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ANALYSIS OF AN EFFECTIVENESS OF EXPANSION JOINTS IN THE MULTI-FAMILY BUILDING LOADED BY MINING ACTIVITIES

There are a lot of possibilities to protect the existing building against the negative impact arising from conducted or projected mining exploitation. These additional loads on the mining area are dependent, among others, from the effects on the surface from an exploitation of coal. One of the basic methods of protection of a building is to carry out the distribution of an object into smaller and regular in a horizontal section parts, what is called dilatation. In consequence of this treatment the decrease of the effort of supporting elements, additional loaded by mining impacts, is expected. The problem is realization of a proper and efficient dilatation in a complicated plan of an existing building.
The paper contains the results of numerical analyzes of a model of a multi-family building with a large and irregular horizontal projection, where two systems of expansion joints were used. The results were compared to the results of the analysis of a model without taking into account additional building protection. The different solutions of the analyzes, where the different directions of mining were included, are presented. The distribution of forces in the bearing walls of the building was analyzed.

Keywords: mining influence, ground deformation, building protection, FEM, numerical analyzes

1. Introduction

An extremely densely-populated area of Upper Silesia is constantly exposed to impacts resulting from operation related to underground mining of hard coal deposits. As a result of said operation we may observe, inter alia, a constant deformation of land surface. The determination of the rate of such deformation is

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a complex issue, still essential from the point of view of ensuring safety of a building structure. Having known the expected impact of mining areas we are able to assume, as early as at the stage of building structure design, an adequate method and level of protecting the structure. A range of possible solutions will be reduced in the case of an existing building structure which is not resistant to impacts caused by continuous deformation of mining area. One of the methods to reduce the internal forces resulting from additional mining impact on a building is the division of its horizontal projection into regular parts. Such procedure consists in implementing an adequate expansion joint with minimum alterations of the utility functions of the building structure. Execution of expansion joints in an existing building is complex and costly in technical terms and additionally burdened with a significant role of residents' emotions being involved. Having regard to the aforementioned, a profound analysis of the effective selection of expansion joints system is justified. Our studies are conducted on actual multi-family residential building with computer-based numerical method being applied.

2. Characteristics of the structure and geological-mining conditions

2.1. Overview of the structure of the building under the study

The subject of the analysis is a load-bearing structure of the detached three-staircase residential building built with a use of traditional method and having different heights. From administrative point of view the building structure is

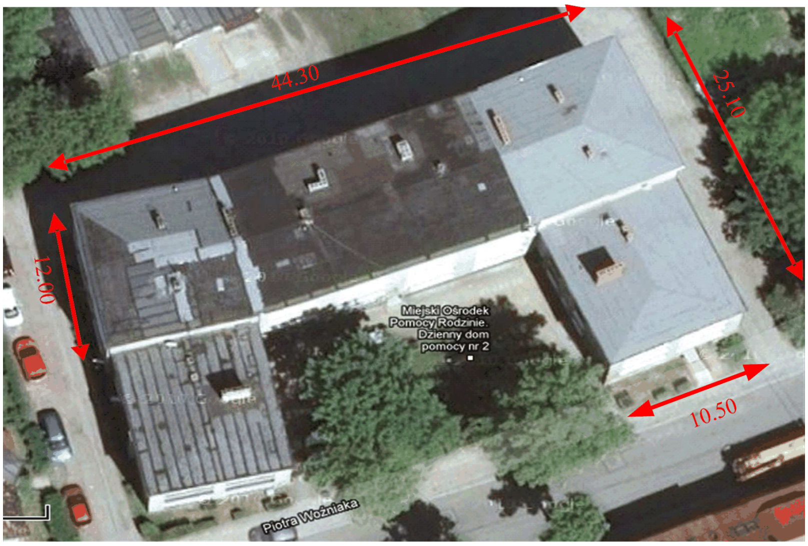

Fig. 1. View of the object

Rys. 1. Widok obiektu

composed of three buildings the horizontal projection of which is **C**-shaped. The building structure is founded on one level (all three buildings) with a complete basement (Fig. 1). The particular features of the structure are as follows:

