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NUMERICAL ANALYSIS OF BUILDINGS LOCATED ON THE EDGE OF THE POST-MINING BASIN

The rim of a post-exploitation basin is a particularly dangerous zone for buildings. This is due to the impact of mining on the nearby buildings, which persists even after exploitation activities are finished. The rim of the basin remains constantly deformed. This paper presents numerical analyses of buildings located in Marklowice (Silesian Voivodeship, Poland). They are located in an area that was exploited for mining, above the initial exploitation edge on the rim of the basin. The area of the analysed buildings was geodetically monitored during mining works. The results of the measurements allowed the observation of changes in terrain deformation indicators, together with the determination of the settlement's final values after the operation was completed. Knowledge of the results enabled the preparation of numerical analyses of buildings with the use of the finite element method (FEM), the purpose of which was to determine the residual stresses in the structures after the end of the exploitation. The results are presented in the form of stress maps, which show changes in the internal forces in buildings left by mining operations. Specific examples are used. Two residential two-storey buildings were analysed; they were built using traditional brick methods, with a single-storey outbuilding. All of the analysed buildings are located in the mining commencement zone, in which the deformation of the surface has not faded away.

Keywords: mining subsidence; masonry structures; numerical analysis; post-mining areas

1. Introduction

The currently dominant tendency in the energy sector is to abandon energy production from fossil fuels and replace them with renewable sources. This is especially visible in Europe, for example in publications [2] and [6]. However, the transformation of the energy sector is a long

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and very expensive process. In this case, Poland is a unique country due to the existing strong connection of energy safety with the mining industry, presented in [22] and [23]. For at least the next few years, hard coal will still be exploited in Poland [10]. The effects of mining activities carried out in Poland will be felt for many years after the end of mining operations. The Upper Silesian Coal Basin is the main operating training ground in the country. Here, exploitation is performed in a deep underground way, almost exclusively with the collapse of the roof. Such activity poses a significant threat to buildings and infrastructure, as presented in [10], [14] and [19], not least because it results in depressions forming at the ground surface. When analysing post-mining areas, particular attention should be made to the basin's edges. These are the zones where deformation indicators 'freeze', to some extent [1] and [20] (Fig. 1) for the fixed shape of the basin.

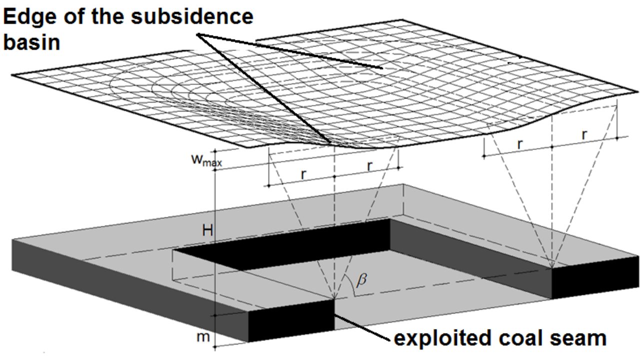

Fig. 1. The subsidence basin created as a result of exploitation
(*Source:* own study)

The deformed ground surface that remains after the exploitation ceases, has continuously affected buildings, leaving traces in the form of additional stresses in the building structures. The most destructive in this range is the horizontal deformations and the curvature of the terrain, which affect the structure of buildings, changing the original system of internal forces presented in [7], [14], [25], [29], [31]. Objects located on the route of the advancing operational front are subjected to impacts that vary over time. Located inside the exploited field, at a safe distance from the edge after exploitation, they rest on the bottom of the basin where, apart from lowering the terrain, the remaining influences fade away, theoretically. In the case of buildings located above the edge of the exploited field, the situation is different. In this case, the horizontal deformations and curves resulting from exploitation have a fixed character and do not fade away [14] (Fig. 2). For the structures located there, this means the introduction of additional stresses, permanently disturbing the balance of already existing internal forces. Buildings with a high centre of gravity are also exposed to a change in internal forces as a result of the slope of the terrain created on the outskirts of the basin [24]. For low-rise buildings, changes in inclination have little effect on the change of internal forces. It should also be mentioned that geotechnical methods reduce the impact of deformable subsoil on building structures, which are presented in [18] and [26]. These methods, however, are much less used than the protection and strengthening of the structure itself.

