The influence of the fault zone width on land surface vibrations after the high-energy tremor in the "Rydułtowy-Anna" hard coal mine

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Abstract. In the article, a numerical analysis of the impact of the width of the fault zone on land surface tremors on the area of the "Rydułtowy – Anna" hard coal mine was performed. The analysis covered the dynamic impact of the actual seismic wave after the high-energy tremor of 7 June 2013. Vibrations on the land surface are a measure of the mining damage risk. It is particularly the horizontal components of land vibrations that are dangerous to buildings which is reflected in the Mining Scales of Intensity (GSI) of vibrations. The run of a seismic wave in the rock mass from the hypocenter to the area's surface depends on the lithology of the area and the presence of fault zones. The rock mass network cut by faults of various widths influences the amplitude of tremor reaching the area's surface. The analysis of the impact of the width of the fault zone was done for three alternatives.

Keywords: fault zone, surface vibrations, high-energy tremor

1 Introduction

1.1 Character of high-energy mine tremors in the area of GZW

Urbanized areas of the Upper Silesian Coal Basin (*Górnośląskie Zagłębie Węglowe, GZW*) are exposed to tremors induced by underground mining operations. The tremors which are most dangerous for buildings on the area's surface are high-energy tremors with the energy limit of above $E \geq 10^5$ J for GZW. Particularly dangerous are the tremors with an energy of above $E \geq 10^7$ J. Low-energy tremors are related directly to hard coal mining and do not cause damage on the area surface. High-energy tremors have a slip mechanism in the tremor epicenter and are the result of interactions between tectonic and operational tensions [1,2,3,4,5,6,7]. The nature of the slip mechanism in the hypocenter of the high-energy tremor is similar to that in the formation of natural earthquakes. High-energy tremors cause mining damage on the area surface and have an adverse effect on the comfort of living of GZW residents. There are faults in the rock mass which cause distortions in the propagation

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of the seismic wave after a high-energy tremor. The article assesses the impact of the width of the fault zone in land vibrations on the area's surface. The analyses was performed after on actual signal recorded after a high-energy tremor in the hard coal mine (KWK) "Rydułtowy – Anna" on 7 June 2013 with an energy of E = 8.12e7 J. The computational model was based on a simplified actual cross-section along the Kolejowy fault within the mining area of "Rydułtowy – Anna" with a width of the fault zone of 30 m [8]. For comparison, calculations were done for other fault zone alternatives.

1.2 Threats to buildings in the area of GZW

The impact of the soil vibrations caused by mining tremors on the area's surface depends on the energy of the tremors, the epicentral distance and the structure of the rock mass through which the seismic wave passes [8]. A measure of this effect is the intensity of the vibrations which may be expressed in the degrees of intensity according to empirical scales, which has its equivalent in the maximum values of the velocities of accelerations of the vibrations. Vibrations caused by tremors induced by mining operations are recorded on the earth surface by means of seismometric sensors. These sensors measure, in three perpendicular directions, the amplitudes of acceleration, velocity or displacement of vibrations of soil particles in the function of time. The impact of the vibrations originating from mining tremors on buildings is determined through the actual runs of the vibrations at the point on the land surface which is examined or in a building. From the viewpoint of the influence of mining tremors on buildings, most important are the horizontal components x, y of the vibrations [9]. The relevant figures of the vibration parameters which were measured were used to design empirical scales of the impact of tremors induced by mining operations on building structures. In the Polish conditions, the dynamic impact of mining tremors is established using the empirical Mining Scales of Intensity (GSI) developed at the Central Mining Institute in cooperation with other institutions. For the area of GZW, the vibrations scale GSI-GZW_{KW} [10] was developed in 2007. The GSI-GZW_{KW} is an empirical scale based on the amplitude of the velocity of the horizontal land vibrations the while they continue to appear. The GSI-GZW_{KW}-2012-V was an improvement of the GSI-GZW_{KW}. The GZW_{KW}-2012-V scale takes account of the technical condition of the buildings within the area of the GZW (e.g. the timber-frame, large-block, concrete-slab, brick, traditional technologies). Currently, the GSIS-2017 scale has been designed using the experience of the application of the former GSI [11] scales. This is an empirical and measurement-based scale used to monitor and assess the impact of mining tremors induced by hard coal mining on the buildings on the surface and the perceptibility of vibrations by humans. Unfortunately, the GSI does not take into account the impact of faults on the value of vibrations on the surface after high-energy tremors.

The area of "Rydułtowy-Anna" is characterized by a thick network of multi-family housing, public buildings and industrial facilities. In "Rydułtowy-Anna", there are surface points to measure accelerations of vibrations on land surface. Statistical analyses based on the actually measured data demonstrated the directionality of damage following high-energy shocks corresponding to the tectonics of the faults [8]. The main damage to buildings occurred on the front of the propagating seismic wave. Behind the fault, the amount of damage was much smaller.

