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New Ground Motion Prediction Equation for Peak Ground Velocity and Duration of Ground Motion for Mining Tremors in Upper Silesia

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Abstract

This article presents a method of predicting the peak horizontal velocity of ground motion, *PHV,* and the duration of vibration, t_H, for strong seismic events ($E \geq 5 \cdot 10^6$ J, $M_L > 2.5$) in the Upper Silesian Coal Basin (USCB). For the prediction of *PHV*, a model proposed by Si and Midorikawa was used. The regression method takes into account the impact of the local geology under seismic stations on the ground motion according to the Eurocode 8 classification. The ground classification was based on the results of a seismic survey conducted near the seismometer stations. This method is of great practical use because it allows the degree of vibration intensity to be determined on the basis of the Mining Seismic Instrumental Intensity Scale MSIIS-15 (acronym $\mathrm{GSI}_{\mathrm{GZW}}$ in Polish version) at any distance from the epicentre of the seismic events induced or triggered by mining.

Key words: Ground Motion Prediction Equation, GMPE, peak ground velocity, Upper Silesian Coal Basin, mining seismicity.

1. INTRODUCTION

Hard coal mining, which has been conducted in Silesia for centuries, often in highly urbanized areas, poses serious hazards and significantly affects the safety of the surface. Mining tremors, *i.e.*, dynamic phenomena resulting

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from rock mass cracking and displacement, are one of sources of such a hazard. Mining tremors cause additional dynamic loads on buildings, which are designed to withstand static loads. These dynamic loads therefore can damage the buildings, weaken their structure and lower their durability and value (Tatara 2012, Zembaty *et al.* 2015).

In Poland, tremors are induced by mining operations in the Upper Silesian Coal Basin (USCB; Mutke and Stec 1997, Lasocki and Idziak 1998, Idziak *et al.* 1999, Marcak and Mutke 2013), Bełchatów open pit mine (Wiejacz and Rudziński 2010) and Legnica-Głogów Copper District (LGCD; Orlecka-Sikora 2010, Lasocki 2013, Lizurek *et al.* 2014), which are associated with the mining of hard coal, brown coal, and copper ore, respectively. The article concerns the USCB and seismicity in the area associated with underground hard coal mining. The seismicity is of two types – the first type, induced seismicity, includes typical mining tremors directly related to mining operations in the area of operating workings and mining (Stec 2012) and the second, tectonic type, includes tremors triggered by a combination of mining and tectonic factors, resulting in disturbance of the rock mass stress equilibrium on a regional scale (Kozłowska *et al.* 2016). Tremors of the first type are much more numerous and fall within an energy range of up to 10^7 J (so-called mining tremors), which corresponds to a magnitude of $M_L = 2.7$. The other group are tremors occurring over a dozen times a year with energies of 10^7-$5\cdot10^9$ J (M_L within the range of 2.7 and 4.2), and these are regional-scale tremors. Tremors with a seismic energy of 10^5 J ($M_L = 1.7$) are felt by inhabitants of the epicentral zone. Every year, in the USCB area, there are between a few hundred and 2 000 tremors with energies between 10^5 and 10^7 J and several to a few dozen tremors with energy of $E \geq 10^8$ J ($M_L \geq 3.3$) (Stec 2007).

The seismic events that cause most of damage to buildings are the triggered ones (Mutke *et al.* 2015, COMEX 2012-2015), despite their lower vibration velocity and acceleration in the epicentral zone relative to the induced ones. The essential differences in the characteristics of the vibrations triggered by regional seismic events are the lower frequency of the vibrations and the longer signal duration. Consequently, higher levels of dynamic loads occur in construction elements of buildings (Zembaty *et al.* 2015). This confirms the importance of the duration of the main phase of vibrations as one of the basic parameters that fundamentally influence the credible assessment of the effects of vibrations on the surface and influence of the mining tremors on buildings (observed intensity).

The protection of the surface in the USCB requires considering the influence of mining seismic events, especially the strongest ones, with seismic energies of 10^7-10^9 J. To assess this influence, seismic intensity scales are used. They describe directly the impact of vibration on surface. The scales of vibration intensity that were applied until recently for such assessments were formulated for earthquakes or other types of paraseismic vibrations, and the assessment criteria they contained were not sufficiently credible for mining tremors. The example includes the most popular Medvedev–Sponheuer–Karnik scale (MSK-64) (Drzeźla *et al.* 2002) and Modified Mercalli Intensity Scale used by United States Geological Survey (Wald *et al.* 1999).

For the last few years, the effects of vibrations in the USCB have been assessed with a special intensity scale, named Mining Seismic Instrumental Intensity Scale, MSIIS-15 (GSI_{GZW} in Polish version) (Mutke *et al.* 2015). It relates the two parameters: peak horizontal velocity of ground motion, PHV, and vibration duration time, t_H, to the observed intensity of the surface environment and therefore its use requires knowledge of these two parameters. MSIIS-15 scale can be easily used for measuring these parameters during the seismic measurements, yet it is difficult to apply in areas located at any distance from the epicentre. To do this it is necessary to define GMPE that enables to predict the parameters PHV and t_H. This way we may determine the degree of intensity of vibrations in the MSIIS-15 scale for a point on the surface at any distance from the epicentre for an induced or predicted seismic event with a given seismic energy E. Moreover, knowledge of the right model of propagation of seismic waves around an epicentre of seismic event enables drawing seismic hazard maps for a given area without installing extensive measuring equipment.

