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The influence of the Kłodnica fault tectonic zone on the degree of damage to buildings resulting from high magnitude tremors

Wpływ strefy tektonicznej uskokukłodnickiego na wielkość uszkodzeń w budynkach spowodowanych wysokoenergetycznym wstrząsem

Abstract

On 18 April 2015, a regional tremor with an energy $E=4\cdot10^9$ J occurred in the main saddle of fault VIa. This phenomenon emerged as result of summing up of stresses caused by underground exploitation conducted in the vicinity of natural faults with unrelaxed tectonic stresses, which resulted in the very strong influence of this tremor on the surface infrastructure and on the emotional well-being of local people. This analysis suggests that there is a statistical relationship between these values. Diversity of location both of the size of measured vibration parameters, damages in the buildings and of feelings of the vibrations prove an unequal radiation of the seismic waves caused by the amplifying influence of the fault zone.

Keywords: mining tremors, tectonic faults, mining damage

Streszczenie

18 kwietnia 2015 r. w strefie uskokowej uskoku VIa w siodle głównym wystąpił wstrząs regionalny o energii $E=4\cdot10^9$ J. Zjawisko to miało miejsce w wyniku sumowania się naprężeń wywołanych podziemną eksploatacją prowadzoną w otoczeniu naturalnych uskoków z niezrelaksowanymi naprężeniami tektonicznymi, co miało przełożenie na bardzo silne oddziaływanie tego wstrząsu na infrastrukturę powierzchniową i odczucia przez ludzi. Przeprowadzona analiza wykazała, że istnieje statystyczny związek między tymi wielkościami. Zróżnicowanie położenia zarówno wielkości pomierzonych parametrów drgań, uszkodzeń w budynkach, jak i odczuć wstrząsów świadczą o nierównomiernej radiacji fal sejsmicznych spowodowanej amplifikującym oddziaływaniem strefy uskokowej.

Słowa kluczowe: wstrząsy górnicze, uskoki tektoniczne, szkody górnicze

1. Introduction

In the Upper Silesian Coal Basin, mining induced seismic events of varying intensities occur, from weak events which go unnoticed to people, to very strong events of a tectonic character which are described as being regional [5, 9]. Regional seismic events cause numerous instances of damage to buildings and surface infrastructure. The connection between regional tectonics and damage to buildings resulting from high-intensity mining tremors has been the subject of studies carried out since 2011 by Renata Szermer-Zaucha and Elżbieta Pilecka. The studies were carried out using statistical methods verified using selected archive materials from coal mines and they explicitly showed that there is such a connection. The results are presented in works [6–8].

The present article focuses on the results of research referring to the determination of statistical dependence between the distance of the damaged buildings from the tectonic zone of the Kłodnica fault (dk) or accompanying faults (d) and the amplitude of horizontal vibration velocity PGV_{Hmax}, (determined as the horizontal maximum length of the ground vibration vector) of the tremor of 18 April 2015 of energy $E=4\cdot10^9$ J, calculated for the foundation place of the building.

The epicenter of this tremor belonging into "regional events", was located in the zone of the VIa fault. This fault is situated is a meridional of the Kłodnica fault zone which is situated of latitudinal.

The Kłodnica fault zone and the accompanying faults are located in a region in which for years, strong tremors of 10^8 and even 10^9 J have occurred as a result of the accumulation of exploitation stresses caused by coal exploitation carried out and the tectonic stresses. Exploitation stresses are an additional factor which triggers the energy in tectonic structures. The occurrence of tectonic stresses in this region is documented by studies [1, 2]. A fault is usually a zone in which the orogenic belt is strongly cracked. When a seismic wave approaches the fault, various phenomena take place in it. The fault is the border of two centres which have different acoustic impendences; thus, in accordance with Snellius' law, reflection and refraction of the seismic wave follows.

