The Impact of High-Energy Mining-Induced Tremor in a Fault Zone on Damage to Buildings

Elżbieta Pilecka 1, Krystyna Stec 2, Jacek Chodacki 2, Zenon Pilecki 3,*, Renata Szermer-Zaucha 1,† and Krzysztof Krawiec 3

Abstract: Seismic energy propagation from the hypocentre of mining-induced tremors usually causes an uneven distribution of the peak ground velocity PGV$_{H\text{max}}$ in tectonically complicated structures, and consequently, an uneven distribution of damage to buildings located on the ground surface. This study aimed to estimate the impact of high-energy mining-induced tremors in fault zones on damage to buildings. In the study, we describe a case of one of the highest-energy mining-induced tremors $E = 4.0 \cdot 10^8$ J (local magnitude ML = 3.6) that occurred in the Upper Silesian Coal Basin (USCB), Poland. The hypocentre of the tremor was most probably located in the Barbara fault zone, one of the larger faults in that western part of the USCB. Numerous damaged buildings on the terrain surface were registered, both in the epicentral zone and at a greater distance from the epicentre, mostly from the southern side of the Barbara fault zone. We calculated that the tremor was characterised by a normal slip mechanism associated with the same kind of fault as the Barbara fault. The azimuth of the nodal planes was similar to the west-east direction, which is consistent with the azimuth of the Barbara fault. From the focal mechanism, the greatest propagation of seismic energy occurred in south and west-east directions from the tremor hypocentre towards the surface. It was found that from the northern side of the hanging wall of the Barbara fault, there were 14 instances of damage (19%), and in the southern part of a hanging wall, there were 58 (81%). Therefore, the directionality of seismic energy propagation is aligned with the focal mechanism acting in the Barbara fault. From the focal mechanism, the greatest propagation of seismic energy occurred in south and west-east directions from the tremor hypocentre towards the surface. It was found that from the northern side of the hanging wall of the Barbara fault, there were 14 instances of damage (19%), and in the southern part of a hanging wall, there were 58 (81%). Therefore, the directionality of seismic energy propagation is aligned with the focal mechanism acting in the Barbara fault. It has also been concluded that a width of the zone of up to about 1200 m along the Barbara fault is the most threatening on the basis of registered building damage in the geological conditions of USCB. The study has shown that in assessing the impact of mining-induced tremors on buildings and the environment, the disturbance of seismic energy propagation by larger faults should be considered.

Keywords: high-energy tremor; mining-induced tremor; focal mechanism; peak ground velocity; faults; building damage

1. Introduction

In seismically active mining areas, the problem of accurately forecasting the zones of intensity of ground vibrations after the occurrence of high-energy tremors is not completely resolved—e.g., [1–3]. The issue is important in the context of the impact of ground vibrations on the environment, the construction of new facilities, and the strengthening of existing buildings [4–6].

The impact of mining-induced tremors on the environment is very diverse, from weak—imperceptible by people—to very strong [7–10], which often causes specific damage...
to the existing infrastructure on the ground surface [4,6] and sometimes in underground mining workings [4,11,12].

Many years of observations and analysis in the Upper Silesian Coal Basin (USCB), Poland, have shown the bimodality of mining-induced tremors [13]. There is a group of tremors that are directly associated with mining advancement of the longwall face, so-called “exploitation tremors” of seismic energy $E < 10^7$ J, and a group of so-called “regional tremors”, strong tremors of $E \geq 10^9$ J. Regional tremors are associated with mining operations over a large area, covering many longwall panels, and their occurrence is related to greater faults, folds, or overlaps in the area of mining operations. Dubiński et al. [10] underlined that unfavourable changes of the stress field caused by mining are only a trigger in reducing energy stored in geological structures disturbed by mining. Regional tremors are particularly hazardous for buildings on the terrain surface.

The most accurate method to estimate changes of ground vibrations with the epicentral distance is direct measurement. However, most often, there are either insufficient or no detectors at all in the research area. This makes it impossible to precisely determine the impact of the tremor on ground surfaces and buildings. To estimate the changes of ground vibrations with the epicentral distance, various kinds of universal seismic scales are used [14], as well as local scales developed for specific geological and mining conditions, e.g., Mining Seismic Instrumental Intensity Scale (MSIIS-15) [5]. Various kinds of analytical relationships are also used to estimate the size of ground vibrations [3,15]. Unfortunately, analytical solutions usually provide approximate results due to the complex nature of the wavefield, which is often distorted by the geological structure.

This study aims to estimate the impact of high-energy mining-induced tremor in the fault zone on damage to buildings on the ground surface. In particular, we highlighted the role of the fault in mining-induced regional tremors and its impact on the propagation of seismic energy. This issue is not widely discussed in published studies. In practice, when planning buildings or reinforcing existing ones in mining areas, the impact of larger faults on the expected occurrence of damage to facilities is not taken into account.

In the article, we describe a case of one of the highest-energy tremors $E = 4.0 \cdot 10^8$ J (local magnitude $ML = 3.6$), which occurred on 8 November 2018 in the USCB (Figure 1). Numerous damaged buildings on the ground surface were registered, both in the epicentral zone and at a great distance from the epicentre.