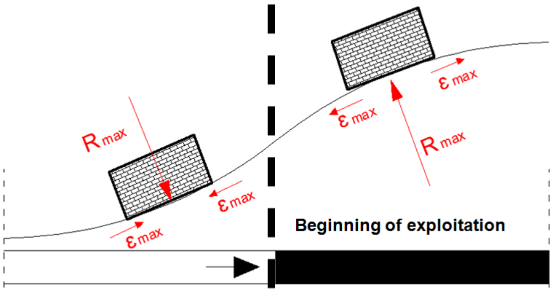

Fig. 2. Diagram of the impact of the basin edge on the building (*Source:* own study)

2. Characteristics of the research field and mining activities

Marklowice is a small town in the Silesian Voivodeship in Wodzisław County, Poland. Nearly 80% of the area is farmland. The dominant buildings are small, single-family houses with outbuildings. It is a mining area, and the exploitation in the Marklowice region is continuing. Due to the cave-in of exploited deposits lying at a depth of approximately 300 m, very large deformations are forecast here (categories IV and V of mining area deformation in the Polish mining industry). The exploitation analysed in this study is characterised by the following parameters: depth of exploitation – 320 m, the height of the exploited wall – 3 m, and mining technology – caving in. The width of the exploited wall is about 190 m. Due to the high variability and the hard-to-predict pace of change of the deformation rate, the place of the commencement of exploitation is very special, presented in [8]. This interesting area was adopted in the study as a testing ground (Fig. 3).

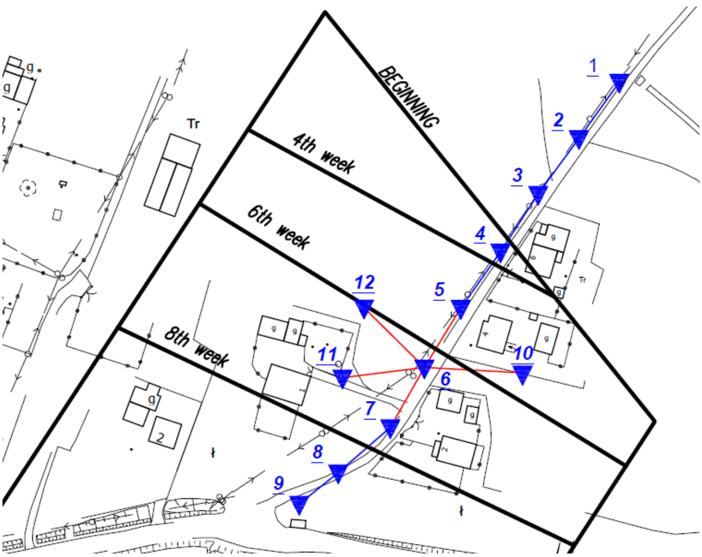

Fig. 3. Location of the points of the field rosette and the progress of the operational front in time
(*Source:* own study based on materials from the Marcel Coal Mine)

According to forecasts, after exploitation, this area will settle by about 2.0 m in the central part; the terrain deformations will be classified as category IV. The area above the plot in use is built-up. These are mainly small residential buildings with accompanying outbuildings. The building structures are described as traditional brick walls with densely ribbed ceilings, as well as partially wooden ones. The lack of a reinforced concrete skeleton makes the objects highly exposed to the negative effects of mining activities [29].

3. Field research

To monitor the extent of the deformation of the terrain surface, two auxiliary systems were stabilised in the field: a line consisting of eight sections (points 1-9) and a five-pointed rosette with a central point (no. 6), see Fig. 3. This location of points was dictated by the desire to determine the difference in surface deformation between the points, and not the total settlement, which does not affect changes in internal forces in the structure. Each of the installed geodetic field marks is a steel bar, stabilised at a depth of about 1.3 m below the ground surface on a concrete foundation, according to [21]. Periodic geodetic measurements were performed at the field points of lines 1-9. A Sokkia SDL 50 code leveller was used for levelling. The accuracy of the instrument is defined as a standard deviation, e.g. for 1 km of double-levelling it is ±1.5 mm. The first, so-called ‘zero measurement’, took place four weeks before the start of the exploitation. Changes in the geometry of the subsoil were then monitored at two-weekly intervals. After just over a year, the measurements were finally completed, once no further changes in the geometry of the line had been observed for three months. Additionally, along with the levelling measurements, a change in the length of individual sections of the rosette was also observed. The diagram in Fig. 4 presents changes in the shape of the field line. The measurements were only performed to find the size of the terrain deformation indicators, hence the monitored area points were not linked to fixed benchmarks outside the impact zone. Only the impact of the deforming subsoil on the development was investigated in the study; analysis of land subsidence was not the subject of the study. Fig. 4 only shows the changes in the shape of the field line.