The article presents a new regional GMPE that can predict the PHV and t_H in the USCB by considering the ground type according to the Eurocode 8 standard.

2. REVIEW OF PUBLICATIONS CONCERNING GMPE AND DURATION OF VIBRATIONS

Many authors have researched empirical models of seismic wave propagation. Most of the models are based on seismological research and describe the tremors of strong earthquakes.

Seismological observations in Europe, aimed at creating a model of vibrations in a medium to determine the seismic hazard, were conducted by Ambraseys and researchers at Imperial College in London (Ambraseys *et al.* 1996, 2005; Ambraseys and Simpson 1996). These observations enabled them to formulate GMPE for Europe and the Middle East. Other researchers focused on smaller areas of heightened seismic activity, such as Greece (Skarlatoudis *et al.* 2004), Italy (Rinaldis *et al.* 1998, Zonno and Montaldo 2002), Turkey (Kalkan and Gulkan 2004) and Romania (Sokolov *et al.* 2008). Verified GMPE for European and some of the Middle East countries were formulated for both vertical and horizontal peak values of ground vibration acceleration (Ambraseys *et al.* 2005)

In Poland, research was conducted into GMPE of seismic waves in the rock mass. However, this research, unlike the examples of research presented above, was not associated with earthquakes but with mining induced and triggered seismicity (Dubiński and Gerlach 1983, Mutke 1991, Lasocki 2002, Olszewska 2008, Mutke and Stec 2010), mainly in the area of the USCB and LGCD.

Dubiński and Gerlach (1983) determined general relationships that enabled the determination of the degree of intensity of vibrations induced by a rock mass tremor at any distance from the epicentre. The qualitative and quantitative assessment of the influence of rock mass tremors on the natural environment was based on relationships between the intensity of vibrations and their influence on given forms of the environment contained in the MSK scale.

Mutke (1991) formulated regional GMPE for the whole area of the USCB. These relationships can be used to quantitatively determine the peak horizontal velocity and acceleration of ground motion and the dominant frequency of the horizontal components of the vibration acceleration and velocity in Carboniferous and Triassic hard rock. Mutke and Dworak (1992) also demonstrated the importance of local geological structures in the Quaternary overburden, which increases the recorded amplitudes of vibration acceleration and velocity (the phenomenon of vibration amplification).

Signal duration is one of basic parameters describing vibrations in the ground caused by mining seismic events and plays an important role in investigating the effects of the tremors on the surface. Bolt (1973), and Trifunac and Brady (1975), among others, made important contributions to the research into the dependence of signal duration on selected seismic parameters. Although they studied the signal duration of strong earthquakes, their results, especially defining the factors that determine signal duration, can be applied to investigate tremors induced by mining operations.

Esteva and Rosenblueth (1964) describe signal duration as a function of earthquake magnitude and distance from the epicentre. Bolt (1973), based on results of Housner (1965), determined the dependence of signal duration on magnitude, but this relationship is for strong earthquakes and great distances from the epicentre.

Trifunac and Brady (1975) also demonstrated the influence of other factors on signal duration. In their article, apart from magnitude and distance from the epicentre, they considered the influence of local geological structure and investigated a correlation between signal duration and the 12-degree modified Mercalli scale.

3. MATHEMATICAL MODELS

3.1 GMPE for ground motion

GMPE is a relationship between a selected vibration parameter and factors determining its value. It allows for forecasting the seismic effect on the land surface at any distance from the source and assessing the impact of seismic events on surface environment. The vibration intensity scales are used for such assessment. Seismic effects can be represented by various vibration parameters. *PHV* and t_H is such a parameter for MSIIS-15 scales. The factors that influence the magnitude of the parameters are seismic energy, distance from the seismic source, and the local geological and topographical conditions.

GMPE can be determined using measurements of ground vibrations (seismic measurements) in association with known seismic parameters. With respect to the influence of tremors on buildings, strong seismic events play a key role, because they are the only ones that can exert forces that exceed the limit values of the buildings and may be harmful.

3.2 Si-Midorikawa model

Si and Midorikawa (2000) proposed a novel approach to the issue of GMPE. It applies regressions, in which factors associated with the seismic source parameters (volume of energy and source mechanisms) and the path of wave propagation are analysed together with local geological conditions.

For the purpose of this article, this model was modified so that the ground type forming the near-surface zone of the rock medium is an additional factor influencing the amount of vibration recorded on the surface. This model was selected due to the fact that there was a good correlation between the forecast obtained with this model and empirical data. Additionally, the forecast in the epicentral zone gave better results than forecast obtained based on other previously used GMPE.

The proposed in the article model for *PHV* prediction is written as follows:

$$\log(PHV) = b - \log(R) - k \cdot R \ , \tag{1}$$

where *PHV* is the peak horizontal velocity of ground motion, *R* is the source distance,

$$R = \sqrt{d^2 + h^2} \ ,$$

d is the epicentral distance, and *h* is the depth.

Offset parameter *b*, determined for each seismic phenomenon, is the first component. The second one is responsible for non-linear geometric dispersion, and the third one is responsible for non-elastic damping. Coefficient k in the equation assumes the value of 0.002.