We present the methodology of observation and calculations to estimate the impact of high-energy tremors on damage to buildings on the ground surface. We also present information on geological and mining conditions in the research area, emphasising the parameters of the Barbara fault. In the following sections of the article, we discuss the estimation of ground vibration distribution due to the occurrence of tremor. We emphasise seismic energy propagation initiated by the focal mechanism of the tremor occurring in the existing Barbara fault. We present the location of damaged buildings depending on the distance to the Barbara fault. The measurement and theoretical calculations of horizontal peak ground vibration are also compared with the location of damaged buildings.
2. Methods and Data

In general, the impact of high-energy mining-induced tremors on the environment depends on many factors [7,16–21]:

- Seismic source parameters—physical quantities describing the focal mechanism;
- Structure and properties of rock mass in the way of propagation of the seismic waves;
- Seismological properties of the loosened overburden at the vibration reception station (site effect), determined by the vibration amplification factor;
- The types and properties of buildings threatened by seismic energy.

In the USCB, seismological observations have been conducted for several decades by the mine networks and the Upper Silesian Regional Seismological Network (USRSN) (Figure 1) [22]. Using both networks enables the observation of induced tremors occurring in the USCB from energy levels of $10^5$ J (ML $\geq 1.7$). We can locate their foci and determine their seismic energy levels.

2.1. Focal Mechanism

The parameters of the focal mechanism tremor are determined based on seismo-grams recorded by the USRSN (Figure 1) using the seismic moment tensor method (SMTM) [23,24]. It describes the system of forces occurring in a seismic source as a linear combination of force paired with a tensor moment. The total displacement in the far wave field $u_k$ is the sum of the displacements caused by individual pairs of forces:

$$u_k = M_{ij} \frac{\partial C_{ki}}{\partial x_j} = M_{ij} \ast G_{ki,j}$$

where:

- $u_k$ are the displacement amplitude measurements of the first maximum of the P-wave;
- $M_{ij}$ is a $j_{th}$ component of the vector of moment tensor terms ($M_{xx}$, $M_{yy}$, $M_{zz}$, $M_{xy}$, $M_{xz}$, $M_{yx}$);
G_{ij} is a matrix of appropriate Green’s function in a whole homogeneous space.

In the study, we calculated tremor models from amplitudes and the polarity of P-waves using FOCI software [25]. As a result, three models of tremor focus can be identified, described by three types of seismic tensor: full, deviatoric, and pure shear tensor. The full moment tensor can be broken down into an isotropic component (ISO), describing the volume change: explosion (+) or implosion (−), and into a compensated linear vector dipole (CLVD) corresponding to the uniaxial compression (−) or tension (+), and into the double-couple component (DC) corresponding to the shear motion. The deviatoric tensor has a CLVD component and the shear component DC. The pure shear tensor only has the double-couple (DC) component. The full, deviatoric, and pure shear moment tensor was calculated using the L2 norm. To estimate the errors of each moment tensor solution, the maximum error is calculated as the square root of the maximum element of the covariance matrix:

\[ \text{cov}(m) = \sigma(G^T G)^{-1} \]  \hspace{1cm} (2)

The variance \( \sigma \) represents the measurement error and is assumed to be around 25% of the measured displacement amplitude.

2.2. Ground Vibrations

The seismic intensity of ground vibrations in the USCB is assessed based on the MSIIS-15 scale [5]. This scale combines instrumental measurement parameters of ground vibrations with observed macroseismic effects. This is a two-parameter scale based on the maximum amplitude of horizontal vibration velocity, \( PGV_{H_{\text{max}}} \), and the duration of the horizontal ground motion velocity, \( t_{HV} \) (Table 1). The maximum amplitude of horizontal vibrations velocity \( PGV_{H_{\text{max}}} \), designated as the resultant of the horizontal maximum of vector length:

\[ PGV_{H_{\text{max}}} = \max\left(\sqrt{V_x^2 + V_y^2}\right) \]  \hspace{1cm} (3)

where:

- \( V_x \) is the horizontal ground motion velocity in the x-direction, m/s;
- \( V_y \) is the horizontal ground motion velocity in the y-direction, m/s.

The vibration intensity degrees \( I_{\text{MSIS}} \) are assigned for the harmfulness levels correlated with specific types of building structures. During the development as well as the verification of the MSIIS-15 scale, various buildings characteristic for the research area were observed, including the buildings with the unreinforced weakest structures and in poor technical condition (for example, the buildings located in the area of the previous mining activities and subjected to a process of subsidence).

For traditional brick buildings, the most common in the USCB, the first new damage to non-structural elements may occur at \( I_{\text{MSIS}} \) intensity levels of III and above. Structural damage may occur at \( I_{\text{MSIS}} \) intensity levels of IV and above. The enlargement of scratches, cracks, or fissures existing in buildings may already occur at the II degree of \( I_{\text{MSIS}} \), i.e., in the area or even several kilometres from the epicentre of the tremor. For buildings in poor technical condition, the harmfulness limit is reduced by one degree.