The diagram shows that, in the initial stage of the measurements, slight changes in the ground geometry were observed. The dynamics of the changes intensified in the 16th week after the commencement of the exploitation. Each subsequent measurement was carried out at

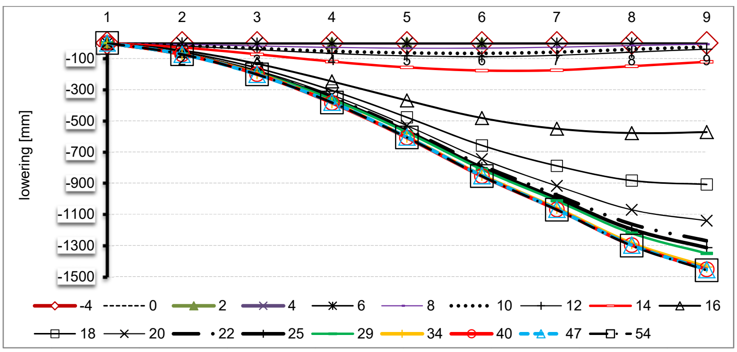

Fig. 4. Lowering the field line during the exploitation (*Source:* own study)

approximately two weekly intervals, showing significant changes in the shape. 22 weeks after the start of the measurements, a slowdown in the dynamics of the changes in the shape of the terrain surface was observed. Starting from the 40th week until the end of the observations, no significant changes in the geometry were observed, therefore, it was decided that the measurements on the 54th week should be terminated.

Based on the known slopes of individual sections of the field line, changes in the terrain curvature were also determined, as observed at the points of the line: 2-8 (Fig. 5).

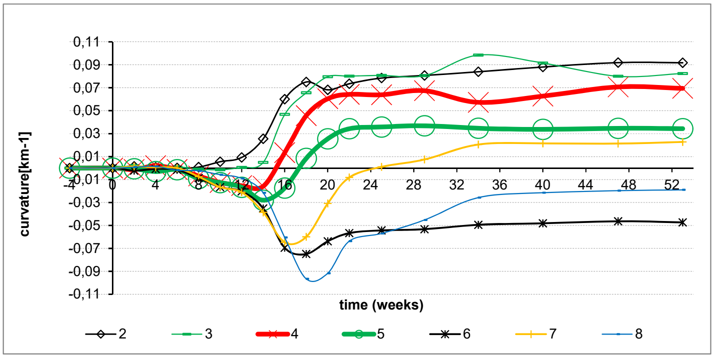

Fig. 5. Variable curvature of the terrain at the points of the field line over time (*Source:* own study)

The diagram in Fig. 5 shows that the accumulation of changes in curvature took place between the 8th and 22nd week after the commencement of the exploitation. The following weeks represented the period of curvature index stabilisation. The maximum convex curvatures were recorded at points 2, 3, and 4, which is consistent with the initial predictions. The closer to the interior of the subsidence basin, the greater the spread of curvature sizes. At points 6 and 8, the end of the curvature is concave. Point 7 shows a slightly convex curvature. The results show that the interior of the basin after exploitation remained 'wavy' and variable in terms of curvature.

While observing the changes in the length of the rosette sides, changes in the horizontal deformations inside the exploited field were also observed (Fig. 6).

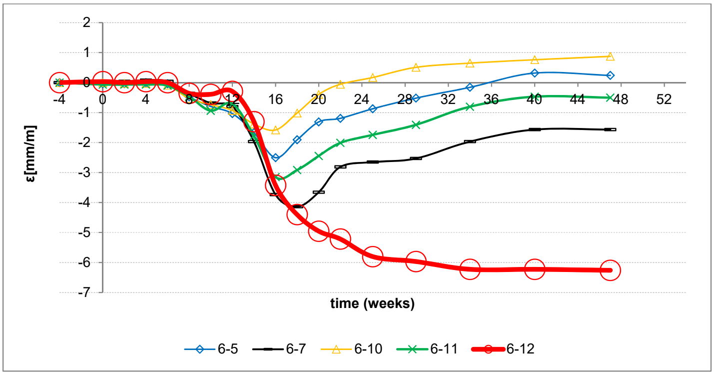

Fig. 6. Time-varying horizontal deformations on the sides of the rosette (*Source:* own study)

Fig. 6 shows that, as in the case of curvatures, the horizontal deformations began to increase two months after the start of the exploitation. The final values of the indicators, with one exception, are small and range from –2 mm/m (rosette arm 6-12) to 1 mm/m (rosette arm 6-10) (Fig. 3). By interpreting the results, it can be concluded that the sides of the rosette are in a zone that is neutral, in terms of horizontal deformation. This is near the bottom of the interior of the basin. On the other hand, the 6-12 arm shows the effect of overlapping impacts from two edges: left-western and right-eastern (Fig. 3). The short length of the exploited wall (190 m) may result in the formation of an incomplete basin. The arm of the rosette 6-12 is parallel to the exploited wall and perpendicular to the rim. Such a location allowed for the capturing of the overlapping compressive strains from the two edges inside the basin in the bottom area [11].