In article [3], it was claimed that the results of refraction studies of consolidated substrate in Poland provide evidence that even at depths of several kilometres, changes to the velocity occur in the faulting zones. Assuming that open fissures do not occur in dislocation zones, it has to be taken into account that there is a strong probability of the zones being filled with dislocation material of different elastic properties – this has been proven by making exploratory boreholes. Velocity diversification also occurs and this creates favourable conditions for the formation of waves reflected from the plane of the fault zones. The border of layers in the orogenic belt and cracked layers in the fault fissure is then the border of reflected waves and form an additional hazard for building objects in the vicinity of the faults.

2. Characteristics of the scope of studies

The area of studies encompasses the Panewniki exploitation field, which is located in the northern part of the Upper Silesia Coal Basin, in the southern wing of the main saddle. The main saddle is a structure with a very complex nature – it is a row arranged in a sequence of elevations and dome folds. In the main saddle area, there are many fault structures (Fig. 1). The majority of large faults cutting the main saddle and the main basin come from the Variscan age. Some of them were rejuvenated later in the Mesozoic and Tertiary ages. Many new faults (so-called Alpine faults) appeared in the discussed area during those period. One of such fault is the Kłodnica fault – a several-kilometre-long fault zone stretching in the east-west direction.

In the eastern and western part the fault, it changes its direction to south-east. The discussed fault generally throws the layers to the south. Throw amplitude reaches 40–160 m in the eastern part, about 360 m in the middle part and further to the west, the throw amplitude decreases to about 15–20 m. The Kłodnica fault is accompanied by a number of smaller faults of a few to several metre throws, arranged in steps or fan-shaped and faults of throws of several to a few dozen meters. The Kłodnica fault is also accompanied by non-continuous deformations of small lengths of up to 150 m and throws of 2–3 m faults. The described faults have different azimuths as well as throws. It can be observed in the zones and junctions that when smaller faults reach the Kłodnica fault, their throws accumulate. The Kłodnica fault fissures and the accompanying faults are filled with breccia in the form of sandstone, mudstone, carbonaceous substances and sandstone blocks.

In the area of research, there is also a system of meridional faults. The size of their throws is changeable and fluctuates from 5–120 m and the layers of the orogenic belt are thrown to the west or the east. Similarly varied is the dip angle of the planes of these faults (40–90^{o}). The most important characteristics are:

- Fault IV – a natural eastern border of the Panewniki field. The fault runs from NNE to SSW and throws the layers towards the NW by about 50–70 m. Fault IV reaches the Kłodnica fault and continues in a northerly direction as fault VII.
- Fault V runs from north to south. A the beginning a single fault zone to the south separates into a number of fissures following different course azimuths from NE to SW, through N to S and NW to SE and of different throws, forming a characteristic fan-shaped structure in the vicinity of the Kłodnica fault. The fault throws layers to the E by 40–50 m in the northern part of the discussed area. In the southern part, a number of dislocations forming the fault V zone has throws from 1–6 m and changeable angles of plane inclinations from 60–80^{o}. This fault ends at the Kłodnica fault.
- Fault Jakub is in the southern part of the Panewniki field on the extension of fault V. This is a meridional fault, throwing layers to the west from 40 m at Kłodnica fault to 70 m south of it, that is in Panewniki field. What is characteristic about this fault is that its inclination angle changes from 60–90^{o}. Two echelon fault zones accompany this fault their throws being 3–4 m and a number of small faults in generally sub-meridional directions, and seldom of parallel latitude.
- Fault VIa runs a parallel course to that of fault IV and throws its layers to the south-east. The size of the throw is $h \sim 50$ m. In the northern part, the discussed fault crosses the

Kłodnica fault and goes meridionally through the Panewniki field throwing layers to the east by about 70–90 m. In the southern part, the fault diverts into a westerly direction.