To calculate the predicted value of horizontal velocity vibrations \( PGV_{H} \), the empirical formula was developed for type “A” subsoil according to the Eurocode 8 standard [14]. Ground-type “A” represents “rock or other rock-like geological formations, including at most 5 m of weaker material at the surface” characterised by average S-wave velocity > 800 m/s.

The statistically developed equation describes the normalised decrease in the \( PGV_{H} \) as a function of seismic energy \( E \), epicentral distance \( d \), and ground-type “A”, in the form [2]:

\[ \log(PGV_{H}) = 0.209 \cdot \log(E) - \log(d) - 0.035 \cdot d - 0.814 \]  \hspace{1cm} (4)

The standard estimation error \( S \) for the \( PGV_{H} \) equals to 0.314, and the standard estimation errors for the given regression coefficients (which are estimates of the regression coefficients for the whole population) are as follows: \( S_{\log(E)} = 0.0298, S_d = 0.0086, \)
Sintercept = 0.2283. The coefficient of determination R² = 0.86 indicates that the model explains variation of PGV_H in 86%.

Table 1. Short form of the Mining Seismic Instrumental Intensity Scale [5].

| I_{MSIS} | PGV_{Hmax} for short duration (tHV ≤ 1.5 s) [m/s] | PGV_{Hmax} for long duration (tHV > 1.5 s) [m/s] | Perceived Shaking | Potential Damage |
|----------|-------------------------------------------------|-------------------------------------------------|-------------------|------------------|
| I        | <0.005                                          | <0.005                                          | Not felt or weakly felt. | None |
| II       | 0.005–0.020                                     | 0.005–0.010                                     | Felt indoors by many people, outdoors by few. Dishes rattle, hanging objects begin to sway. Felt strongly indoors by many people, weak rocking of the whole building. Open windows and doors may close. | None |
| III      | 0.020–0.035                                     | 0.010–0.025                                     | Felt strongly by most people. Many people are frightened and run outdoors. The furniture may shift, the whole building rocks. Felt very strongly by most people. Most people are frightened and try to run outdoors. A few people lose their balance. A large number of objects fall from shelves. | Intensification of existing damage |
| IV       | 0.035–0.050                                     | 0.025–0.040                                     | Damage to decorative elements |
| V        | 0.050–0.070                                     | 0.040–0.060                                     | Slight single structural damage |

The predicted PGV_H is also the resultant of the horizontal maximum of vector length (3). It depends on the amplification of ground vibrations caused by the properties and geological structure of loosened overburden. Therefore, the maximum value PGV_{Hmod} modified with amplification factor can be determined from the formula:

\[ PGV_{Hmod} = PGV_H \cdot W_f \]  \hspace{1cm} (5)

where \( W_f \) is the amplification factor.

The Formula (5) is used to analyse the ground vibration intensity degree I_{MSIS}.

3. Geological and Mining Conditions

Figure 2 shows a simplified geological section, named A1-A1’, referring to the area under examination. The location of section A1-A1’ is sketched in Figure 3. In the research area, the rock mass of Carboniferous formations is covered with a loosened overburden of Quaternary formations. The thickness of the overburden is about 180 m. The Carboniferous formations are formed by the Orzeskie and Rudzkie layers with a total thickness of around 1800 m. The Orzeskie layers are made of claystones, mudstones, sandstones, and coal seams with a thickness of around 800 to around 1250 m in the southern part. The thickness of the coal seams is variable and ranges between 0.6 and 3.5 m. Below the Orzeskie layers, there are Rudzkie layers at a depth of approximately 880 to approximately 1300 m. These are composed of a complex of claystones and mudstones with a small amount of sandstone and numerous coal seams with a thickness of 0.6 to 3.9 m.

Figure 2. Cross-section through the research area with the Barbara fault zone and the tremor hypocentre that occurred on 8 November 2018. Description in the text.
In the research area, the Carboniferous formations are quite heavily faulted (Figure 3). The largest faults include the Barbara fault zone with a latitudinal course with a throw of around 30–55 m in the S direction at an angle of around 50° (Figure 2). There are other faults in the neighbourhood with smaller drops: the Dębieński fault with a throw of 22 m to 45 m and a latitudinal course, and the Północny, Paniowski, Knurowski, and smaller faults.

Mining works identified the Barbara fault zone to be at a level of 1050 m and in several coal seams (Figure 3). To the north of the Barbara fault hanging wall, many coal seams have been mined with a total maximum thickness of about 13.4 m. From south of the hanging wall of the Barbara fault, the coal seams have been exploited to a total maximum thickness of about 6.5 m. The unevenness of the coal seam exploitation on both sides of the Barbara fault can cause high-stress values in the fault zone. The dynamic reduction of these stresses can be a direct cause of tremors of higher energies.