A simplified interpretation of the results of the geodetic measurements is presented in Fig. 7.

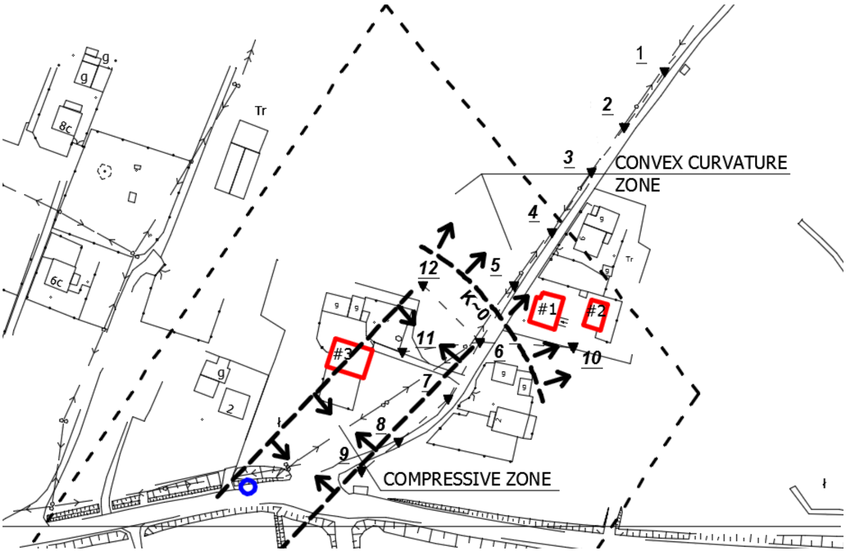

Fig. 7. Interpretation of the results of geodetic measurements for the monitored subsidence basin (*Source:* own study)

The outcome of the geodetic measurements shows that the process of exploitation resulted in the following:

- a convex curvature with a radius of approximately 15 to 30 km on the north-eastern edge;
- a zone of compressive strain concentration in the basin's interior in a northwest-southeast direction.

Both of the above conclusions were confirmed by observations of the field situation. The relationships between the terrain curvature and horizontal deformations according to the Budryk-Knothe theory can be seen in Fig. 5 and 6, between the measurement points 5, 6 and 7. Fig. 8 shows the structure of the lower parts of building no. 1 (Fig. 7), together with the surrounding asphalt surface. Tensile deformations, accompanying convex curvatures, caused the asphalt to detach from the structural elements of the building.

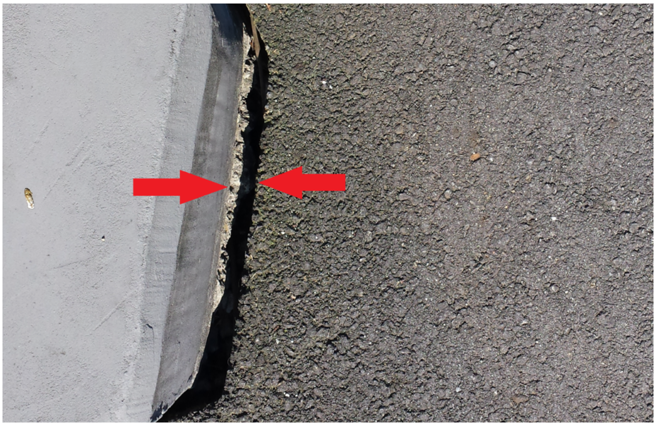

Fig. 8. Detachment of the asphalt surface from building no. 1 (Fig. 7) (*Source:* own study)

Fig. 9 shows the impact of compressive stresses inside the basin in the bottom zone. In this case, the paving stones on the sidewalk on the main street were raised in several places. The location of the damaged pavement is marked in blue in Fig. 7.

Fig. 9. The uplift of paving stones (location – blue circle, Fig. 7) (S*ource:* own study)

