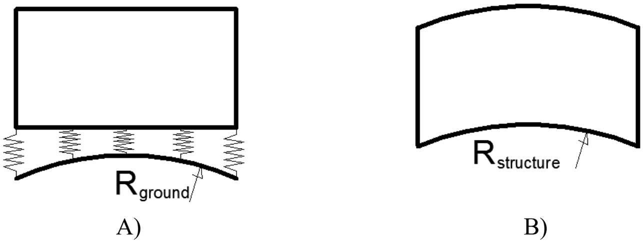

Fig. 9. A) Model of the building on a flexible ground, B) Model of a rigidly supported building with a curvature of the structure

To compare the amount of stress in both models, graphs of horizontal stress distribution (through the centre of the wall) were generated in the place of the expected maximum values caused by the curvature of the area. The model calculation of stress distribution for low disks according to the Building Research Institute is shown in Fig. 10.

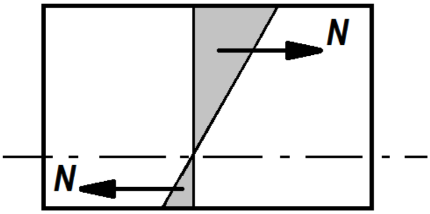

Fig. 10. Model calculation stress distribution in the low wall

Two bending (longitudinal) walls of the building were selected for comparison. Middle, much less perforated (Fig. 11 – red) and entrance area with a larger number of window openings

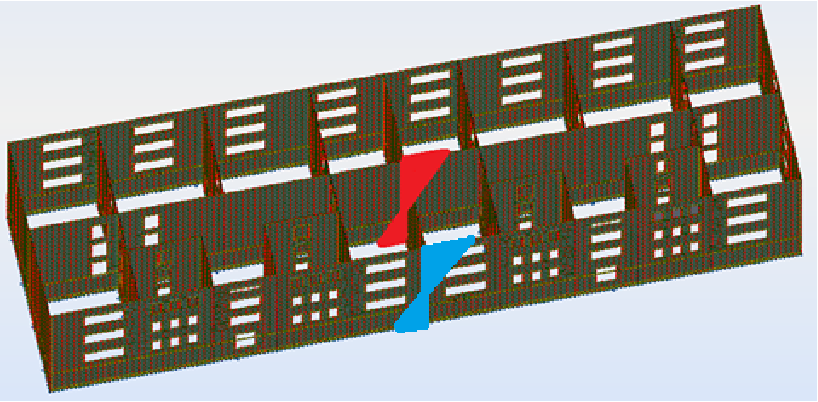

Fig. 11. Sections in which the distribution of stresses in the walls of the analysed structure was determined: central-red, incoming-blue

(Fig. 11 – Blue). The model distribution of calculation stress according to the Building Research Institute is shown on the analysed building walls with the colours red and blue (Fig. 9).

The results of numerical analyses are presented in Figures 12 and 13. These are differences in the amount of stress between the two models shown in Fig. 9A and 9B.

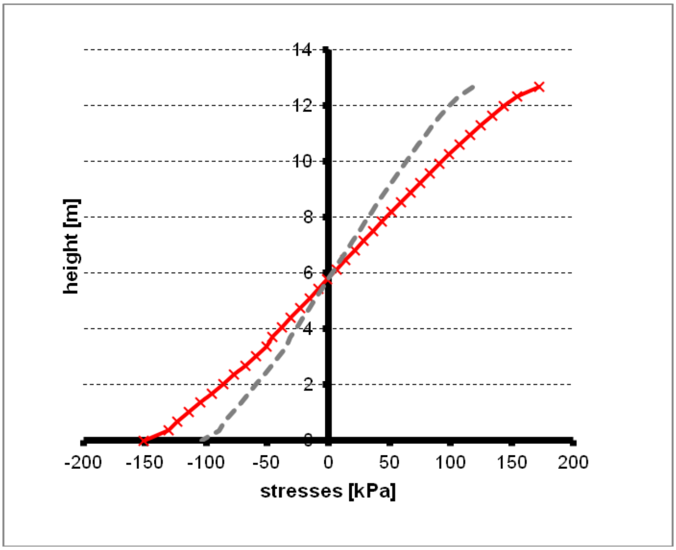

Fig. 12. Differences in the amount of horizontal stress in the cross-section of the middle wall between the building model on a curved ground (red) and the building model bent to the curvature of the structure (grey)