2 Numerical simulation

2.1 Characteristics of the area

In this article, a fragment of the area of the "Rydułtowy-Anna" coal mine was subjected to numerical simulations in order to determine the impact of the width of the fault zone on the vibrations of land on the area surface caused by the high-energy tremor on 7 June 2013 with an energy of E = 8.12e7 J. Tectonically, the study area is made of faults and folds. It is made of carboniferous formations interrupted by numerous latitudinal and longitudinal faults. Such faults always affect mining works which influence the stability of mining roadways as well [12]. Figure 1 presents the local tectonics at "Rydutowy-Anna". The locations of the sensors (Nos. 4, 6, 7/23, 8, 15/27, 21A, 28, 29, 33) recording the tremor of 7.06.2013 were also taken into account [8].

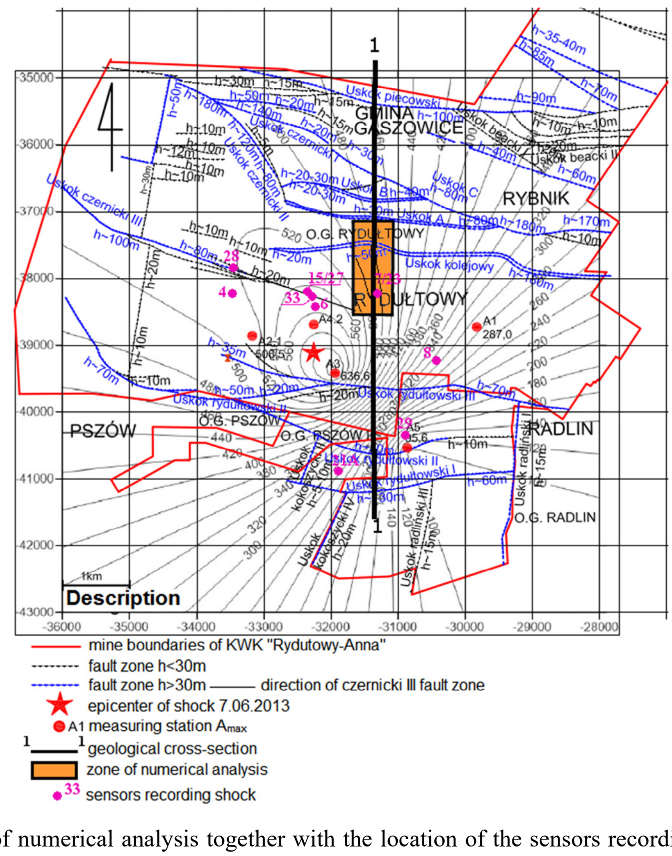

Fig. 2. The area of numerical analysis together with the location of the sensors recording the tremor of 7.06.2013 [11]

Because of the complicated tectonics of the area, the numerical simulation included the fragment which was located, in the I-I cross-section, on the marked rectangular area (Fig. 2). Only the impact of the Kolejowy fault zone of the actual width of 30 m, and two other widths of possible fault zones were taken into account: 15 m and 45 m.

2.2 Assumptions for numerical simulation

The area covered by the numerical analysis comprised the cross-section in the area of the Kolejowy fault in "Rydułtowy-Anna" coal mine, of 1100m in width and 830m in height. Because of its complicated lithological geometry, a simplified structure of the layers was adopted. The analysis covered the impact of the variable width of the Kolejowy fault on land vibrations on the area's surface before and after the fault.

The numerical model was discretized with 900000 quadrangular finite elements. The mesh size was adapted to the layer concerned, account being taken of the velocity of wave propagation in the medium and the frequency of excitations implemented in the program [13]. The material was modelled as elastoplastic and Mohr-Coulomb, and the failure criterion was employed with the linear condition of plasticity. Table 1 presents the parameters of lithological layers based on [14], as adopted in numerical simulation. Information was also included on the maximum permissible size of finite elements which was applied in the calculations.

Table 1. Parameters of the lithological layers included in the numerical simulation.

Layer:	Overburden	Shale	Sandstone	Coal 620	Zamecki sandstone	Tectonic breccia
E [MPa]	0.20	10929.00	17368.00	481.00	31980.00	0.40
ν [-]	0.30	0.26	0.22	0.32	0.22	0.30
ρ [kg/m^3]	2005.00	2324.00	2256.00	1216.00	2502.00	2150.00
ϕ [°]	38.40	30.15	44.05	7.40	52.10	21.00
c [kPa]	0.10	1800	300	120	3260	43.00
v_s [m/s]	6.19	1366.07	1776.28	387.08	2288.76	8.46
v_p [m/s]	11.59	2398.73	2964.69	752.35	3820.05	15.83
f_{max} [Hz]	50.00	50.00	50.00	50.00	50.00	50.00
h_e [m]	0.02	4.80	5.93	1.50	7.64	0.03
unit [m]	0.2	4.00	4.00	1.00	4.00	0.2

E- longitudinal displacement model, ν –Poisson's ratio, ρ –bulk density, φ – internal angle of friction, c – cohesion, v_s – velocity of the horizontal wave, v_p – velocity of the longitudinal wave, f_{max} – tremor frequency, h_e – element size.