4. The Impact of the deformed basin edge on the existing buildings

4.1. Introduction

The curvature of the mining area, in combination with the horizontal deformations, is a significant threat to the construction of traditional residential buildings posed by the deforming mining area. For this reason, several thousand such facilities are subject to damage every year as a result of mining activities in Poland [13]. On the one hand, it is difficult to estimate internal forces in a building cooperating with deforming subsoil. However, it is necessary to be able to effectively assess the safety of structures located in the impact zone. Due to the high degree of difficulty in describing the phenomenon of building cooperation with the mining substrate, the engineering approach usually uses simplified models for both the building and the substrate. The currently used FEM-based software is usually focused on the analysis of the substrate or structure [27]. The analysis of the cooperation between the building and the deforming subsoil requires the construction of a common model: subsoil + building [4] and [5]. Additionally, the works [12] and [17] present the problem of soil-structure interaction, also outside the area threatened by mining influences. This has proved the importance of this problem, also in areas considered to be calm. The commercial software used for the analyses carried out in this study (including Robot Structural Analysis) allows for detailed modelling of the structure and simplified modelling of the subsoil in [3], [9] and [28]. Similar problems were also presented in works [15] and [16]. The building is represented in the numerical calculations as a spatial, elastic shell model that accurately reflects the geometry of the object. Despite the dynamically developing numerical methods in the analysis of the rock mass (e.g. [30]), the subsoil model described by Winkler is sufficient for the purposes of engineering analysis. Such an approach, in the context of the assessment of the impact of terrain curvature on the state of internal forces in the structure, is one of the recommended solutions in the Building Research Institute (BRI – in Polish: ITB – Instytut Techniki Budowlanej) technical instruction 'Designing buildings in mining areas' (Instructions, Guidelines, Guidance No. 416/2006) [32], which is used by engineers in Poland.

4.2. The Impact of the convex curvature of the terrain on buildings

In an attempt to take into account the influence of the convex curvature of the terrain on the existing buildings in the area covered by the field research, two buildings, numbered # 1 and # 2, were selected (Fig. 7). Building # 1 is a residential building. It is a two-storey building with a basement made of brick with traditional technology. The dimensions of the building, in projection, are 12.1×10.2 m. Building # 2 is a single-storey outbuilding with an attic serving as a loft (Fig. 10). It was made of bricks using traditional techniques and with dimensions in the projection of 10.1×6.6 m.

Based on the technical documentation of the buildings, and supplemented with an on-site inspection, both objects were modelled as spatial shell models with panel thicknesses corresponding to the actual wall thicknesses, respectively: 38 cm external walls, 25 cm internal walls and

Fig. 10. Buildings # 1 and # 2 located in the zone of the convex curvature of the terrain (*Source:* own study)

12 cm partition walls for building # 1 and 25 cm for all walls in building # 2. The buildings were made with reinforced concrete ceilings.

Material parameters adopted for numerical analysis:

- compressive strength of the wall, $f_c = 2.2$ MPa,
- wall weight by volume $\gamma = 18$ kN /m3,
- long-term modulus of elasticity of the wall $E = 910$ MPa.

The resilient shell model of the building (made in the Autodesk Robot Structural Analysis Professional 2019 software) was based on flexible supports, to which the appropriate curvature of the terrain was applied in the form of forced vertical displacements. The structure of the object was set up on elastic linear supports representing the work of foundation footings. The modulus of elasticity of the supports was adopted on the basis of information obtained from the mining entrepreneur; for the subsoil, Pd-$I_D = 0.40$. The value of the modulus depends on the foundation dimensions at the level; an approximate $K_z = 28$ MN/m was determined using a ground calculator, which is an integral part of Autodesk Robot Structural Analysis Professional 2019 (Manual of Robot Autodesk Structural Analysis 2019). For building # 1, the radius of curvature adopted in the calculations was $R = 28$ km, and for building # 2, $R = 15$ km, which was dictated by the results of curvature measurements for benchmarks 4 and 5 located in the vicinity of the buildings. The models of the buildings, after applying forced displacements in elastic support nodes, are shown in Fig. 11.

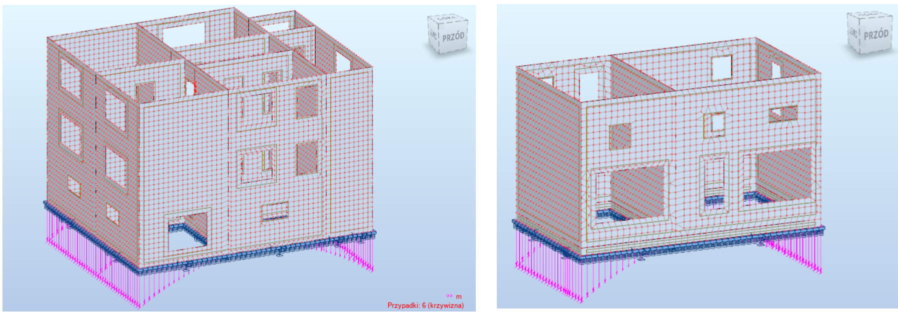

Fig. 11. FEM calculation models of buildings # 1 and # 2 with the applied terrain curvature (*Source:* own study)

The most common symptom of structural damage due to ground deformation is cracks appearing on the object. The cracks appear when the tensile strength is exceeded in a given stress state. In the calculation program, s1 shows the main tensile stress in a finite element according to relation (1).

$$s1 = \frac{sXX + sYY}{2} + \sqrt{\frac{(sXX - sYY)^2}{4} + sXY^2} \tag{1}$$

Fig. 12 and 13 are the result maps of the stresses caused by the curvature of the terrain, for both analysed buildings.