- load bearing system – predominantly longitudinal,
- total length of the building (length of **C** letter) L=43.30 *m*,
- total height of the building (measured from the foundation footing) approx. H=17.90 *m* in central part and H=13.80 *m* in side parts,
- total broadness of the building B=24.40 *m* and 10.85 *m*.
- foundations – made of concrete, on which widened brick masonry walls 60-104 *cm* wide and 40÷60 *cm* high rest,
- load bearing walls of the building made of solid bricks:
  - external and internal walls of basement and first storey being 51 *cm* thick,
  - external and internal walls of higher storeys made of bricks being 38 *cm* thick,
- the ceiling over the basement storey - ceiling *DMS*,
- wooden ceilings over the higher storeys,
- reinforced concrete lintels, prefabricated,
- reinforced concrete stairs, slab-type, double staircase.

2.2. Overview of the foundation soil as well as geological-mining conditions in the area of founding of the building under the study

In the area of the location of the building under the study the geological structure is composed of Quaternary and Triassic layers. The Quaternary layers are composed of boulder clays and sandy deposits whereas Triassic is represented by dolomites and marlstone and limestone deposits. The coal measures are represented by Ruda, saddle and marginal layers. The coal seams are deposited in regular layers with 11° south-west saddle. Mining in this area was carried out in early 20th century in a number of Ruda series layers and saddle layers deposits. The final mining of hard coal deposits took place in April, 2015.

The building structure under the study has been and still is impacted by the damage of the structure which cause hindrance in regular operation of the building and which deteriorate its current technical condition. Therefore, materials from our archives which are related to the nearest neighbourhood of the building under the study have been used in this document as well as all records concerning the consequences of mining operations carried out in recent years. Below is presented selected information concerning the consequences of mining in the area under the study in which the building concerned is located as well as supplementary information on ore excavations. Table 1 presents characteristics of selected layers.

Table 1. The main characteristics of exploited decks

Tabela 1. Podstawowe charakterystyki eksploatowanych pokładów

Deck	**Distance from the building** [m]	**Years**	**Deep** [m]	**Thickens of the deck** [m]	**Expl. coef.** α
Done Exploitation					
410/1z2	105	1932	380	2,2	(0,8)
414/2	200	1955	485	2,0	(0,8)
416/1z2	230	1964	520	2,3	(0,8)
417	0	1967	535	2,0	(0,2)
418	0	1970	560	2,3	(0,2)
419	0	1977	570	2,3	(0,2)
501/1	240-290	1976-1977	540-580	2,3	(0,2)
507	0	1982	720	3,2	(0,5)
414/3	245	1986	520	2,0	(0,2)
507 WD	0	1987	720	2,3	(0,2)
504 WD	0	1988-1989	660	2,4	(0,2)
507 WG	130	1989	710	1,8	(0,8)
414/1	0	1995	475	2,8	(0,2)
419	295	1999-2000	480	2,75	(0,2)
510 WG	210	2001	710	1,9	(0,7)
504 WG	180	2003	650	3,0	(0,8)
510 WD	265	2005-2006	695	3,0	(0,2)
510 WD	100	2007	705	2,8	(0,2)
510 WD	140	2011	710	2,4	(0,2)
620	440	2014	945	1,8	(0,8)
Design Exploitation					
510 WD	155	2013-2017	750	2,4	(0,2)
510 WS	155	after 2020	745	2,8	(0,2)
615	440	2016	895	1,8	(0,8)
510 WG	155	after 2025	745	2,8	(0,2)
414/2	0	after 2030	565	3,0	(0,2)

The geological-mining opinion said that the basic indicators which characterize the deformation of the area surface in relation to post-mining are ε_{max}=2.9 *mm/m*, *T*=2,6 *mm/m* and R_{min}=-27.0 *km*, *w*=260 *mm*. In the case of projected mining until 2030 the most likely total impacts of mining will be characterized by indicators equal to ε_{max}=1.4 *mm/m*, *T*=3.3 *mm/m*, *w*=933 *mm* respectively and fall within group II of mining area category. The opinion also said that the area under consideration was located within the reach of mining tremors caused by operation of the coal mine. Below is listed a record of mining tremors which took place between 2010 and 2013 and the energy of which exceeded $1{\cdot}10^5$ *J* plus maximum likely amplitude of acceleration estimated under empirical relationships. The information contained therein lead to the conclusion that in the period under the study several dozen mining tremors the acceleration amplitude of which might have exceeded the value of 150 mm/s^2, took place so it might have exceeded, according to [1, 2, 3, 4] the limit of minor arduousness. The parameters of mining tremors have been listed in Table 2.