Figure 3 presents the model implemented in the MIDAS GTS NX numerical program. Non-displaceable boundary conditions at the model base were applied. The model's own parts were set in order to determine the visco-elastic parameters of the boundary conditions, for a model with semi-seismic excitation [15]. In order to minimize the effect of wave reflection and the numerical model size, the boundary conditions of the free field on the vertical boundaries of the analyzed area [16,17] were applied. The boundary conditions which were applied take account of the Rayleigh damping.

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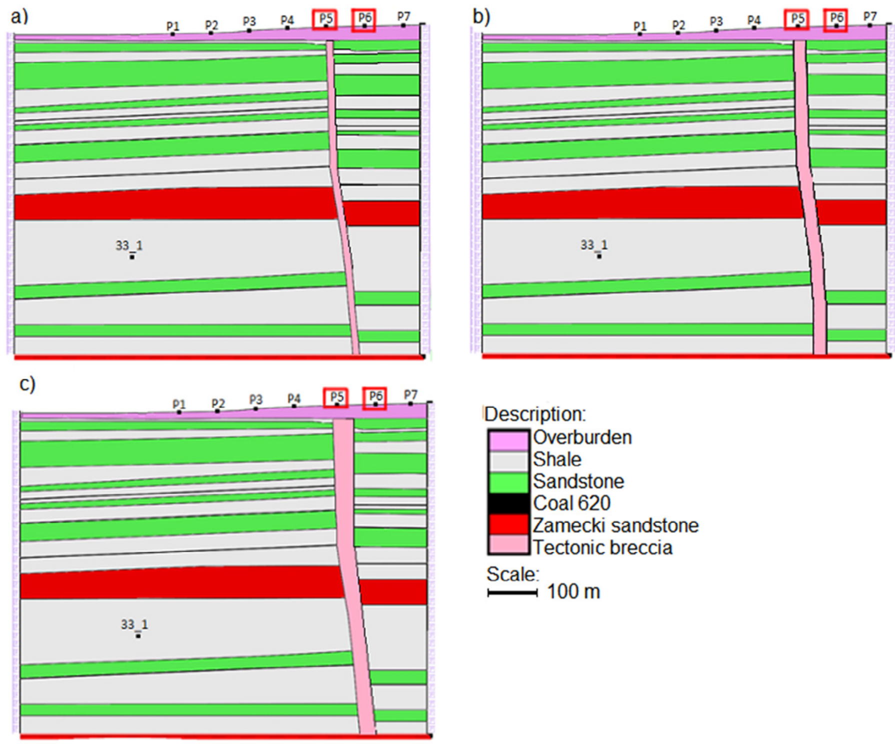

Fig. 3. Area covered by the numerical analysis. Location of points (P1 to P7) on the area surface, together with point 33_1 of the input excitation task, a) - fault zone of 15 m in width, b) – actual width of the fault zone 30 m, c) fault zone of 45 m

2.3 Semi-seismic excitation

The numerical analysis took account of the semi-seismic excitation, recorded on 7.06.2013, in the form of the course of the velocity of vibrations. Account was taken of the horizontal signal 33_X and the vertical signal 33_Z. The excitation components were implemented in the numerical model at the depth of 600 m. The load set for the model is located at a distance of 535 m from the extreme surface of the Kolejowy fault. The frequency of the recorded signal was 500Hz. The optimization of the duration of the numerical calculations necessitated the application of the discretization of the horizontal and vertical velocities of the vibrations. The time step of 0.02 s was adopted which corresponded to the signal frequency equaling 50 Hz. The duration of the excitation, introduced into the model, comprised a range of between 0.5 s and 3 s. Figure 4 presents a diagram of the velocity of vibrations of the horizontal component from the recording device, and the horizontal component introduced into the numerical model.

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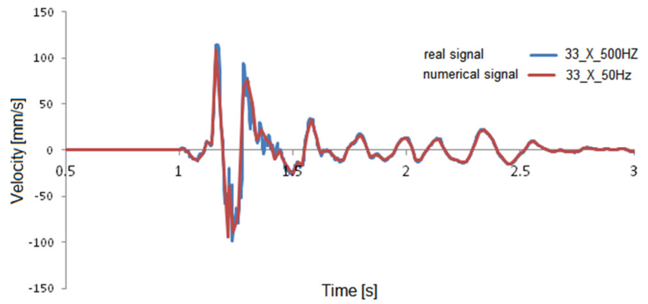

Fig. 4. Run of the horizontal component of the excitation, taking account of the frequency of sampling in the numerical program [11]

Figure 4 presents the run of the vertical component of the wave velocity recorded on the measuring sensor on 7.06.2013 and the discretized signal in the numerical program.