The stress values observed for the residential building are lower than for the outbuilding. This is due to the fact that building # 1 is in a zone of smaller curvature. The degree of wall

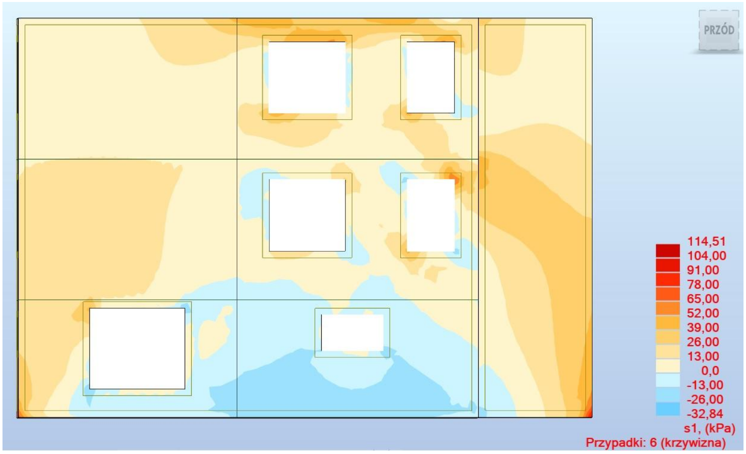

Fig. 12. Map of main stresses s1 for the building # 1 – east elevation (*Source:* own study)

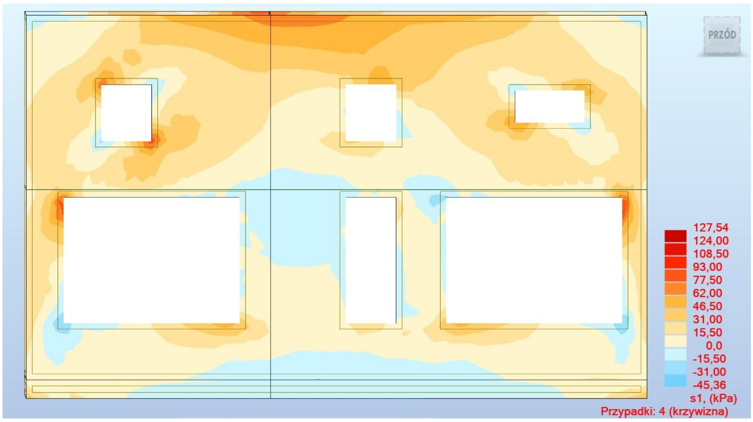

Fig. 13. Map of stresses s1 for the building # 2 – west elevation (*Source:* own study)

perforation also influences the amount of stress obtained. Besides, the stress distribution for both analysed buildings is similar. As a result of the applied curvature of the terrain, dangerous concentrations of tensile stresses occur in the corners of window openings and the upper parts of the walls. It should be noted that the relatively fragile brick structure is not resistant to the appearance of even slight tensile stresses. Fig. 14 shows a diagram of the scratches on the western wall of building # 2. The damage coincides with the stress image in Fig. 13.

4.3. The impact of horizontal deformation of the terrain on the buildings

The analysis of the impact of horizontal compressive strains on structures was carried out for building #3. The results of the measurements presented in point 3 show that this object is in

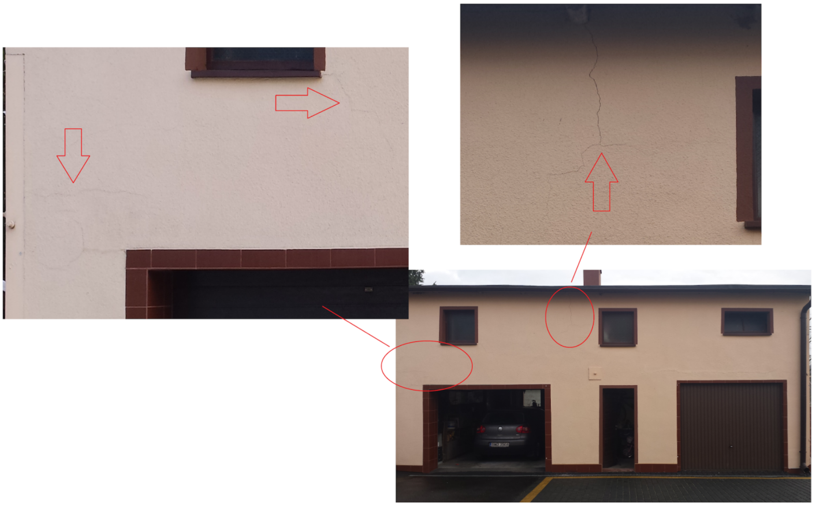

Fig. 14. Cracks on the western wall of the building # 2 (source: own study)