Table 2. The tabulated summary of selected recorded impacts during the 2010÷2013, w przypadku których oszacowano przyspieszenie o wartości powyżej 150 *mm/s²*

Tabela 2. Zestawienie wybranych zarejestrowanych wstrząsów w okresie 2010÷2013 years, where the value of the resultant acceleration was estimated in excess of 150 *mm/s²*

No.	Data	Time	X	Y	Energy [*J*]	Deck	Acceleration [*mm/s²*]
1	2010-01-07	21:32:21	5000	-3400	2,00E+07	620	158,0
2	2010-01-22	20:23:11	5130	-3170	4,00E+07	620	358,0
4	2010-05-11	13:42:37	5370	-3370	9,00E+06	620	399,7
5	2010-07-30	15:36:37	5000	-3470	8,00E+06	620	300,8
11	2010-09-16	05:37:43	4850	-3470	2,00E+07	620	617,0
13	2010-10-01	16:49:17	4900	-3500	9,00E+05	620	273,0
15	2010-10-09	03:48:21	4870	-3530	4,00E+06	620	711,0
16	2010-10-13	11:01:29	4860	-3520	3,00E+06	620	464,0
17	2010-10-15	12:39:54	4930	-3710	5,00E+06	620	394,0
23	2011-01-11	23:44:17	4930	-3580	8,000E+07	620	174,1
25	2011-06-03	19:49:33	5800	-3460	3,000E+06	510	269,9
26	2011-06-29	17:56:53	5790	-3450	3,000E+06	510	208,2
28	2011-07-19	18:06:39	5830	-3500	8,000E+06	510	311,6
29	2011-09-09	18:08:03	5860	-3520	5,000E+06	510	301,0
30	2011-09-19	17:47:08	5840	-3540	4,000E+06	510	209,1
31	2011-10-08	3:30:06	5850	-3580	2,000E+06	510	220,9
33	2012-09-27	18:11:16	5100	-3220	2,000E+07	615	301,8
34	2012-10-02	12:43:20	5290	-3230	9,000E+06	615	195,2
36	2012-11-21	5:22:35	5390	-3430	6,000E+07	615	310,4
38	2013-01-14	14:44:17	5500	-3340	5,000E+06	615	178,7

3. The system of expansion joints of the building including numerical equivalents

The determination of the most efficient division of the building structure with expansion joints being applied was preceded by an analysis of the results acquired in the course of numerical calculations with a use of the finite element method (*FEM*) [6, 7, 8]. The method provides for the creation of credible models of the building with the following being considered: structural components [5], loads (including mining loads) and expansion joints (as a modification of contact between the walls).

3.1. Expansion joints adopted

The implementation of an expansion joint is aimed at reducing internal forces caused by inter alia impacts of mining origin. The areas with mining operation in progress need specific principles of shaping the joints [1, 2, 3, 4]. The building under the study has a clear "**C**" letter shape in horizontal projection. Considering the difference in the heights of building wings and its central part a division of the building structure into three parts has been proposed (Fig. 2b). Such operation results in the emergence of one structure with a prolonged projection and two smaller ones. The solution may be modified by dividing the building structure into four parts (Fig. 2d), executed as a result of supplementary (as compared to "**B**" option) division of the central part into two parts. As in administrative terms the building structure is composed of three buildings one suggested division options includes the layout which reflects such situation (Fig. 2c). The result of "**C**" option will be the reduction of the central segment length. Seeking the opportunity to compare the work of structures of the expansion joints systems being presented "**A**" model free of protections (the absence of expansion joints - Fig. 2a) has also been studied. Application of traditional Budzianowski's approach led to the conclusion that the building structure with no expansion joints does not have II category of resistance; hence reinforcement and modernization actions are required.