- Faults VII and VIa form a common zone in a northerly direction from the Kłodnica fault and further separate into two independent faults of large throws of 60 m and 70 m. In the area of the Kłodnica fault, they join into one zone again consisting of a number of faults of different directions and sizes of throws. On the other side of the Kłodnica fault, that is in Panewniki field, the faults continue as two independent exploitation zones with large throws of 80 m and 110 m.
- Fault VIII is a fault which follows a course close to meridional. It forms a zone of the width extend in the southern direction from several meters on the north to about 23 m on the south in the area of Kłodnica fault. Fault VIII at Kłodnica fault separates into a number of faults that have dip from a few to 45 m. The fault plane inclination angle is changeable and fluctuates from 60–80°. The fault throws layers towards the west.

The described system of lower-order multidirectional faults which accompany the Kłodnica fault has caused the studied area to be cut into a number of tectonic blocks of different sizes, differently shifted with regard to one another, both horizontally and vertically. Thus, this is an area prone to all kinds of deformations due to both past and present coal mining exploitation which is accompanied by numerous tremors of the order of 10^8 – 10^9 J.

The tremor from 18 April 2015 occurred during exploitation of coal bed 409 in the western part of the Panewniki coalfield and was localised in the footwall of the Kłodnica fault in the region of the VIa fault.

The coal seam in this area is rated as the III degree of the rockburst hazard in years 2003– 2008 was exploited in two longwalls of its western part by a longitudinal system with the roof fall. Moreover, in the eastern part of the field, coal seam 409 was also exploited in two longwalls in the years 2009–2012 by a lateral system with a roof fall. At the beginning of October 2013, in the western part of the field, the next longwall was exploited by a longitudinal system with a roof fall. During the exploitation of this longwall the analysed regional tremor occurred with a energy $E=4\cdot10^9$ J. Coal seam 409 in the longwall lies at a depth of about 1040 m (786 mbsl) up to about 1097 m (844 mbsl) with an average inclination of 4–7°, in southerly and south-westerly directions and its seam thickness fluctuates between 2.2 m and 3.1 m, with the interlayer of clay slate with a seam thickness of up to about 0.3m. In the roof of the coal seam lies a layer of clay slate with a seam thickness of 4.7 m. Above this seam lies light grey sandstone of various grains with a seam thickness of 5.2 m, below this seam there is a layer of sandstone with a thickness of 3.7 m. In this area there have not been exploitation events so there are no edges, remains or abandoned workings which are mining factors which most often cause stress concentration zones. High seismicity in Panewniki field appeared at the very beginning of exploitation. There were many low-energy phenomena (750 tremors below 10^5 J) and 113 tremors of energy higher than 10^5 J, including five tremors of 10^7 J energy, one of 10^8 J energy and the strongest one which was $4\cdot10^9$ J and is the subject of the present analysis.

3. Soil vibration parameters and damage to buildings due to the tremor of 18 April 2015

Seismic measurements constitute the most precise and direct information which is indispensable for the evaluation of surface vibrations; they also allow for the empirical correlation of the effects of vibrations with measurement sizes. Registration of vibration parameters of the tremor from 18 April 2015 with an energy $E=4\cdot10^9$ J was carried out at five surface seismic stations. Table 1 shows parameter values of soil vibrations from measurement stands on the basis of publication [10] containing soil vibration analysis made according to the methodology used for the GSI_{GZWKW}–2012 scale [12].

After the occurrence of the analysed tremor, the inhabitants of Katowice and the neighbouring towns reported numerous instances of damage to buildings and reported their resulting feelings of anxiety, fear and discomfort.