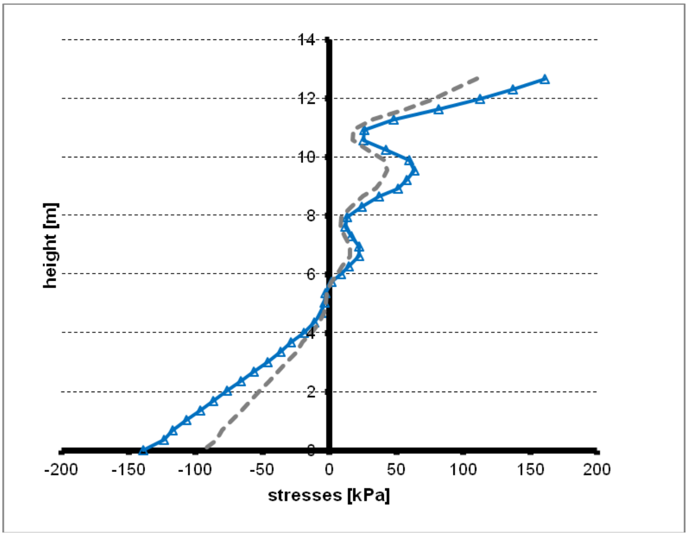

Fig. 13. Differences in the amount of horizontal stress in the cross-section of the entrance wall between the building model on a curved bed (blue) and the building model bent to the curvature of the structure (grey)

To visualise differences in the distribution of stresses in the partitions of both models, Figure 14 A, B presents the maps of horizontal stresses in the same scale.

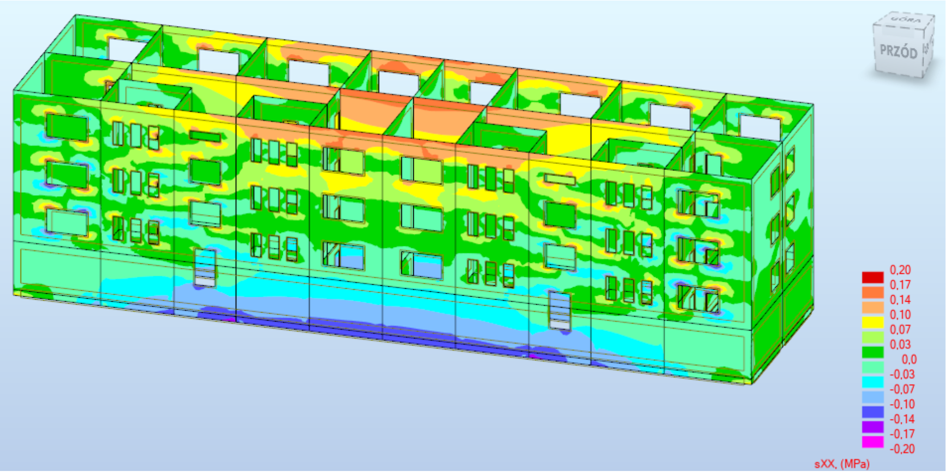

Fig. 14A. The map of the amount of horizontal stress in the building model on a curved ground