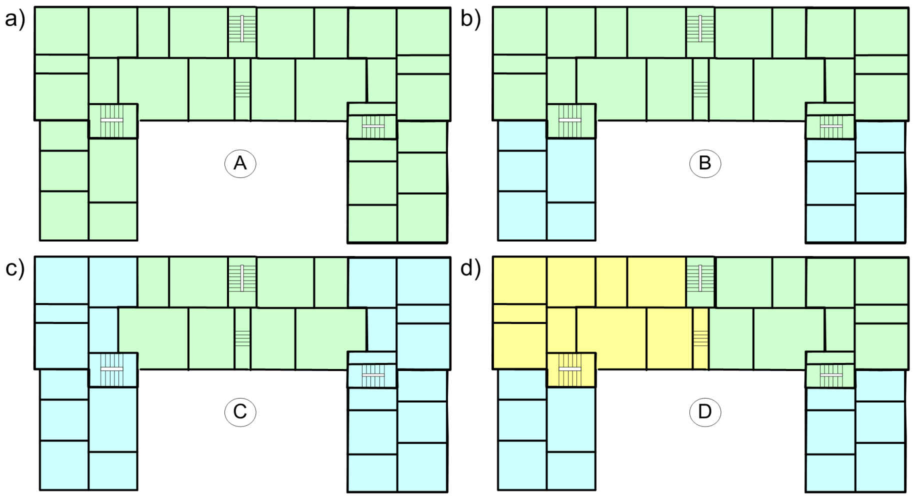

Fig. 2. Expansion joints adopted

Rys. 2. Zastosowany układ dylatacji

The systems of expansion joints as referred herein do not cater for all possibilities of their application in the building under the study. However; every time expansion joints require to be formed at the entire height of the building structure as well as a load bearing wall to be erected to form the completion of the part being expanded by joints.

3.2. Description of numerical model being applied

Numerical models of the building have been made with actual dimensions of the structure being maintained and with a use of *FEM* [5, 6, 7, 8]. The models include window and door openings in the load bearing walls of the building. The models consider direct foundation on the soil described under the vertical modulus of subgrade reaction according to [1, 2] as C_0=20 MN/m^3. The load bearing walls with various thickness have been described as masonry walls made of bricks with lime-cement mortar. The ceiling above the basement has been modelled as concrete slab with the ceilings made of wood. The work of materials considered in the model is described by linear-elastic relationship. Details concerning material parameters adopted for calculations are contained in Table 3. The building models being applied did not include the structure of wooden roof due to its low stiffness as compared to wall components. The load per roof structure was juxtaposed (q_{roof}=4.7 kN/m^2) and brought to linear load of external walls of the building structure. The calculations considered variable loads applied on ceilings.

Table 3. Tabulated summary of material parameters adopted in the calculation

Tabela 3. Zestawienie parametrów materiałowych przyjmowanych w obliczeniach

Material	ρ [kg/m^3]	E [GPa]	f_c [MPa]	f_t [MPa]	v
Masonry	1900	2,1	2,1	0,4	0,20
Concrete	2400	30	16	1,6	0,16

Numerical analyses have been conducted with a use of *FEM* with a division into finite elements (*FE*) of the structural part into 4-node square shell elements with a side equal to approx. 10 *cm* (Fig. 3b). The division resulted in approx. 170 000 *FE* to which adequate material and geometrical parameters were attributed. The expansion join has been considered by appropriate modelling of segments (Fig. 3a), followed by application of unilateral ties providing for the transfer of compression forces between parts.