Regression analysis is conducted in two stages. In the first step of each recorded phenomenon, the offset parameter b is determined. In the following step, having determined parameter b, we can determine parameters of a regression equation for seismic parameter A.

By transforming Eq. 1, the value of offset parameter b for each recorded phenomenon can be determined. Then, by applying regression analysis, the coefficients a, c, d, and e in the equation were determined:

$$b = a \cdot \log(E) + c \cdot R + \sum d_i S_i + e + \varepsilon \ , \tag{2}$$

where S_i represents the soil classification, assuming a value of 1 for a given site or 0 for others (qualitative variable). This is how we finally obtain the distribution of values for vibration velocity on the surface depending on tremor energy, distance from the seismic source and local geological conditions.

3.3 Influence of the local geological structure on the magnitude of vibrations

Seismological observations show that the magnitude of vibrations on the surface depends on seismic energy, epicentral distance, and geological conditions of the near-surface zone. The amplitudes of vibrations are amplified by a near-surface low-velocity zone. Passage of a seismic wave through the zone also results in changes in the characteristics of the vibrations, including longer durations and a change in their frequency characteristics (Savarienskij 1959). We observe a similar effect in the area of the USCB, which tends to amplify vibrations induced by mining tremors.

The measured amplitude of vibrations can be amplified several times, which has a significant influence on the predicted magnitude of ground vibrations and assessment of the influence of tremors on buildings on the surface (Mutke and Dworak 1992).

There are several methods for determining the level of amplification of vibrations: an analytical method, a method involving direct measurement of the amplification effect, and a method involving studying the spectral relationships of recorded seismic signals known as the HVSR method (Nakamura 1989). In the presented study, the amplification phenomenon was considered directly in a GMPE by applying an additional parameter representing the ground type at the seismometer site in a regression equation.

The classification of the ground was made using the European construction standard “seismic design of buildings”, *i.e.*, Eurocode 8. In the classification, the ground is divided into types depending on average wave propagation velocity in 30-m-thick overburden (V_{S30}). This is a convenient tool for engineering applications because methods of surface seismic measurements enable direct measurement of the parameter. Table 1 shows division of the ground into types according to the standard.

Table 1

Classification of the ground according to European standard Eurocode 8

Ground type	Stratigraphic description	V_{S30} [m/s]
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters thick, characterized by a gradual increase in mechanical properties with depth	360-800
C	Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds meters	180-360
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers) or predominantly soft-to-firm cohesive soil	< 180

3.4 Study of duration of ground motion

To determine signal duration, the influence of the factors tremor energy, epicentral distance and local geological structure on the parameter was analysed. Regression analysis was used again, applying the following form of a regression model:

$$t_H = a \cdot \log(E) + c \cdot R + \sum d_i S_i + \varepsilon \ , \qquad (3)$$

where E is the seismic energy, R is the source distance, S_i is the soil classification parameter, $\Sigma d_i S_i$ is the component responsible for influence of geological conditions on signal duration, and a, c, d are regression coefficients.

According to the guidelines to conduct surface seismometric measurements, the duration of the horizontal component of vibration velocity t_H was determined with an integral of the sum of squares of the horizontal components of vibrations. Signal duration represents the time between the moments when the intensity of the vibrations $I_V(t_k)$ reaches 5 and 95% of the maximum value, as determined with the following equation:

$$I_V(t_k) = \int_0^{t_k} \left(v_x^2(t) + v_y^2(t) \right) dt \ , \qquad (4)$$

where v_x^2 is the squared velocity value of x-component, and v_y^2 is the squared velocity value of y-component.

In the equation, the variable t_k determines the dependence of intensity of vibration in time.

4. CHARACTERISTICS OF THE MEASUREMENT DATA

Determining a model of propagation of seismic waves in a rock requires knowledge of the ground vibrations in the site as well as the parameters of the seismic events inducing the vibrations. Moreover, because the propagation model must consider the local geological structure, it is necessary to determine the ground type.

Numerous seismometric, seismological and seismic measurements collected for 25 years at the Department of Geology and Geophysics of the Central Mining Institute were used in the analyses in this study. The seismic data included records of ground vibrations measured by surface seismic stations located all over the USCB area. In total, there were 51 AMAX-GSI-type seismic stations recording amplitudes of ground vibration velocity and acceleration in three perpendicular planes. The distribution of the sites is presented in Fig. 1.