the zone of strong compressions (Fig. 7). Residential building #3 has the dimensions 14.2×9.4 m and has two storeys and a basement. It was built in the 1930s using traditional brick technology, with brick foundations, wooden ceilings and a roof. Fig. 15 shows the southern elevation of the building.

Fig. 15. Southern wall of the building # 3 (*Source:* own study)

The building located on the deforming ground is an obstacle to the moving soil particles. This causes friction between the foundation and the ground. The BRI instruction used in Poland allows the use of a simplified calculation procedure in which the distribution of tangential stresses under the foundation depends on the size of the horizontal deformation of the foundation. If their value does not exceed 2 mm/m, then the adhesion between the foundation and the substrate is not broken. The soil then deforms elastically (Fig. 16a). In other cases, there will be a partial or complete loss of adhesion, and the stress distribution will take a different form (Fig. 16b and 16c).

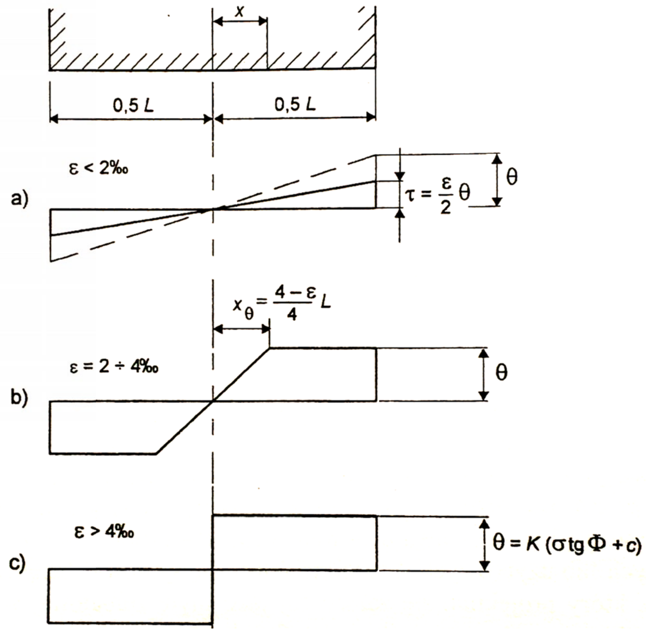

Fig. 16. Change of tangential stresses under the foundation base at different levels of horizontal strains ε, (*Source:* BRI (Instructions, Guidelines, Guidance No. 416/2006 [32]))

In the case of building #3, which was analysed in this study, the distribution from Fig. 16c was used. These results are the direct outcome of field measurements for the arm of the rosette 6-12 (Fig. 6). Knowing the parameters of the foundation at the foundation level, it is possible to determine the value of stresses then applied to the building model. The numerical analysis of the impact of horizontal deformations on the state of internal forces in the structure was carried out based on a shell model set up on an elastic foundation, similar to buildings #1 and #2. According to the documentation provided by the mining plant, fine sand of medium density was inventoried at the foundation level of the building. According to BRI (Instructions, Guidelines, Guidance 416/2006 [32] and 364/2000 [33]), the change in tangential stresses under the foundation base is expressed by equation (2).

$$\theta = K\left(\sigma \cdot \mathrm{tg}\varphi + c\right) = 0{,}65\left(120 \cdot \mathrm{tg}30° + 0\right) = 45\,\mathrm{kPa} \tag{2}$$

Where:

- K — coefficient which takes into account the deformation phenomenon appearing in a static manner and the soil adaptation to the structure loads from 0.5 to 1.0
- σ — structure pressure on the ground,
- φ — soil internal friction angle (PN-EN 1997-1 Eurokod 7 [34]),
- c — cohesiveness (PN-EN 1997-1 Eurokod 7 [34]).

The thickness of the outer walls is 38 cm and the inner walls 25 cm. The building model with the applied loads is presented in Fig. 17.