Table 1. Parameters of 18 April 2015 tremor vibrations as registered at surface seismometric stations [10]

Seismic station	Epicentral distance [m]	Velocity, PGV_{Hmax} [mm/s]
A 4 – Bałtycka	1253	20
A 3 – Panewnicka (wall)	887	100.3
A 3 – Panewnicka (soil)	890	61
A 2 – Kalinowa	2670	12.8
A 7 – Piłsudskiego	2428	14.7
A7 – Mikołowska	6147	3

Table 2 displays the instances of damage to buildings caused by the analysed tremor. This cases were reported right after the tremor and they were then evaluated by personnel from the mining damages department – this was essential for the reliability of such information. On the basis of the measurement data, the dependence describing regional relations between seismic energy, hypocentral distance and maximum velocity parameters of horizontal vibrations registered on the bedrock [4] distribution was calculated of the forecast component amplitudes of the horizontal velocity of vibrations. Next, having taken the vibration amplification factor in this region into consideration, vibration velocity isolines PGV_{Hmax} were plotted. On the basis of the received map of vibration velocity PGV_{Hmax}, the values of vibration velocity for the location of the buildings damaged as a result of the analysed tremor were calculated (Table 2). The location of these buildings and tectonic structures are shown on the PGV_{Hmax} vibration velocity map in Fig. 1.

Table 2. List of damage to buildings following the tremor of 18 April 2015; intensity $E = 4{\cdot}10^9$ J; velocity PGV_{Hmax}; distance from Kłodnica fault *dk*; distance from closest fault *d*

Nr *	Town street	Type of building**/ Description of damages	Distance from epicentre [m]	Distance from the nearest fault [m] - d	Distance from Kłodnica fault [m] -dk	Velocity PGV_{Hmax} [mm/s]
3	Katowice, Tysiąclecia	A/ scratches on the walls	7290	1096	4359	0
6	Świętochłowice, Topolowa	A/ scratches on the ceiling	6145	1481	4359	0
7	Chorzów, Sępołowska	A/ scratches on the ceiling	5065	883	2980	0.9
8	Ruda Śląska, Radoszowska	A/ scratches on the wall	3474	40	2089	2.6
9	Ruda Śląska, Radostowska	A/ fallen roof tile	3450	309	2196	2.6
10	Katowice, Lompy	A/ garage door seisure	8191	2774	2774	0
11	Ruda Śląska, Cegielniana	A/ scratches on the walls	2744	0	1570	3.7
12	Katowice,Ogrodowa	A/ building tilt, uplift of floor tiles	3200	227	227	4.3
13	Katowice, Ogrodowa	A/ cracks of ceiling plaster and plaster coves in two rooms	3134	158	158	4.5
14	Katowice, Heweliusza	B/ numerous cracks in all rooms, cracks and loosening of wall tiles	3313	122	122	4.5
15	Katowice, Orkana	A/ cracks on elevations and walls	4882	185	185	2
16	Katowice, Braci Wieczorków	A/ cracks on elevations and walls	3079	22	22	4.9
17	Katowice, Braci Wieczorków	A/ cracks on elevations , walls and floor tiles	3130	60	60	4.9
18	Katowice, Panewnicka	A,C/ numerous cracks on elevations, walls and ceilings, cracks of window lintels, dilatation of flight of stairs from the building	578	188	188	24
19	Katowice, Panewnicka	B/ crack on walls and ceilings, separation of gable wall from the floor and interior load bearing wall, coming off plaster, door frame relocation	970	178	178	18

20	Katowice, Kuźnicka	A/ numerous cracks on elevation, walls and ceilings	534	235	235	15
21	Katowice, Panewnicka	C/ numerous scratches on walls and ceiling, cracks of floor tiles	1389	214	214	17
22	Katowice, Panewnicka	Church – crack of interior wall, crack of lintel	917	221	221	19
		B/ numerous cracks on elevation, walls and ceilings				
23	Katowice, Kuźnicka	A/ cracks on fencing, elevation and cellar walls	549	307	307	13
24	Katowice, Łąkowa	A/ crack around windows, scratches in joints of floor tiles in the bathroom, , door deformation	533	319	319	25
25	Katowice, Bałtycka	A/ cracks on elevation and walls, twist of door frame	1037	336	336	23
26	Katowice, Koszykowa	A, B/ cracks on elevation, walls and ceilings, cracks of floor tiles, loosening of skirting on the terrace, lowering and deformation of the terrace sett	347	501	501	32
27	Katowice, Bałtycka	B/cracks on walls and ceilings, deformation of balcony window and door joinery	1120	535	535	20
28	Katowice, Bałtycka	B/ cracks on elevation, wall, ceilings in many rooms, scratches of dilatation wall corners	1179	521	521	21
29	Katowice, Koszykowa	B/ cracks on elevation, walls and ceilings, loosening and cracks of the tiles	316	565	565	33
30	Katowice, Poleska	A/ cracks on walls and tiles	3624	779	779	3.7
31	Katowice, Huculska	A/ cracks on elevation, stairs and fence, twist of door frame	3634	717	717	3.7
32	Katowice, Huculska	A/ cracks on walls and ceilings	3659	749		3.5