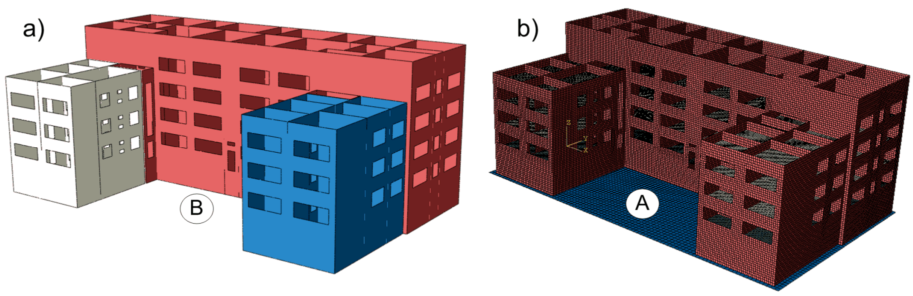

Fig. 3. Numerical model of the object: a) division into parts, b) FEM mesh

Rys. 3. Model numeryczny obiektu: a) podział na części, b) siatka MES

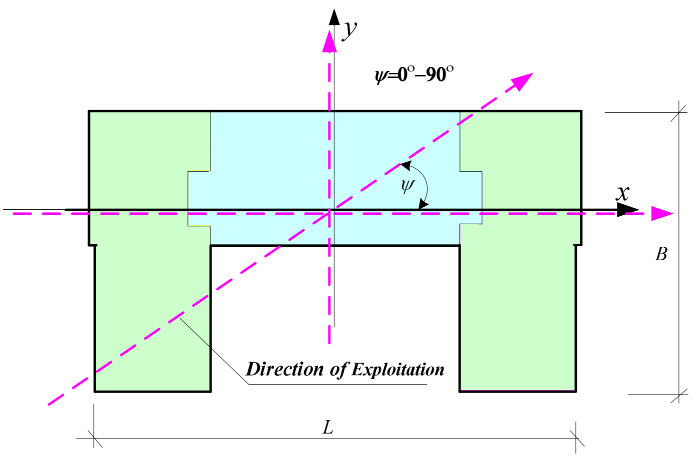

Fig. 4. Analyzed directions of a mining exploitation in view of the object

Rys. 4. Analizowane kierunki prowadzenia eksploatacji górniczej względem obiektu

The impact of mining operation on the building structure has been considered by the impact of a convex subsidence basin of the radius equal to R=12 *km*, corresponding to the impact at the level of upper limit of II category of mining area. The studies covered three directions of mining marked in Fig. 4. They were referred to the described axes of the building structure: in accordance with x axis, in accordance with y axis and at ψ=45° angle. The process of applying mining load consisted in introduction of defined function of ground displacement which corresponds to the first stage of convex basis formation.

4. Selected results of the study of expansion joints system

The effects of implementing expansion joints have been observed by changes in the values of stresses and deformations of wall components. Moreover, the influence of applying expansion joints on the form and values of natural vibrations have been checked.

4.1. Static response

The studies resulted in the values of deformation and stresses. The benchmark (base solution) was determined to be the state received in the model free of expansion joints (**A**) – Fig. 2a, expressing the values acquired in the other models as the percentage share. The selected results of values of vertical stress (σ_{22}), contact stress (σ_{12}), main deformation (ε_{1}) and shape deformation (ε_{12}) have been contained in Table 4. The images of deformation distribution of wall elements have been presented in Fig. 5.

Table 4. Tabulated summary of impact the expansion on the effort of the load-bearing walls
Tabela 4. Zestawienie wpływu dylatacji na wytężenie ścian nośnych obiektu

Radius – *R*=12 *km* on the direction *x* – ψ=0°								
Model	σ_{22} [*kPa*]	**Percentage** [%]	σ_{12} [*kPa*]	**Percentage** [%]	ε_1 [‰]	**Percentage** [%]	ε_{12} [‰]	**Percentage** [%]
A	706	100	486	100	0,419	100	0,555	100
B	666	94	412	85	0,390	93	0,471	85
C	49	7	58	12	0,038	9	0,067	12
D	166	24	128	26	0,101	24	0,147	26
Radius – *R*=12 *km* on the direction *y* – ψ=90°								
Model	σ_{22} [*kPa*]	**Percentage** [%]	σ_{12} [*kPa*]	**Percentage** [%]	ε_1 [‰]	**Percentage** [%]	ε_{12} [‰]	**Percentage** [%]
A	326	100	126	100	0,160	100	0,144	100
B	66	20	43	34	0,053	33	0,049	34
C	290	89	108	85	0,102	64	0,119	82
D	67	21	40	32	0,050	31	0,046	32
Radius – *R*=12 *km* on the direction *xy* – ψ=45°								
Model	σ_{22} [*kPa*]	**Percentage** [%]	σ_{12} [*kPa*]	**Percentage** [%]	ε_1 [‰]	**Percentage** [%]	ε_{12} [‰]	**Percentage** [%]
A	1360	100	546	100	0,666	100	0,624	100
B	439	32	379	69	0,313	47	0,434	71
C	150	11	50	9	0,080	12	0,087	14
D	178	13	106	19	0,104	16	0,121	19