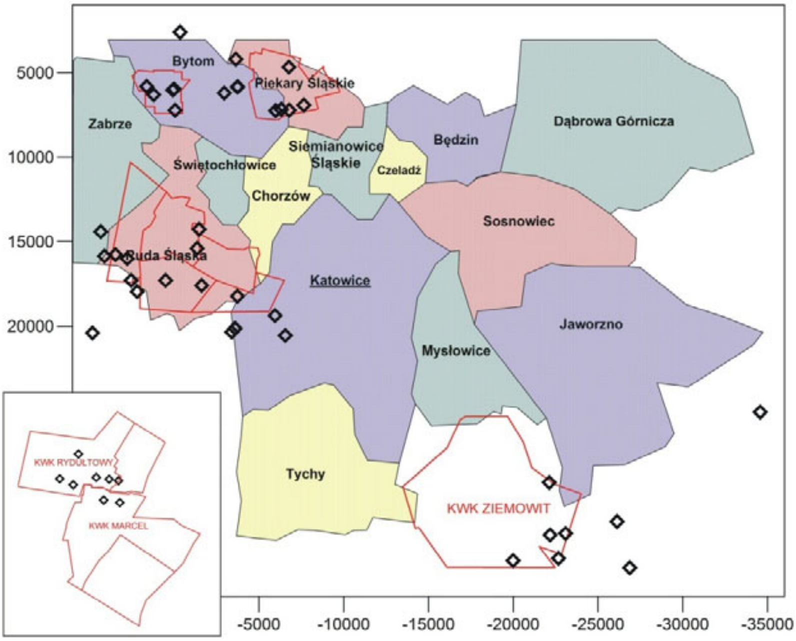

Fig. 1. Location of seismic stations. The main map shows the area of the USCB with boundaries of cities. Additional map shows the area of Rydułtowy and Marcel mines, located about 60 km to the south-west.

This article considers 350 records of tremors with energies between $5 \cdot 10^6$ J ($M_L = 2.1$) and $3 \cdot 10^9$ J ($M_L = 4.1$), because only the so-called high-energy seismic events are important in terms of buildings security. In this group, there were 186 records of tremors with energies of 10^6 J, 137 records of tremors with energies of 10^7 J, 16 records of tremors with energies of 10^8 J, and 11 records of tremors with energies of 10^9 J. The recorded values of ground vibration velocity in given sites were between 0.1 and 44 mm/s, and the recorded values of acceleration were between a few and nearly 1300 mm/s^2.

The analysis of the seismological data involved determining the basic parameters, *i.e.*, energy and location of seismic events, as well as time correlation between the seismological and seismometric data. The ground was classified according to the Eurocode 8 standard based on the results of seismic tests conducted using the multichannel analysis of surface waves (MASW) method (Xia *et al.* 1999). The method can determine the distribution of S wave velocity in depth scale, *i.e.*, the parameter that determines the ground type in the Eurocode 8 standard, based on the analysis of Rayleigh-type surface waves. An example of the application of this method within the area of USCB can be found in the paper of Siata and Chodacki (2005). It presents the results of seismic measurements taken in Ruda Śląska. The research performed and calculations made allowed for detailing the information concerning the near-surface layers. They constituted the basis for the classification of low-velocity near-surface layers according to Eurocode 8.

5. GMPE OF VIBRATION PARAMETERS

This section presents results of the regression analysis made using models 1, 2 and 3. Their aim was to determine PHV and t_H parameters, considering the local geological structure. The analysis was made according to the classical regression method, in which the model is linear (or can be transformed into a linear one).

5.1 GMPE for peak horizontal velocity considering local geological conditions

The construction of a model of wave propagation in rock medium for the USCB area with regression analysis was preceded by calculation of the offset parameter b for each recorded phenomenon using Eq. 1. Then, based on Eq. 2, a function describing the decrease in amplitudes of the ground vibration velocity depending on the tremor energy, epicentral distance and ground type at the measuring site was determined. The influence of the given variables, independent of the value of PHV, was tested.

The first step was to determine the value of the depth parameter h in Eq. 2. As selection of value of the parameter means selecting the regression coefficients with the lowest value of standard estimation error, a regression analysis for parameter h from the range 100-2000 m was conducted. The lowest value of standard estimation error, S_e, was obtained for $h = 525$ m. Therefore, further analysis of the model was conducted using this depth value.

Finally, the GMPE for the PHV values is as follows:

$$\log(PHV) = 0.209 \cdot \log(E) - 0.035 \cdot R - \log(R) + d_i \ , \tag{5}$$

where PHV is the peak ground velocity [mm/s], E is the seismic energy [J], and R is the source distance [km].

Table 2 presents values of coefficient d_i for given ground types.

Table 2

Values of coefficient d_i for ground types A, B, and C

Coefficient	A	B	C
d_i	–0.814	–0.659	–0.598

The data used in the analysis did not contain records from sites located in ground type D (according to Eurocode 8); thus, the determined model considers only types A, B, and C.

The coefficient of determination $R^2 = 0.86$, which indicates that the model explains variation of PHV in 86%. The standard estimation error $S_e = 0.314$, and the standard estimation errors for the given regression coefficients (which are estimates of the regression coefficients for the whole population) are as follows:

$$S_{\log(E)} = 0.0298, \quad S_R = 0.0086, \quad S_\mathrm{A} = 0.2283, \quad S_\mathrm{B} = 0.2146, \quad S_\mathrm{C} = 0.2097.$$

The significance of the relationship between variables was investigated on the basis of Student's t-test. It shows that there is a strong relationship between variables linear, because all the regression coefficients are highly significant:

$$p_{\log(E)} = 0.000000, \quad p_R = 0.000135, \quad p_\mathrm{A} = 0.000418, \quad p_\mathrm{B} = 0.002322, \quad p_\mathrm{C} = 0.004622.$$

The significance of the obtained model was tested by using an analysis of variance (Fisher–Snedocor distribution). The null hypothesis for the lack of significance was rejected at the level of 0.000.