33	Katowice, Huculska	A/ numerous cracks on elevation, walls, ceilings and fence base	3551	760		3.4
34	Katowice, Wczasowa	C/ cracks on balcony, walls, scratches on plaster cove in the bathroom	3153	1212		4
35	Katowice, Żołnierska	A/ cracks on elevation, tiles, entrance door deformation	3853	1445		3
36	Katowice, Komasa	A/ scratches on the walls	4845	2356		1.5
37	Katowice, Sępia	A/ scratches on the walls	4144	2474		2.3
38	Katowice, Armii Krajowej	A/ entrance door deformation	5689	3905		0.5
39	Katowice, Stabika	Collapse of ground floor in the cellar (about 5 cm) (after verification – no connection)	5326	3595		0.8
40	Mikołów, Przyjaźni	A/ cracks on elevationcji	4653	740		1
41	Katowice, Norblina	A/ cracks on external elevation	6145	3811		0.4

* No – the object number on the map

** Type of building : A – (single family house); B – (single family terraced or twin houses); C – (multifamily building)

4. Statistical analysis of the relationship between the distance of the damaged buildings' from the fault and soil vibration velocity PGV_{Hmax}

To determine the influence of the amplification of the Kłodnica fault zone on the amount of damage to buildings caused by high-energy tremors, statistical analysis was used. For the purpose of statistical analysis, two variables were taken into consideration: distance of the buildings from the nearest fault – *dk*; maximum amplitude of horizontal vibrations velocity PGV_{Hmax} at the location of the foundations of the damaged buildings. The first step in the analysis was to check whether the distribution of parameters taken into analysis is a normal distribution. The statistical analysis was carried out by the STATISTICA software program. To check whether the distribution of the variables is normal, Shapiro-Wilk's test was used – this showed that neither variable has a normal distribution; therefore, Spearman's correlation coefficient was used to check correlation. The Spearman correlation coefficient takes values from the interval [-1; 1]. If there is no correlation between the variables, the returned value is 0. The critical values of the Spearman correlation coefficients are given in the statistics tables (Kendall test). The null hypothesis H_o was tested – this states that there is no correlation between the variables. The alternative hypothesis H_1 states that there is a correlation if the calculated correlation coefficient at a specific level of significance (usually $\alpha = 0.05$) is greater than the critical value given.