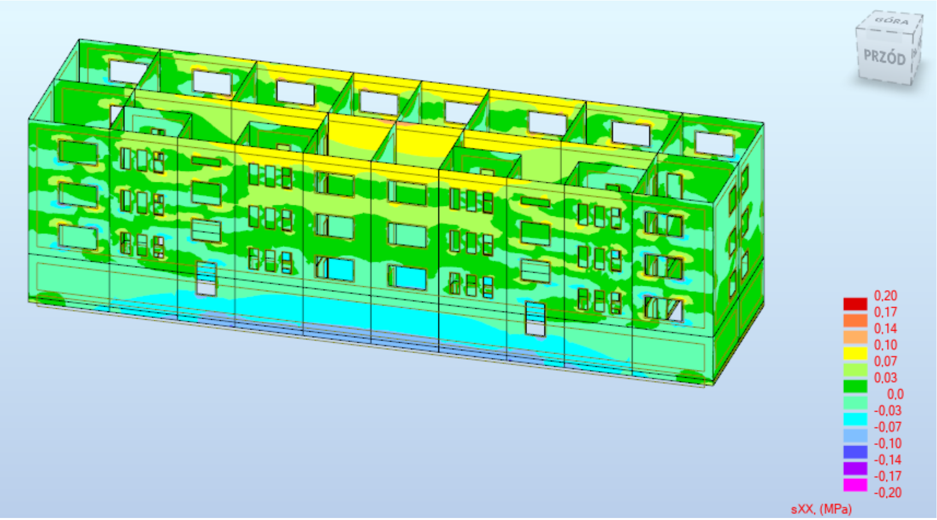

Fig. 14B. The map of the amount of horizontal stress in the building model bent to the actual curvature of the structure

The character of stress distribution for both models is similar. The essential differences occur in the amount of stress. For the building + ground model, in which the curvature of the terrain was applied, much higher stress values were obtained than for the building model bent to the actual curvature of the structure.

5. Conclusions

From the conducted analyses, the amounts of stresses in the elastic partitions of the building model from the system: building + ground are much greater than the stresses obtained in the same structure model bent to the actual curvature of the building. The difference in both cases (Fig. 12, 13 and 14) is approx. 45%. This is undoubtedly related to the fact that the modelled structure is more bent from the layout: bed + building in relation to the real building. The difference in the radius of the curvature of the construction in both cases was about 35%.

Analysing the graph (Fig. 12), the distribution of stresses in the central wall (much less perforated) is actually almost rectilinear. This is similar to the computational stress distribution proposed in the Building Research Institute Instructions, Guidelines, Guidance 416/2006 instructions. This is one of the characteristics of elastic models. The greater the perforation of the bending wall, the greater the disturbances of the straight-line stress distribution in the analysed model.

The main goal of this work was to determine the amount of overestimation of stresses caused by mining influence in a model commonly accepted by the engineering group, building + ground with a poorly advanced model of the ground. The verification for the model was the actual dependence of the curvatures for the building and the ground observed in nature. The most important observation is the fact that the scheme of the elastic bed curved to the curvature of the ground proposed by the Building Research Institute Instructions, Guidelines, Guidance 416/2006 instructions in the consideration of the curvature effect on the building is a solution that is definitely safe and, therefore, consistent with the idea of engineering calculations. Based on the assumptions made according to Building Research Institute in modelling the layout: building + ground, the structure bending was greater than in reality. Consequently, the amount of stresses, in this case, is safely overestimated. However, the adopted model is still only a far-reaching simplification of the actual system: building + ground. This is mainly due to the weakness of the ground bed model. In such a little advanced ground model, it is impossible to observe phenomena that occur in nature during the formation of the convex curvature of the terrain, such as a decrease in parameters describing the strength properties of the bed resulting from the curvature of sliding or plasticisation of the ground in the central zone under the building due to stress concentration in the foundation of the building. Apart from the above phenomena, the ideally elastic bed model affects the building model to a greater extent than it does in natural conditions. Therefore, the obtained stress results in the structure model are overestimated. The problem of correct building modelling on curved ground in a more advanced form undoubtedly requires a skilful interaction of two different design environments: ground and construction.

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