A tool which allows for a quick and effective detection of deviations from the correct analysis of regression is the analysis of residuals and that is

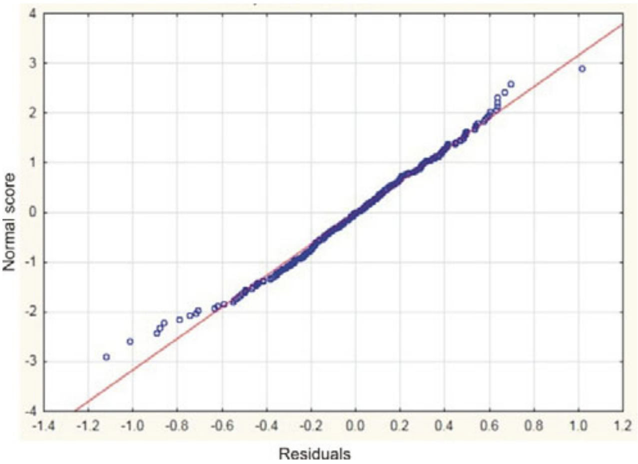

Fig. 2. Normal probability probe for model 5.

why it should constitute one of the most important stages of verification of the regression model. First of all, it allows to verify the assumptions of the classical method of least squares. The first is the assumption stating that the residuals of the model are normally distributed. Normal probability probe for the model 5 has been shown in Fig. 2.

The obtained graph allows to evaluate quickly the conformity of the residuals with the normal distribution. If the residuals are arranged along a straight line, it means that they are normally distributed.

A histogram of residuals provides similar information. At best, the normal curve should go through the centers of upper edges of bars. A slight deviation from the normality, in particular for the samples large in number, does not significantly affect the obtained results. The histogram for the model 5 has been shown in Fig. 3.

Another essential assumption concerns a random component and states that the variance of a random component is the same for all observations. The best method to check this assumption is to create an appropriate scatter plot. If we expect various values of the variance of the random component (σ^2) for different $E(y_i)$, it would be best to create a scatter plot of residuals (which are the estimators of random components) in relation to the expected values (which are the estimators $E(y_i)$). The following scatter plot was obtained for the analyzed model. The scatter plot obtained for the analyzed model has been shown in Fig. 4.

The visible points cloud without a clear trend of increase (decrease) of the residual variation with an increase of the expected values of residuals shows that the assumption of a constant variance of the random component is met.

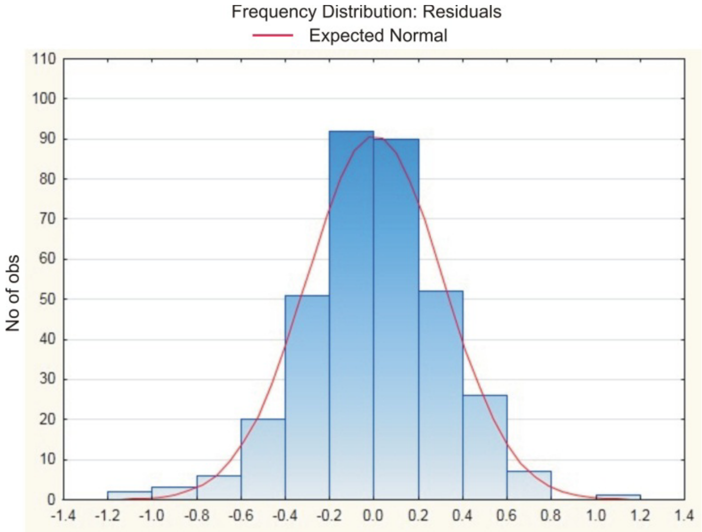

Fig. 3. Histogram of residuals for model 5.

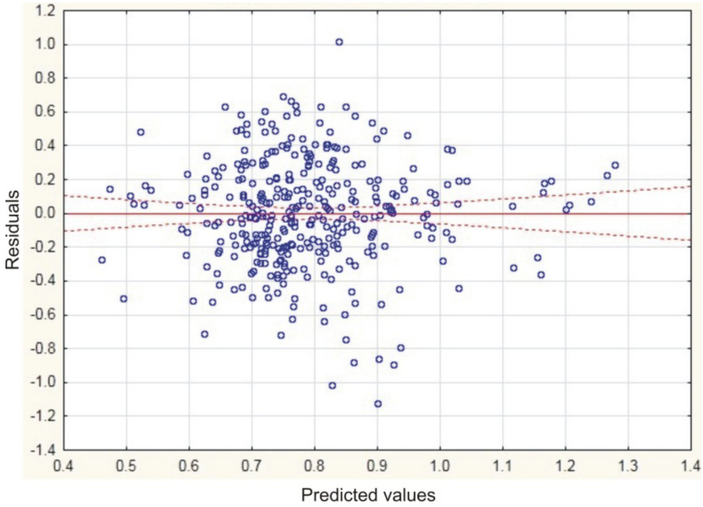

Fig. 4. Plot of residuals against predicted values for model 5.

Once a model of propagation of a seismic wave is ready and verified, it can be used to predict seismic effects on the surface. The predicted values of *PHV* for a tremor with an energy of $1 \cdot 10^8$ J ($M_L = 3.3$) and the 90% upper confidence interval are presented in Fig. 5. In the graphs, the x-axis represents the epicentral distance.