4. Results

A mining-induced tremor of high-energy $E = 4.0 \cdot 10^8$ J and magnitude $ML = 3.6$ occurred on 8 November 2018 in the western part of the USCB. The tremor was recorded at many USRSN stations at distances of up to several dozen kilometres (Figure 4). The focus of the tremor was calculated at a depth of around 800 m. The epicentre location of the tremor is shown in Figures 1 and 5. Moreover, Figure 5 shows the location of the AMAX seismometric stations belonging to the coal mine (i.e., ST1, ST2, ST3).

4.1. Focal Mechanism

The calculation results of the focal mechanism are presented in Table 2. In the calculations, we assumed 3200 m/s for the P-wave velocity and 2500 kg/m$^3$ for ground density. The graphic image of the focal mechanism presented in Table 2 is a projection of the lower hemisphere.
Figure 4. An example of a seismogram of the tremor of 8 November 2018 with seismic energy $E = 4.0 \cdot 10^8$ J registered by seismic stations of the Upper Silesian Regional Seismological Network.

Figure 5. Map of the vibration amplification factor $W_f$ isolines of the tremor of 8 November 2018 with AMAX seismometric stations.
Table 2. Parameters of the focal mechanism of the tremor of 8 November 2018.

| Nodal Plane A, B | Stress Axes C, T | Tensor Component, % | Normal Slip Mechanism |
|-----------------|-----------------|---------------------|-----------------------|
| Φ / δ / λ     | Φ / δ / λ     |                     | ISO | CLVD | DC |
| A  269/60–89   | 86/31–93       | 184/75              | 18  | 20   | 62 |

Symbols: Φ, nodal plane azimuth A, B; δ, dip of plane A, B; λ: slip angle of A, B; Φ: axis azimuth of C, T; δ: plunge of the axis of C, T; ISO: percentage of an isotropic component; CLVD: percentage of compensated linear vector dipole component, compression (−), or tension (+); DC: percentage of shear component (double-couple).

The analysed tremor is characterised by a normal slip mechanism with 62% of the shear component. The remaining isotropic component and compensated linear vector dipole component (compression or tension) were 18% and 20%, respectively. The main compressive stresses C and the tensile stresses T have a plunge of 75° and 14°, respectively. Nodal planes have an azimuth WE: fracture plane A (ϕ = 269°, δ = 60°) and plane B (ϕ = 86°, δ = 31°).

4.2. Ground Vibrations

The tremor of 8 November 2018 was also recorded at the AMAX seismometric stations (i.e., ST1, ST2, ST3), located closest to the tremor epicentre. Table 3 presents the values of PGV as a measured resultant of the horizontal maximum of vector length (3) and basic parameters of ground vibrations at the point of registration by AMAX stations. The large difference in horizontal ground vibration PGV_Hmod values at the individual station is not explained by the values of vibration amplification coefficient W_f at the point of registration. Bearing in mind that seismic waves propagation is affected by lithostratigraphic and topographic local conditions—e.g., [26–34], the distribution of the amplification factor W_f is shown in Figure 5.

Table 3. Ground motion parameters at the point of registration by AMAX coal mine stations for the tremor of 8 November 2018.

| Seismic Station | Epicentral Distance, [m] | Amplification Factor W_f [-] | PGV, [m/s] | PGV_Hmod, [m/s] | Duration Time tHT, [s] |
|----------------|-------------------------|-----------------------------|------------|-----------------|----------------------|
| ST 1- AMAX     | 1816                    | 2.4                         | 0.0206     | 0.011           | 9.20                 |
| ST 2- AMAX     | 2574                    | 2.4                         | 0.0092     | 0.0071          | 8.46                 |
| ST 3- AMAX     | 2360                    | 2.6                         | 0.0040     | 0.0079          | 3.88                 |

The error in determining the value PGV_H indicates that the standard deviation S = 0.314. For example, for tremors with the seismic energy 1.0·10^8 J with a confidence interval of 90%, the theoretical PGV_H values may differ from the average value by up to 50% in the epicentre (Figure 6). Therefore, the error to measured values of PGV at AMAX stations may exceed the predicted values of PGV_Hmod (Table 3).

Figure 7 shows the PGV_Hmod field and the measured vibration values PGV at the AMAX stations. For the analysed tremor, the intensity degree I_MSIS was determined from the distribution of the PGV_H, calculated according to Formula (4).

In the majority of the impact area of the tremor, the vibration intensity I_MSIS ranges from the degree I to II. Only in a small area around the tremor epicentre, the intensity I_MSIS, falls within the III–IV degree range. People in the neighbouring towns felt the analysed tremor several dozen kilometres away from the seismic epicentre (Mikołów, Knurów, Zabrze, Zory, Katowice—Figure 1). In these localities, the ground vibration level was low as 0.0001–0.0008 m/s.
4.3. Damage to the Buildings on the Ground Surface

The tremor of 8 November 2018 caused many instances of damage to the buildings on the terrain surface, but it did not cause any damage to the underground mine workings. In the research area, there are mainly low-rise single-family residential buildings, up to two storeys above the ground, concentrated along the roads (Figure 8a). The buildings are typical of smaller towns and villages in Upper Silesia. The buildings have a historical, traditional structure or a traditional improved one, used from the second half of the 20th century. Traditional buildings have a structure in the form of load-bearing walls made of stone or brick, with wooden ceilings or brick-vault ceilings, set on stone or brick foundations. Buildings with a traditional, improved structure have load-bearing
walls made of bricks and hollow bricks and reinforced concrete ceilings set on reinforced concrete foundations. The technical condition of buildings is directly related to the age of the structure and the impact of coal seams exploitation.