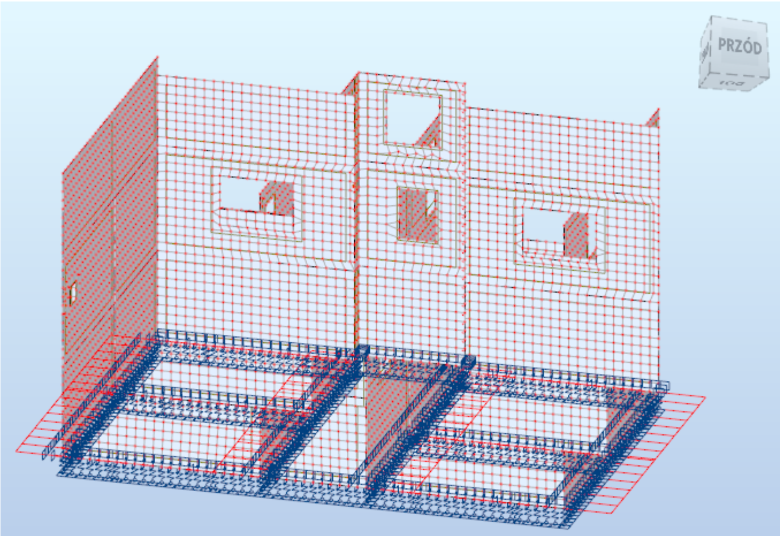

Fig. 17. FEM calculation model of building #3 with the applied tangential stresses at the foundation level (*Source:* own study)

It is worth mentioning that the building is reinforced at the level of the basement walls, with a reinforced concrete band at ground level; this is visible in the photograph (Fig. 15). Such prophylaxis, in the event of sinking occurring, can neutralise ground pressure on the basement walls. For tangential stresses under the footing, it may turn out to be ineffective. Fig. 18 shows the result map of stresses caused by horizontal deformations for building #3.

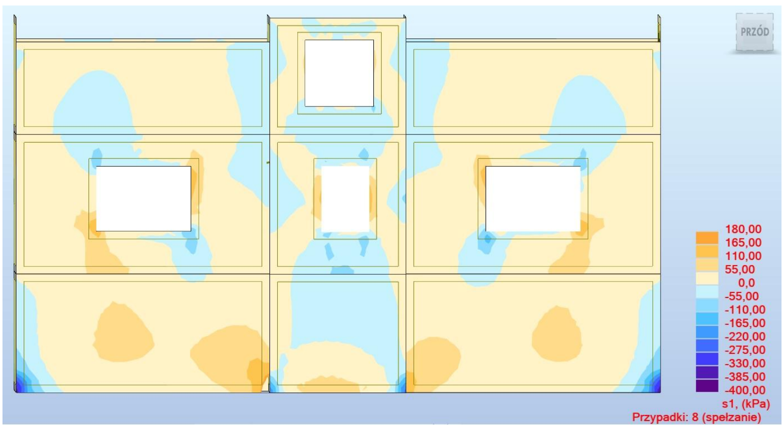

Fig. 18. Map of stresses s1 for the building #3 – south elevation (*Source:* own study)

The impact of horizontal deformations caused much greater stresses than the previously analysed curvatures. Compressive stresses dominate on the presented map. They do not pose any major threat, especially for the lower, more massive walls of basements. However, it should be noted that, as in the case of the curvature of the terrain, horizontal deformations may cause some concentration of tensile stresses in the corners of the window openings. This poses a real threat to the structure. This is because scratches may form in these places. Fig. 19 shows cracks in the structure of building #3, formed after the exploitation front had passed and corresponding to the stress concentration shown in Fig. 18.

Fig. 19. Crack in the corner of the window opening of building #3 (*Source:* own study)

5. Summary

In the presented field studies and local inspections of buildings, the impact of the edges of the post-mining basin poses a real threat to traditional residential buildings. The ground surface of the area remains deformed after the exploitation front has passed. Impacts in the presented case are of a continuous nature. The stress maps of the performed numerical analyses (Figs. 12, 13, and 18) illustrate the stress concentrations that occur in the building structures after exploitation. The results obtained indicate that the observed damage is concentrated in the zones of stretched corners of window openings and may be the result of the impact of terrain deformation resulting from mining exploitation.

The general conclusions of the study are summarised below:

1) geodetic measurements allow the control of the rate and nature of changes in the geometry of the mining subsoil;
2) the results of measurements are the main source of knowledge about the actual indicators of deformation of the mining area surface and can be very useful in numerical analyses aimed at determining internal forces in the structure;
3) the edge of the post-exploitation basin is a dangerous zone for traditional residential buildings due to the fact that after the exploitation, the impacts are of a fixed nature;
4) even a slight curvature of the terrain can pose a real threat to traditional brick buildings due to the appearance of tensile stresses in the window corner zones;

5) compressive strains, although they generate high compressive stresses, also result in the appearance of tensile stress concentrations in the corners of window openings, which are dangerous for the walls.

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