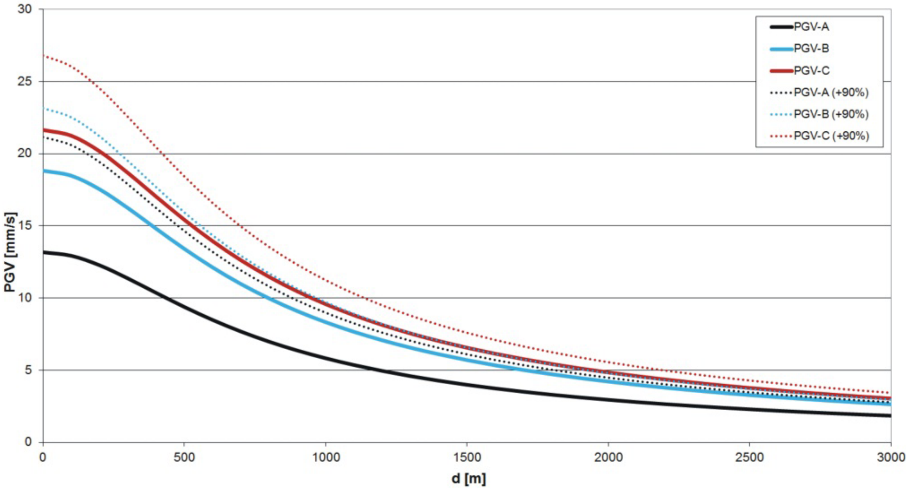

Fig. 5. redicted values of *PHV* with the 90% upper confidence interval for a seismic event with an energy of $1{\cdot}10^8$ J.

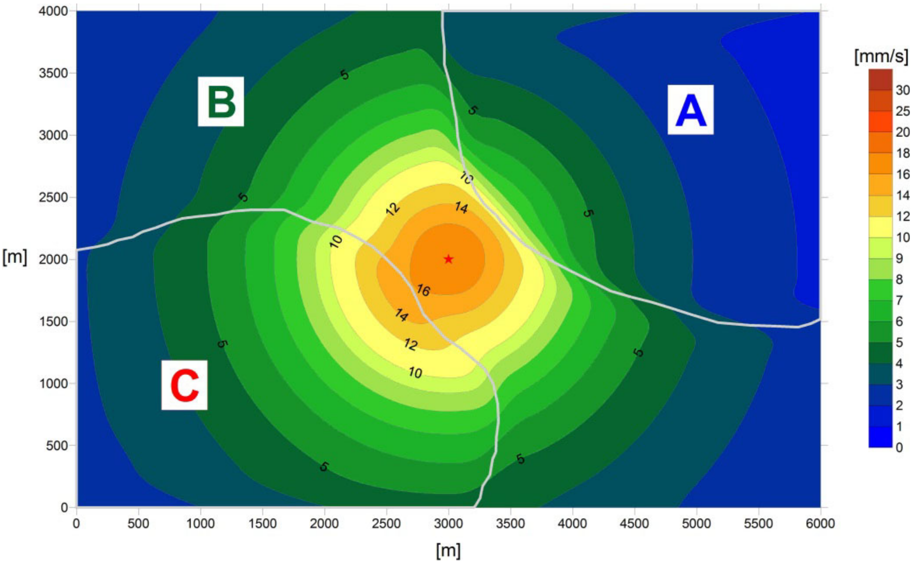

Fig. 6. Distribution map of parameter *PHV* for a seismic event with an energy of $1{\cdot}10^8$ J.

Comparing the *PHV* curves corresponding to different ground types, the influence of a near-surface low-velocity layer on vibrations recorded at the surface is clearly observed. The lower the average wave propagation velocity in the layer, the larger the recorded vibrations. This pattern is confirmed by observations and is a result of the already mentioned phenomenon of increased amplitudes of vibrations as the wave propagates through a low-velocity zone.

The values of the predicted ground vibration velocity of a tremor with an energy of $1 \cdot 10^8$ J in the epicentral zone are within the range of between approximately 13 mm/s for ground type A and approximately 22 mm/s for ground type C. For ground type B, the velocity is approximately 19 mm/s. In the epicentral zone, there is a rapid decrease in the amplitudes of the vibrations (approximately 50% at a distance of 900 m from the epicentre), while for epicentral distances greater than approximately 1500 m, the curves are flatter.

Based on Eq. 5, it is also possible to draw a map of *PHV* around the tremor epicentre. Figure 6 presents such a map. The epicentre of a tremor with an energy of $1 \cdot 10^8$ J is located in the centre of the area. The grey lines mark the boundary areas of ground types A, B, and C.

5.2 Determining the dependence between signal duration and epicentral distance

Signal duration was determined on the basis of Eq. 3. For this relationship, the factor associated with tremor energy (for tremors with energies between $5 \cdot 10^6$ J and $3 \cdot 10^9$ J) turned out to be statistically non-significant (on the basis of Student's *t*-test). During regression analysis, the most extreme values were discarded (residua analysis enabled us to identify and discard them). Overall, the form of the relationship between signal duration, epicentral distance and ground type is as follows:

$$t_H = 3.417 \cdot \log(R) + c_i \ , \tag{6}$$

where R is the source distance [km].

The values of the coefficient c_i for the given ground types are presented in Table 3.

Table 3

Values of coefficient c_i for ground types A, B, and C

Coefficient	A	B	C
c_i	1.9218	2.3503	3.136

The coefficient of determination for Eq. 6 is $R^2 = 0.92$. The standard estimation error is $S_e = 1.12$, and the standard estimation errors for given regression coefficients are as follows:

$$S_{\log(R)} = 0.216, \quad S_A = 0.412, \quad S_B = 0.122, \quad S_C = 0.114.$$

The significance of the obtained model was tested by using analysis of variance (Fisher–Snedocor distribution). The null hypothesis for the lack of significance was rejected at the level of 0.000.