![Figure 8](image_url)

**Figure 8.** (a) The characteristic buildings of smaller towns and villages in Upper Silesia in the research area (google.pl/maps); (b,c) the characteristic damages that occurred in single-family residential buildings (own materials).

The damage occurred in 72 single-family residential buildings, inspected by the professional mining staff. Scratches and cracks in structural elements and elevation, the unsealing of chimney pipes, and the enlargement of existing damage were registered. Most of the damage to buildings occurred in the form of scratches or the enlargement of existing damage (Figure 8b,c).

Table 4 presents parameters of building damage: $\text{PGV}_{H_{\text{max}}-D}$ refers to the location of each building, $DF$ is the horizontal distance between the building and the hanging wall of the Barbara fault, and $DE$, or the distance between the building and the tremor epicentre. The epicentral distance $DE$ was calculated based on the epicentre coordinates and the damaged building coordinates in the local datum used by the mine. For the sake of clarity of graphical presentation, the damage to buildings at short distances has been grouped under one damage number, $Nd$. Distance $DF$ to the Barbara fault has been measured directly from geodetic maps and given an accuracy of 50 m. The assumed accuracy results from the dimensions of the building itself and the accuracy of the graphical representation of the fault line on the maps.
Table 4. Damage to buildings after the tremor of 8 November 2018 relative to the hanging wall of the Barbara fault.

| No. | Nd | Locality    | Description of the damage | Distance from the Barbara fault $+/−$ DF $^{2,3}$, [m] | PGV$_{Hmod-D}$ $^{[m/s]}$ | Epicentral distance [m] | IMSSS $^4$ |
|-----|----|-------------|----------------------------|-----------------------------------------------------|---------------------------|-------------------------|-----------|
| 1   | 1  | Gierałtowice | scratches                 | +4500                                               | 0.003                     | 5332                    | 0         |
| 2   | 2  | Gierałtowice | cracks                    | +3450                                               | 0.006                     | 4870                    | I         |
| 3   | 3  | Gierałtowice | facade cracks             | +3450                                               | 0.006                     | 4870                    | I         |
| 4   | 4  | Gierałtowice | unsealing of the smoke duct, scratches | +3450                       | 0.006                     | 4870                    | I         |
| 5   | 5  | Gierałtowice | damage to the chimney, cracks and scratches | +3450                         | 0.006                     | 4870                    | I         |
| 6   | 6  | Gierałtowice | scratches                 | +3450                                               | 0.006                     | 4870                    | I         |
| 7   | 7  | Gierałtowice | scratches on the garage wall | +2600                                     | 0.006                     | 5050                    | I         |
| 8   | 8  | Gierałtowice | scratches                 | +2650                                               | 0.006                     | 3557                    | I         |
| 9   | 10 | Gierałtowice | scratches                 | +2600                                               | 0.006                     | 3517                    | I         |
| 10  | 10 | Gierałtowice | scratches                 | +2300                                               | 0.005                     | 3514                    | I         |
| 11  | 11 | Ornontowice | broken lintels above the window and scratches | +350                         | 0.023                     | 1367                    | II        |
| 12  | 12 | Ornontowice | farm building crack       | +700                                                | 0.021                     | 1629                    | II        |
| 13  | 13 | Ornontowice | photo frame broken        | +500                                                | 0.023                     | 1364                    | II        |
| 14  | 14 | Ornontowice | scratches and cracks      | +650                                                | 0.021                     | 1597                    | II        |
| 15  | 15 | Ornontowice | slight widening of damage that occurred previously | −1000                  | 0.047                     | 362                     | IV        |
| 16  | 16 | Ornontowice | scratches                 | −1000                                               | 0.047                     | 359                     | IV        |
| 17  | 17 | Ornontowice | scratches and cracks      | −1150                                               | 0.048                     | 391                     | IV        |
| 18  | 18 | Ornontowice | slight widening of damage that occurred previously | −900                     | 0.044                     | 489                     | IV        |
| 19  | 19 | Ornontowice | cracks                    | −1000                                               | 0.040                     | 623                     | IV        |
| 20  | 20 | Ornontowice | scratches and cracks      | −800                                                | 0.030                     | 863                     | III       |
| 21  | 19 | Ornontowice | damage repaired during the last renovation (scratches and cracks) reappeared | −250                         | 0.027                     | 958                     | III       |
| 22  | 20 | Ornontowice | cracks, overturning of a fragment of the firewall | −350                         | 0.041                     | 452                     | IV        |
| 23  | 21 | Ornontowice | cracks in the walls, broken glassware | −350                         | 0.041                     | 452                     | IV        |
| 24  | 22 | Ornontowice | damage to the water system and water leakage | −500                         | 0.033                     | 745                     | III       |
| 25  | 23 | Ornontowice | scratches                 | −750                                                | 0.047                     | 242                     | IV        |
| 26  | 23 | Ornontowice | scratches                 | −950                                                | 0.048                     | 214                     | IV        |
| 27  | 24 | Ornontowice | scratches                 | −1200                                               | 0.043                     | 601                     | IV        |
| 28  | 25 | Ornontowice | scratches, luxfer rupture | −1200                                               | 0.041                     | 628                     | IV        |
| 29  | 27 | Ornontowice | scratches                 | −300                                                | 0.025                     | 1103                    | II        |
| 30  | 28 | Ornontowice | scratches                 | −300                                                | 0.022                     | 1465                    | II        |
| 31  | 29 | Ornontowice | scratches                 | −700                                                | 0.046                     | 370                     | IV        |
### Table 4. Cont.