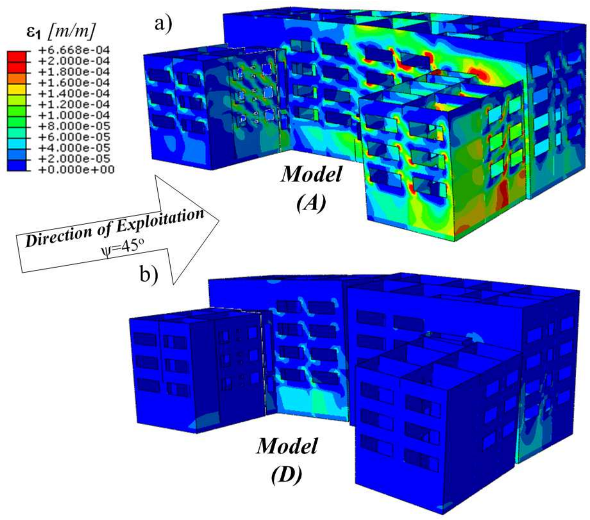

Fig. 5. The distribution of main strain: a) model **A**, b) model **D**
Rys. 5. Rozkład odkształceń głównych: a) model **A**, b) model **D**

Considering the largest decrease in structure effort received in the study for efficient selection of expansion joints, the most efficient model is **C** – Fig. 2c. There is one prerequisite, namely mining may not be conducted in Y direction as this model gets the worst results as compared to the other models. The division of the building structure with expansion joints in line with administrative division seemed the most convenient; still not the best one as the results of the dynamic analysis show. Nevertheless, in the worst case i.e. with Y direction mining, the decline of effort reaches the level of about 20%. This means that such expansion joints system might be applied if it were the most convenient from the point of view of consequent use of the building structure. Another possibility for this expansion joints system is to assume a specific direction of mining. In the event the direction is unknown or variable and seeking to obtain better results in effort reduction, the expansion joints system represented by **D** model should be applied. This division results in four parts of the building structure - Fig. 2d. It is efficient regardless of the direction of mining operation and the value of effort of wall structure of the building including expansion joints measured with the rates of analyzed stresses and deformations according to **D** system is by over 70% lower as compared to **A** model, i.e. the model with no expansion joints being applied in the building.

4.2. Dynamic response

With reference to the results obtained in static analysis, **A** and **D** models have been adopted for the second stage, i.e. dynamic analysis. An impact of expansion gap application on the forms and values of natural vibrations frequency has been analyzed. They were compared with the model without expansion joints considering bending shapes on *y* axis (ω_1), on *x* axis (ω_2) and torsion shape (ω_3). The values of natural vibrations of models **A** and **D** are contained in Table 5, and the primary shapes of natural vibrations of models **A** and **D** are presented in Fig. 6. When comparing the shapes of natural vibrations frequencies of numerical models, the value of natural vibrations frequency in model **D** is by 33% lower as compared to the model without expansion joints. In the event of calculations under response spectrum analysis, by applying a master spectrum of the specific area, lower values of forces are obtained.