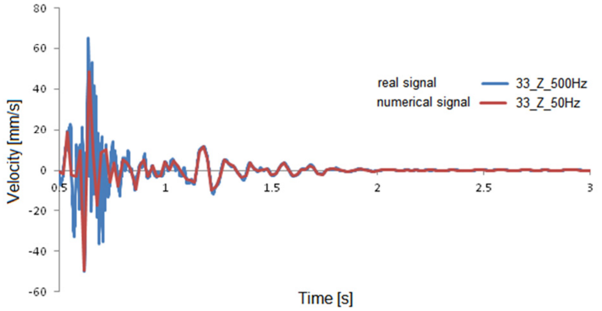

Fig. 5. Run of the horizontal component of the excitation, taking account of the frequency of sampling of the numerical program [11]

Figure 5 presents the amplitude spectra of the recorded signal. The dominating frequency was 5 Hz.

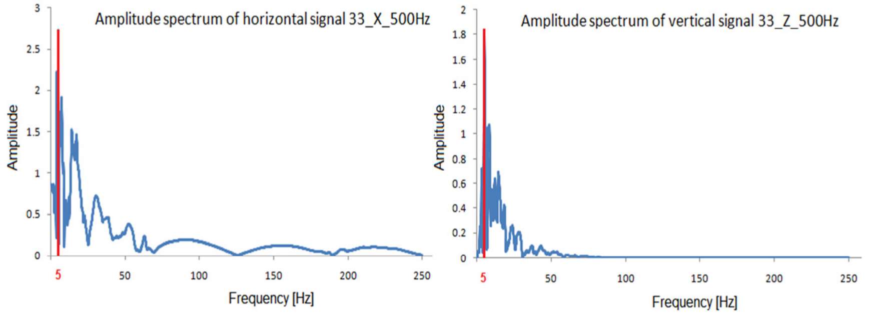

Fig. 6. Amplitude spectrum for the horizontal and vertical components of wave velocity, recorded on 7.06.2013 [11]

3 Results and final conclusions

The numerical analyses of the impact of the fault zone width on surface deformations of the areas of “Rydułtowy-Anna” demonstrated an impact of the width on the deformations generated before and after the fault. Figure 7 presents horizontal displacements obtained in

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point 5 before the fault. The displacement figures are close one to another. There is no clear effect of the impact of the width of the fault on the results which were obtained.

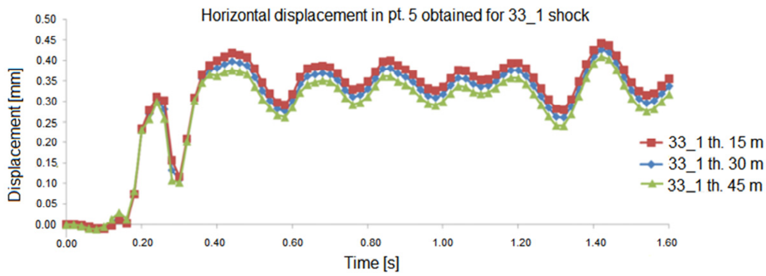

Fig. 7. Horizontal displacements at pt. 5, located on the border of the fault zone with a different thickness

Figure 8 shows the horizontal displacements obtained for pt. 6 located behind the fault zone. There is a clearly visible reduction in the horizontal displacements of vibrations for the propagating excitation in the fault zone of 45m in width. The greatest displacements were obtained for the fault zone of 15 m in width.

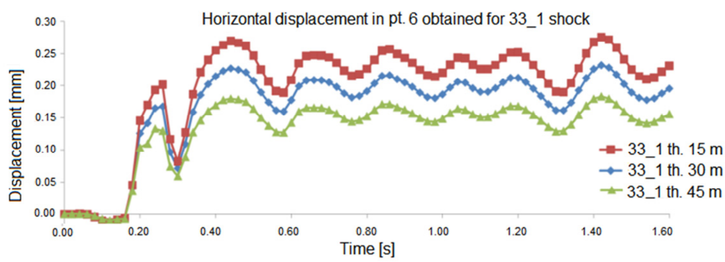

Fig. 8. Horizontal displacements in pt. 6, located after the fault zone with a different thickness

A greater width of the fault zone generates increased damping of the excitation in the form of a mining tremor. The effect of the width of the analyzed zone disappears for surface points located before the fault. The figures of total displacements are close one to another regardless of the zone width. The buildings located on mining areas after the fault zone are less exposed to negative effects of tremors induced by underground mining operations.

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