| No. | Nd | Locality    | Description of the damage                              | Distance from the Barbara fault $+/−$ DF $^{2,3}$ [m] | PGV$_{Hmod-D}$ [m/s] | Epicentral distance [m] | IMSNS $^4$ |
|-----|----|-------------|--------------------------------------------------------|-----------------------------------------------------|-----------------------|-------------------------|------------|
| 32. | 30 | Ornontowice | scratches and detachment of a fragment of the glazing  | −700                                                | 0.026                 | 1074                    | III        |
| 33. | 33 | Ornontowice | separating the vestibule from the rest of the building | −2000                                               | 0.021                 | 1753                    | II         |
| 34. | 34 | Ornontowice | cracks in the ceiling, along steel beams and walls     | −1850                                               | 0.019                 | 2031                    | II         |
| 35. | 35 | Ornontowice | scratches and cracks                                   | −1650                                               | 0.028                 | 1140                    | III        |
| 36. | 36 | Dębierżko   | cracks                                                 | −1950                                               | 0.018                 | 2037                    | II         |
| 37. | 37 | Dębierżko   | cracks in the chimney and walls                         | −2000                                               | 0.017                 | 2081                    | II         |
| 38. | 38 | Dębierżko   | scratches                                              | −2000                                               | 0.018                 | 2051                    | II         |
| 39. | 39 | Dębierżko   | scratches and cracks                                   | −1750                                               | 0.018                 | 1874                    | II         |
| 40. | 40 | Dębierżko   | scratches                                              | −1700                                               | 0.019                 | 1796                    | II         |
| 41. | 41 | Ornontowice | wall scratches, cracks in ceramic tiles                | −2000                                               | 0.018                 | 2006                    | II         |
| 42. | 42 | Ornontowice | scratches                                              | −1950                                               | 0.028                 | 1165                    | III        |
| 43. | 43 | Ornontowice | scratches                                              | −1950                                               | 0.027                 | 1170                    | III        |
| 44. | 44 | Ornontowice | scratches and cracks                                   | −1950                                               | 0.027                 | 1145                    | III        |
| 45. | 45 | Ornontowice | scratches, plaster losses                              | −1950                                               | 0.027                 | 1145                    | III        |
| 46. | 46 | Ornontowice | scratches                                              | −1800                                               | 0.029                 | 1071                    | III        |
| 47. | 47 | Ornontowice | scratches                                              | −1250                                               | 0.023                 | 1590                    | II         |
| 48. | 48 | Ornontowice | scratches and cracks                                   | −1200                                               | 0.020                 | 1996                    | II         |
| 49. | 49 | Mikołów     | scratches that have formed before                      | −1000                                               | 0.011                 | 2567                    | II         |
| 50. | 50 | Dębierżko   | scratches, cracks, chimney damage                       | −2300                                               | 0.018                 | 2049                    | II         |
| 51. | 51 | Dębierżko   | minor scratches                                         | −2950                                               | 0.013                 | 2640                    | II         |
| 52. | 52 | Dębierżko   | facade crack                                            | −3100                                               | 0.008                 | 4370                    | I          |
| 53. | 53 | Dębierżko   | facade crack, separation of the stairs                  | −3250                                               | 0.009                 | 3624                    | I          |
| 54. | 54 | Dębierżko   | scratches and cracks                                   | −3250                                               | 0.009                 | 3609                    | I          |
| 55. | 55 | Dębierżko   | scratches and cracks                                   | −3250                                               | 0.010                 | 3283                    | II         |
| 56. | 56 | Dębierżko   | scratches and cracks                                   | −3200                                               | 0.009                 | 3983                    | I          |
| 57. | 57 | Ornontowice | enlargement of existing scratch                          | −2900                                               | 0.010                 | 2068                    | II         |
| 58. | 58 | Ornontowice | enlargement of existing cracks                          | −2750                                               | 0.010                 | 2031                    | II         |
| 59. | 59 | Dębierżko   | enlargement of previous cracks                          | −3250                                               | 0.013                 | 2592                    | II         |
| 60. | 60 | Dębierżko   | scratches and cracks                                   | −3050                                               | 0.011                 | 2920                    | II         |
| 61. | 61 | Dębierżko   | scratches and cracks                                   | −3250                                               | 0.010                 | 3102                    | II         |
5. Results