Normal probability probe, histogram of residuals and plot of residuals against predicted values for model 6 are shown in Figs. 7-9.

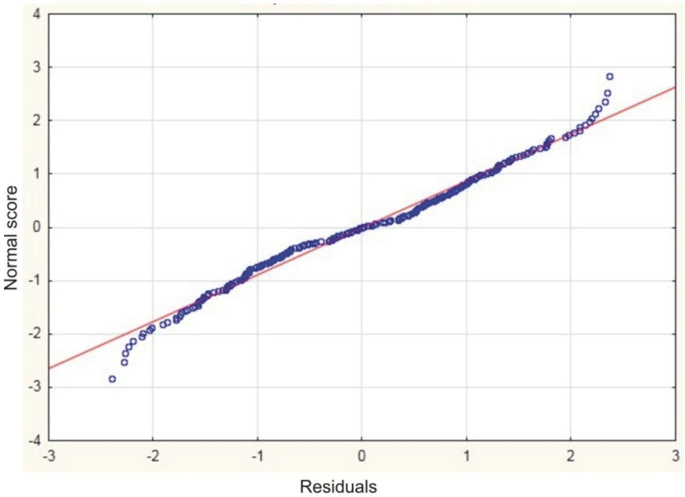

Fig. 7. Normal probability probe for model 6.

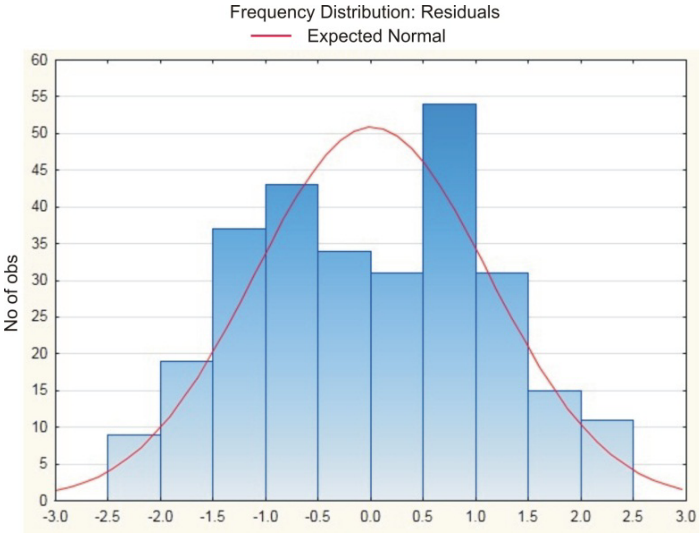

Fig. 8. Histogram of residuals for model 6.

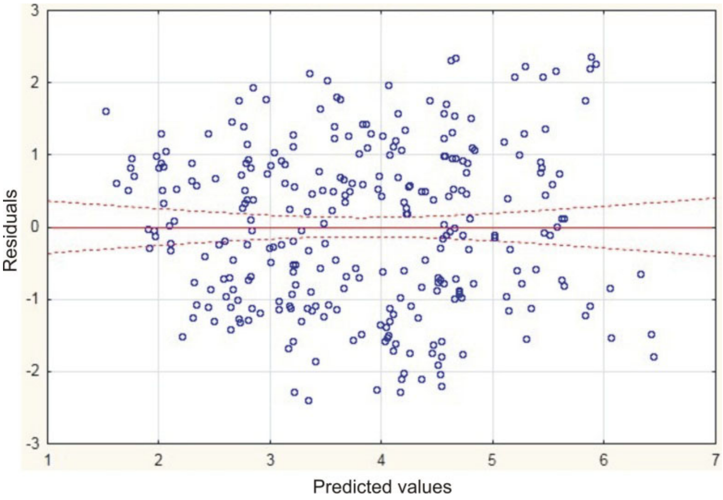

Fig. 9. Plot of residuals against predicted values for model 6.

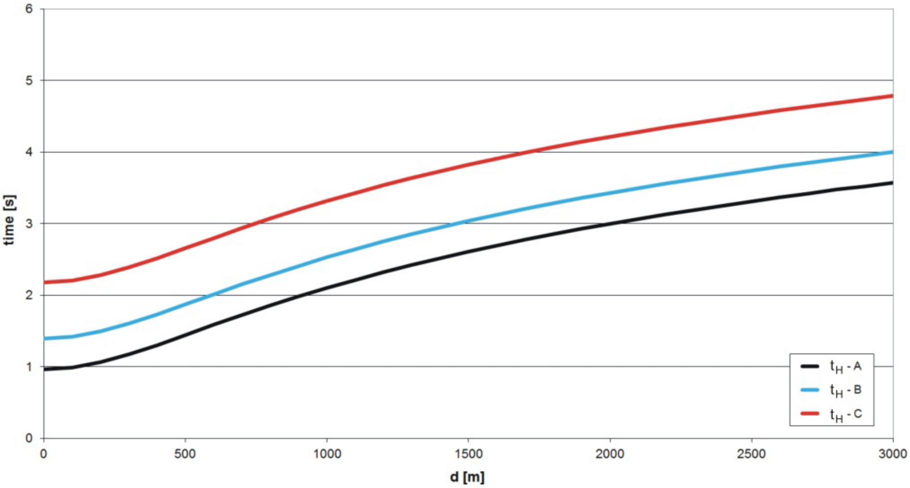

Fig. 10. The relationships between signal duration, the epicentral distance and ground type.