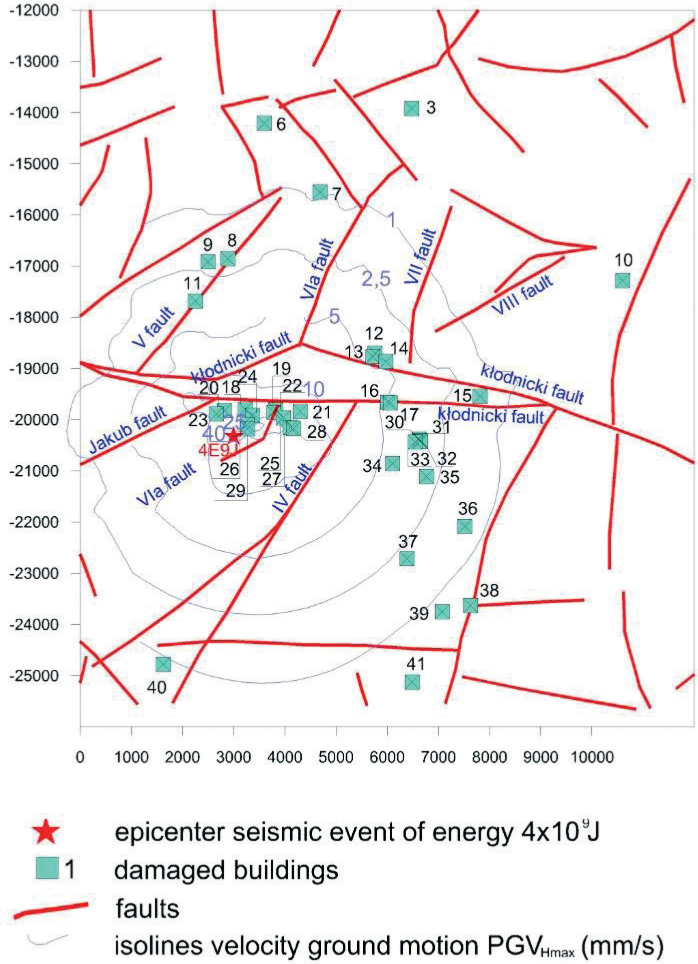

Fig. 1. Location of damaged buildings and tectonic structures on the map of vibration velocities PGV_{Hmax} from the tremor of 18 April 2015 with seismic energy of $E=4{\cdot}10^9$ J

Table 3. Correlation matrix PGV_{Hmax} and *dk* for the tremor of 18 April 2015 of seismic energy $E=4{\cdot}10^9$ J

	PGV_{Hmax} [mm/s]	**dk [m]**
PGV_{Hmax}	1	-0.74
dk [m]	-0.74	1

As a result of calculations, the statistically essential correlation coefficient **R = |– 0.74| = 0.74** for level of significance 0.05 was obtained (Table 3). In order to establish the significance of the correlation coefficient for the given level of significance, a method of hypothesis testing (test t – Student's) was applied. It appeared that the correlation coefficient is essential. Thus, with a 95% level of probability both variables, that is PGV_{Hmax} – horizontal velocity of ground vibrations [mm/s] in the foundation place of a building and *dk* – distance of the damaged building from Kłodnica fault [m], are related to each other.

In the second analysis, the influence of the fault on damage to buildings located closest to it was investigated. As in the first analysis, two variables were taken into consideration in statistical tests: distance of the buildings from the nearest fault – *d*; the maximum amplitude of horizontal vibrations velocity PGV_{Hmax} at the location of the foundations of the damaged buildings. The first step in the analysis was to check whether the distribution of parameters taken into analysis is a normal distribution. The statistical analysis was carried out by the STATISTICA software program. To check whether the variables have normal distributions, Shapiro-Wilk's test was used – this showed that neither variable is of a normal distribution; therefore, Spearman's correlation coefficient was used to check correlation.

Table 4. Correlation matrix PGV_{Hmax} and *dk* for the tremor of 18 April 2015 of seismic energy –=$4{\cdot}10^9$ J

	PGV_{Hmax} [mm/s]	**d [m]**
PGV_{Hmax}	1	-0.57
d [m]	-0.57	1

As a result of calculations, a statistically essential correlation coefficient of **R=|-0.57|=0.57** for level of significance 0.05 was obtained (Table 4). In order to check the significance of the correlation coefficient for the given level of significance, a method of hypothesis testing (test t – Student's) was applied. It appeared that the correlation coefficient is essential. Thus with a 95% level of probability both variables, that is PGV_{Hmax} – horizontal velocity of ground