The model of the focal mechanism of the tremor of 8 November 2018 characterised a relatively high value of 62\% of the shear component. In this context, the direct cause of the tremor could probably be the reduction of mining-induced tectonic stresses in the Barbara fault zone existing in the area where the tremor occurred. This also means that the hypocentre of the tremor was located in the Barbara fault zone. The tectonic stresses were concentrated, due to past mining, on both sides of the Barbara fault. The current mining operation was only a trigger for the tectonic stress reduction and, as a consequence, the occurrence of the tremor in this region [35].

From the model of the focal mechanism of the tremor, one can observe that the nodal plane in the west-east direction is consistent with the extent of the Barbara fault. The orientation of fracture plane A (Table 2) means that the greatest radiation of seismic energy occurred in the south and west-east directions because this radiation is perpendicular and parallel to the fault plane in focus. Therefore, the intensity of ground vibrations on the terrain surface should be much greater towards the south of the focus and along the Barbara fault. This is confirmed by the location of damage to the buildings (Table 4, Figure 7, and Figure 9). The theoretical field of the PGV_{Hmod} (Figure 7) is aligned with the observed damage, which was greatest for intensity degrees III and IV; additionally, the extent of observed damage was greater south of the Barbara fault than north of the fault. It shows an agreement with values measured at the ST1–AMAX and ST3–AMAX stations (Table 3). The exception is the recording at ST2–AMAX.

Figure 9 shows the distribution of PGV_{Hmax-DF} at the site of the damaged building in terms of the distance DF from the hanging wall of the Barbara fault and number of damaged buildings. Distances DF with a minus sign from the Barbara fault indicate the building’s location south of the fault, while distances DF with a plus sign indicates distances north from the Barbara fault. One can observe that the number of instances of damage to buildings from the side of the hanging wall of the fault in the southern part of the research area is much greater than from the side of the footwall of the Barbara fault in the northern part of the research area. In the northern part, the number of instances of

| No. | Nd ¹ | Locality | Description of the damage | Distance from the Barbara fault +/- DF ², [m] | PGV_{Hmod-D} [m/s] | Epicentral distance [m] | IMSSS ⁴ |
|-----|------|----------|---------------------------|----------------------------------------------|---------------------|------------------------|--------|
| 62. | 64   | Dębieńsko | cracks in chimneys and facades | −3100                                         | 0.013               | 2790 I                 |        |
| 63. |      | Dębieńsko | horizontal crack, deformation of the door’s woodwork | −3100                                         | 0.013               | 2790 II                |        |
| 64. | 65   | Dębieńsko | scratches                   | −2950                                         | 0.010               | 3051 II                |        |
| 65. | 66   | Dębieńsko | scratches and cracks        | −2950                                         | 0.010               | 3051 II                |        |
| 66. | 67   | Dębieńsko | scratches                   | −3150                                         | 0.011               | 2930 II                |        |
| 67. | 68   | Dębieńsko | scratches                   | −3200                                         | 0.012               | 2655 II                |        |
| 68. | 69   | Dębieńsko | scratches and cracks        | −2900                                         | 0.015               | 2365 II                |        |
| 69. | 70   | Ormontowice| roof-tile scratches and cavities | −2550                                         | 0.013               | 2308 II                |        |
| 70. | 71   | Dębieńsko | scratches in the farm building | −3100                                         | 0.009               | 3859 I                 |        |
| 71. | 72   | Orzesze   | cavities in chimneys and roof tiles | −3450                                         | 0.005               | 4926 I                 |        |

¹ (Nd), damage number in the drawing; ² (+DF), north of the hanging wall of the Barbara fault; ³ (−DF), south of the hanging wall of the Barbara fault; ⁴ IMSSS, intensity degree according to the MSIS-15 scale.
damage was 14, which means 19% of all cases of damage. In the southern part, it was 58 cases and 81% of all instances of damages, which was much greater (Table 4).

The greatest PGV$_{H_{\text{max}}-DF}$ occurred in the southern area of the Barbara fault. At most, they reached the value of about 0.05 m/s. North of the fault, the PGV$_{H_{\text{mod}}-DF}$ were much smaller than on the south side. Such occurrences of damage to buildings indicate the probable impact of the fault and the seismic site effects on the size and number of cases of damage to buildings [36–38].

Table 4 and Figure 9 also show most instances of damage in buildings located at a distance of up to around 1200 m from the Barbara fault. This is consistent with other studies [6] conducted in the geological conditions of the Upper Silesian Coal Basin.

6. Conclusions

The study aims to estimate the impact of high-energy mining-induced tremor $E = 4.0 \times 10^8$ J (local magnitude ML = 3.6) in a fault zone on damage to buildings on the ground surface. The study was performed in the seismically active mining area in the vicinity of the Barbara fault zone in the Upper Silesian Coal Basin, Poland.