Table 5. Tabulated summary of values of the natural frequency of the analyzed models

Tabela 5. Zestawienie wartości częstotliwości drgań własnych analizowanych modeli

Model	Shape of a natural frequency	ω_i [Hz]	Model	Shape of a natural frequency	ω_i [Hz]
A	bending on the *y* axis	3,27	***D***	bending on the *y* axis	2,20
	bending on the *x* axis	3,56		bending on the *x* axis	2,69
	torsion	4,70		torsion	5,16

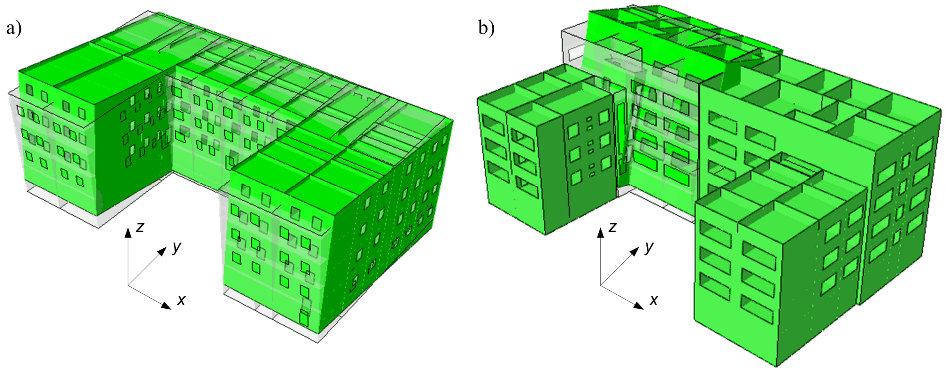

Fig. 6. The comparison of the first shape of the natural frequency: a) model **A**, b) model **D**

Rys. 6. Porównanie postaci pierwszych częstotliwości drgań własnych: a) model **A**, b) model **D**

5. Summary

Economic profitability of protecting the existing building structure against mining impacts with a use of expansion joints depends upon the shape, dimensions of horizontal projection of the building structure and significance of the building structure for its owner. The results of analyses conducted in the study lead to the conclusion that with respect to structure effort:

- under any division of the building body into smaller parts with simpler horizontal projection and equal heights, the effort of structure elements is lower than in the case of non-divided building – even by up to 70%,
- the most efficient system of expansion joints in the case under the study is the division described as model **D**. In this case the efficiency measured by the decline of the intensity of stress and deformation state in structure elements is noticeable regardless of mining operation in relation to the location of the building structure,
- the application of expansion joints each time resulted in considering the building structure to be resistant to the activity of II category of mining area,
- the system conforming to **D** model resulted in the reduction of natural vibrations frequency by 30%.

Conducting the process of protecting a building structure requires different directions of mining operation in relation to the location of the building structure to be considered. In such case the nearest planned mining operation presented in geological-mining opinion may not be solely and exclusively taken into account.

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ANALIZA EFEKTYWNOŚCI UKŁADÓW DYLATACJI W BUDYNKU WIELORODZINNYM OBCIĄŻONYM WPŁYWEM EKSPLOATACJI GÓRNICZEJ

S t r e s z c z e n i e

Istnieje szereg możliwości zabezpieczenia istniejącego budynku przed negatywnym wpływem wynikającym z prowadzonej lub prognozowanej eksploatacji górniczej. Te dodatkowe obciążenia na terenie górniczym zależą m.in. od skutków eksploatacji złóż węgla kamiennego na powierzchni. Jedną z podstawowych metod zabezpieczenia obiektu budowlanego jest przeprowadzenie podziału bryły budynku na mniejsze i regularne w rzucie poziomym części, czyli jego dylatowanie. W wyniku takiego działania oczekiwane jest zmniejszenie wytężenia elementów nośnych konstrukcji, obciążonej dodatkowo wpływem górniczym. Problemem jest zrealizowanie prawidłowej i efektywnej przerwy dylatacyjnej w złożonym rzucie istniejącego budynku.

Praca zawiera wyniki analiz numerycznych modelu budynku wielorodzinnego o rozległym i nieregularnym rzucie poziomym, z zastosowaniem trzech układów jego dylatowania. Rezultaty obliczeń porównano z wynikami analizy modelu bez uwzględnienia dodatkowego zabezpieczenia. Dokonano zestawienia rozwiązań z uwzględnieniem różnych kierunków prowadzenia eksploatacji górniczej pod obiektem. Analizie poddano m.in. rozkład sił w ścianach nośnych budynku.

Słowa kluczowe: eksploatacja górnicza, deformacje podłoża, zabezpieczenie budynków, metoda elementów skończonych

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