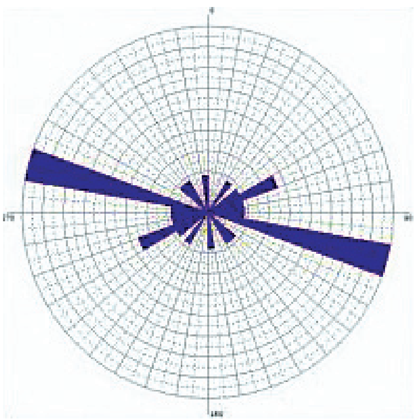

Fig. 2. Direction diagram of mining damage for tremor of 18 April 2015 of seismic energy $E=4{\cdot}10^9$ J

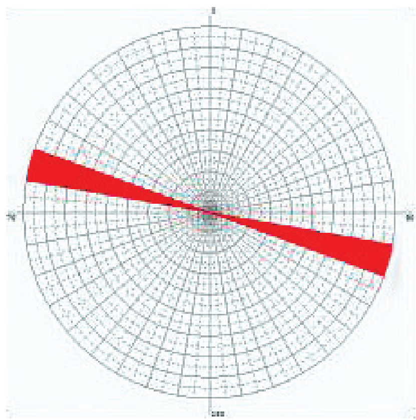

Fig. 3. Direction diagram of the Kłodnica fault zone for tremor of 18 April 2015 of seismic energy $E=4{\cdot}10^9$ J

vibrations [m/s] in the foundation place of a building and *dk* – distance of the damaged building from Kłodnica fault [m], are related to each other. Taking into consideration the values of the obtained correlation coefficients, it can stated that the influence of the Kłodnica fault on the occurrence of damage to the buildings was larger than that of the other faults, in spite of the fact that the buildings are located in their vicinity in some cases. Therefore, for the buildings in the Kłodnica fault region, a statistical analysis of their location direction was carried out. The analysis was performed according to a method described in work [11]. To obtain direction diagrams of mining damage, straight lines were drawn through each of the two closest instances of mining damage in the studied area. The obtained distribution direction of the analysed mining damage and the zone of the Kłodnica fault is presented in Figures 2 & 3.

The performed analysis shows that when evaluating the influence of vibrations on the buildings except tremor energy, the epicentre distance, the vibration amplification coefficient, and the location of the buildings in relation to the tectonic zones also has to be considered. From the data set in Table 2, it appears that damage found in the buildings is, in some cases, located even at a distance of over 3.5km from the centre of the tremor. These buildings, however, are located up to 0.8km from the fault zone (Table 2 – number of buildings from 12–33).

5. Summary

The analysis focused on the influence of the Kłodnica fault zone on the size of damage in the buildings caused by the regional tremor of 18 April 2015 of seismic energy $E=4\cdot10^9$ J. On the basis of statistical analysis of the relationship between the distance of the damaged buildings' from the tectonic zone of Kłodnica fault (*dk*) or the nearest fault (*d*) and the maximum amplitude of horizontal vibrations velocity PGV_{Hmax} (at the locations of foundations of these buildings), it was shown that the influence of the Kłodnica fault in this region on damage caused to these buildings is of key importance.

As a result of the performed calculations, statistically essential values of correlation coefficients were obtained, wherein the correlation value of PGV_{Hmax} velocity with the distance of the damaged buildings from the Kłodnica fault is larger than with the distance of the buildings from the nearest fault – this is also proved by the analysis of the distribution direction of the damaged buildings.

From the analysis, it can be seen that the dominant direction of mining damage distribution is the direction of the Kłodnica fault zone, which is close to being latitudinal. This is also a dominant direction of tectonics in the southern wing of the main saddle.

On the basis of the performed analysis, it can be stated that when evaluating or forecasting the influence of vibrations on buildings – apart from seismic energy of the tremors, epicenter distance and amplification coefficient of the vibration – the location of buildings in relation to the tectonic zones also has to be taken into consideration; this is extremely essential when designing buildings and in site planning.

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