Based on the results of the study, the following conclusions can be drawn:

1. The high-energy tremor, which occurred on 8 November 2018, had a regional and tectonic character. The stress generated by the current mining was only a trigger reducing the elastic energy accumulated in the Barbara fault zone. This elastic energy accumulation resulted from historic exploitation in a large area from both sides of the fault zone;

2. The tremor was characterised by a normal slip mechanism with 62% of the shear component. The location and orientation of the focal fracture plane correlate with the orientation of the hanging wall of the Barbara fault zone. The orientation of the fracture plane means that the greatest radiation of seismic energy occurred in the south and west-east directions because this radiation is perpendicular and parallel to the plane in focus;

3. The seismic energy propagated in most in the south and west-east directions from the tremor focus has been confirmed with the location of damage to buildings on the ground surface. To the south of the Barbara normal fault, the number of cases of damage was greater than to the north of the fault. In the northern part, the number of instances of damage was 14 (19%), and in the southern part, it was 58 (81%). Another reason for the different cases of damages from both sides of the fault was the seismic energy attenuation by the rather wide Barbara fault zone of several dozen meters;
4. The most serious cases of damage to buildings were located at a distance of up to about 1200 m from the Barbara fault. This is in line with previous studies [6] on the geological conditions of the Upper Silesian Coal Basin.

The results confirm that the assessment of the impact of ground vibrations on buildings caused by mining-induced tremors should consider: (1) the directionality of seismic energy propagation resulting from the focal mechanism acting along a fault; (2) possible seismic energy attenuation by a wider fault zone. The study will be developed for other cases of high-energy mining-induced tremors in the geological conditions of the Upper Silesian Coal Basin.

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References
1. Li, T.; Cai, M.F.; Cai, M. A Review of Mining-Induced Seismicity in China. *Int. J. Rock Mech. Min. 2007*, *44*, 1149–1171. [CrossRef]
2. Chodacki, J. New Ground Motion Prediction Equation for Peak Ground Velocity and Duration of Ground Motion for Mining Tremors in Upper Silesia. *Acta Geophys.* *2016*, *64*, 2449–2470. [CrossRef]
3. Barúa, P.; Lier, E.; Fernández, M.M.; Chmiela, A.; Muñiz, Z.P.; Sanchez, A.B. Directional Attenuation Relationship for Ground Vibrations Induced by Mine Tremors. *J. Min. Sci.* *2020*, *56*, 236–245. [CrossRef]
4. Dubinski, J.; Pilecki, Z.; Zuberek, W.M. (Eds.) *Badania Geofizyczne W Kopalniach [Geophysical Surveying in Mines]*; IGSMiE PAN: Cracow, Poland, 2001. (In Polish)
5. Mutke, G.; Chodacki, J.; Muszyński, L.; Kremers, S.; Fritschen, R. Mining Seismic Instrumental Intensity Scale MSIS-15 Verification in Coal Basins. In Proceedings of the 5th International Symposium: Mineral Resources and Mine Development, Aachen, Germany, 27–28 May 2015; RWTH Aachen University: Aachen, Germany; pp. 551–560.
6. Pilecka, E.; Stec, K.; Szmermer-Zaucha, R. The influence of the Kłodnica fault tectonic zone on the degree of damage to buildings resulting from high magnitude tremors. *Tech. Trans.* *2017*, *7*, 53–64. [CrossRef]
7. Gibowicz, S.; Kijko, A. An Introduction to Mining Seismology; Academic Press Inc.: London, UK, 1994.
8. Gibowicz, S.J. Seismicity induced by mining: Recent research. *Adv. Geophys.* *2009*, *51*, 1–563. [CrossRef]
9. Marcak, H.; Pilecki, Z. Assessment of the subsidence ratio be based on seismic noise measurements in mining terrain. *Arch. Min. Sci.* *2019*, *64*, 197–212. [CrossRef]
10. Dubinski, J.; Stec, K.; Mutke, G. Relationship between the focal mechanism of magnitude ML 3.3 seismic event induced by mining and distribution of peak ground velocity. In Proceedings of the 3rd International Conference on Applied Geophysics, Gniezno, Poland, 21–23 June 2017; Volume 24. [CrossRef]
11. Pilecki, Z. Dynamic Analysis of Mining Tremor Impact an Excavation in a Coal Mine. In *FLAC Numerical Modeling in Geomechanics*; Hart, D., Ed.; August Aime Balkema: Rotterdam, The Netherlands, 1999; pp. 397–400.
12. Wang, G.; Gong, S.; Li, Z.; Dou, L.; Cai, W.; Mao, Y. Evolution of stress concentration and energy release before rock bursts: Two case studies from Xingan Coal mine Hegang, China. *Rock Mech. Rock Eng.* *2016*, *49*, 3393–3401. [CrossRef]
13. Kijko, A.; Drzężła, B.; Stankiewicz, T. Bimodal character of extremal seismic events in Polish mines. *Acta Geophys.* *1987*, *35*, 1157–1168.