A graph of dependence 6 is presented in Fig. 10. The curves – a solid line, a dashed line, and a dotted line – present the dependence of signal duration on the epicentral distance for ground types A, B, and C, respectively. With an increase in epicentral distance, the time increases. There is also a visible influence of geological conditions on the signal duration: the weaker the formations, the lower the velocity of wave propagation *S* in the 30-metre-thick overburden and the longer the signal duration for a given epicentral distance.

6. DISCUSSION AND SUMMARY

There are various models of GMPE and the choice of the best is not obvious. The commonly used models come from the regression model of Joyner-Boore (Lasocki *et al.* 2000), but there are also non-linear models (Mutke 1991). The selection of factors influencing the vibrations which we analyse also plays an important role. In this article, in addition to commonly applied parameters such as tremor energy and distance from the seismic source, the influence of the local geological structure was also investigated. For the first time, the model proposed by Si and Midorikawa was used to investigate the influence of mining tremors on the surface in the USCB. The results show that the model well represents the physical characteristics of seismic wave propagation in a rock medium. An increase in tremor energy causes an increase in the ground vibration velocity at the surface, whereas an increase in the epicentral distance results in a decrease in vibration velocity. The relationships between values of tremors for different ground types also agree with actual measurements and analytical solutions (Savarienskij 1959). According to these relationships, a seismic wave passing through weaker ground (of lower seismic wave propagation velocity) results in amplified vibrations at the surface. The same phenomenon occurs in the predicted signal duration. Passing through a low-velocity medium results in a change in frequency characteristics and a longer signal duration.

So far, two equations for ground motion prediction have been used in the USCB. The first one is a non-linear model developed by Mutke (1991) which describes the dependence between the amplitude of a horizontal component of acceleration and velocity of bedrock vibrations, and the epicentral distance and seismic energy. This model is used for forecasting vibration resulting from high-energy seismic events and it allows to specify the values of acceleration and velocity of vibrations at the surface of hard rock layers. If weaker soil layers which form a zone of low velocities of seismic wave propagation are above a hard rock, the vibration amplitudes can be strengthened. This phenomenon is called the amplification of vibrations and it is considered analytically in the subject model. The results of the forecast obtained based on model of Mutke coincides generally with the results obtained on the basis of GMPE for the soil class A presented in this paper (Fig. 11).

For the epicentral distances above 1000 m, these results are almost the same. On the other hand, the model designated by Mutke has more “flat” course in the epicentral area. It may result from the adopted depth of the source which was 600 m for Mutke model as well as the energy of seismic events which were used to develop the model (model of Mutke refers to seismic events with energy greater than $1 \cdot 10^5$ J).

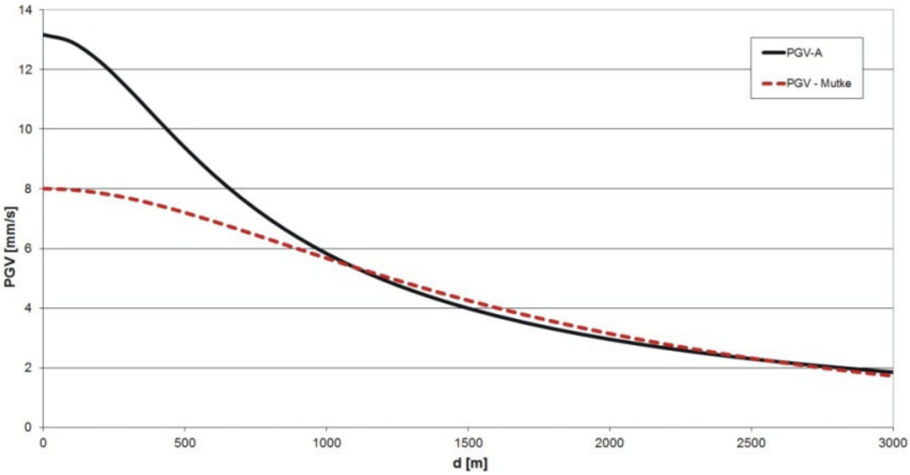

Fig. 11. Comparison of the forecast results for model of Mutke and for model presented in article.

The second model is the linear Joyner-Boore model (Joyner and Boore 1981), mostly used locally by coalmines having a network of seismic stations. In this case, the coefficients in GMPE are designated for particular mining areas and they take into account the local seismic nature for a certain coalmine. These models are developed based on mining seismic events and the possibility of their application in forecasting vibrations resulting from regional events is limited. The peak value of ground motion is determined in this model for the average geological conditions in the place where the seismometer stations are located.

As far as the forecast of the parameter t_H is concerned, it is the first paper concerning USCB presenting how the distance from the seismic source and the structure of the rock influence the duration of vibrations, and thus the parameter which plays a key role in the study of the seismic effects on the surface.

The GMPE proposed in the article is of great practical importance and will be applied to solve problems of seismic engineering in mining areas; the obtained results will be used to assess hazards associated with the seismic influence of actual tremors, thereby helping to minimize the effects of future mining operations in the USCB.

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