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A PROCEDURE FOR FORECASTING THE RESULTS OF INDUCED SEISMICITY ON BUILDINGS FOLLOWING EXCEPTIONALLY STRONG MINE TREMORS

PROGNOZOWANIE SKUTKÓW INDUKOWANEJ SEJSMICZNOŚCI DLA ZABUDOWY POWIERZCHNIOWEJ Z UWZGLĘDNIENIEM EFEKTÓW SZCZEGÓLNIE SILNEGO WSTRZĄSU GÓRNICZEGO

A b s t r a c t

Sometimes, deep mining introduces particular seismic risk to buildings on the surface; therefore, special procedures are needed to assess the safety limits of ground motion. This paper demonstrates such a procedure for use when the standard approach fails to properly asses intensity. Peak velocity is chosen to measure seismic intensity. Forecasted and past seismicity is compared with structural damage assessments to make a decision allowing safe mining in a given location.

Keywords: mine tremors, structural vibrations, ground motion, induced seismicity

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

Zdarza się, że górnictwo podziemne stwarza podwyższone ryzyko sejsmiczne dla obiektów budowlanych, co wymaga specjalnych procedur oceny ograniczeń akceptowalnego ruchu podłoża. Niniejszy artykuł opisuje taką specjalną metodologię, gdy standardowe podejście nie może być zastosowane. Jako miarę sejsmicznej intensywności wybrano prędkość ruchu podłoża. Prognozowana i dotychczasowa sejsmiczność są porównane z uwzględnieniem uszkodzeń budowli w celu umożliwienia bezpiecznej eksploatacji dla zabudowy powierzchniowej.

Słowa kluczowe: wstrząsy górnicze, drgania budowli, ruch podłoża, sejsmiczność indukowana

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1. Introduction

In addition to the static, surface deformations of mining basins [1], deep mining also introduces substantial seismic risk on the ground surface (see, for example, [2]). The resulting rockbursts are well described in the geophysical literature [2] and respective surface ground motions [5] may lead to structural damage similar to the effects of small earthquakes [6].

The majority of the strong rockbursts are of a moderate magnitude m_L with a value less than around 4; however, some exceed $m_L = 4$ leading to alarming vibrations and structural damages. In the case of South African mines, induced quakes may even reach up to $m_L = 5.3$ [7] with disastrous effects on surface infrastructure (see, for example, photographs of destroyed buildings shown in reference [9]). Such strong seismic risks have prompted research aimed at the adaptation of seismic engineering structural codes into the design of buildings and civil infrastructure [8, 9].

When deep mining is carried out in areas within the city perimeters, a more common type of engineering problem needs to be confronted; this involves the evaluation of the seismic resistance of existing buildings and civil infrastructure. This is a two-stage process:

- forecasting the level of expected surface ground vibrations – this is carried out using geophysical models of mining seismicity and eventually deciding whether to give the 'green light' for the mine to operate below the city [2];
- analysing respective building stock and its I'm not sure what you mean by this phrase, it doesn't seem to make sense, maybe change to 'affected buildings and their' seismic resistance to the expected levels of excitation as well as to the expected static ground deformations [6].

When it comes to assess dynamic effects on buildings, the key role is played by seismic data records gathered by surface seismic networks run by the mine or (sometimes) by the municipal authorities. Geophone sensors are installed directly in the ground in special seismic stations or on the foundations of selected buildings. An interesting account of the methodology used to analyse various types of these records is given in a recent paper by Maciąg, Kuźniar & Tatara [10]. The data acquired using surface seismic networks is used to calibrate the seismological models which forecast the surface effects of future mining [2–4].

To provide an insight into the structural destructiveness of generated ground motion for the purposes of surface protection, special 'scales' were developed by the Central Mining Institute in Katowice. One scale was prepared for the LGOM Copper Basin (Legnicko Głogowski Okręg Miedziowy) [11], and another for the Silesian Coal Basin GOW (Górnośląski Okręg Węglowy) [12]. Both scales are similar, particularly with respect to their two key parameters: horizontal peak ground velocity (PGV) and the duration of strong motion.

In some, exceptional cases, these scales can, however, be exceeded and decisions regarding the suitability of future mine exploitation with respect to building safety requires reconsideration.

The purpose of this paper is to present a methodology for assessing the safety of the building stock exposed to induced ground motion, based on existing seismic records and forecasts of mining activities for the years 2015–2017. The need to reassess seismicity forecasts and the seismic resistance of civil infrastructure became apparent after a strong rockburst with a magnitude of m_L = 4.2 occurred on April 18th 2015 in Katowice. The paper proposes a unique methodology to reassess the resistance of the buildings which is based on the analyses of the damage from previous quakes and seismic risk forecasts. Using seismic networks of the mine, future horizontal peak ground velocities can be forecasted and compared with the ones associated with the past tremors. This may help to localise places where there are buildings requiring closer examination with respect to their eventual damage and reserves in seismic load capacity.

2. Description of the mine tremors from May 26th 2014 and April 18th 2015

On April 18th 2015, a rockburst of magnitude m_L = 4.2 occurred in the area of activity of the KHW S.A. KWK Wujek – Ruch – Śląsk mining holding. The rockburst resulted in a catastrophic underground failure as described by popular media as well as on the website of the State Mining Authority in Katowice [13]. The energy released during this rockburst was assessed as 4×10^9 Joule. Respective surface ground motion records were obtained using the mine network of acceleration sensors and six of these were analysed in detail (see e.g. [14])

In Fig. 1, the velocity version of GSI_{GZWKW} – *2012* scale is presented. The asterisk shows the value of peak ground velocity and strong motion duration, as obtained from the surface record of the April 18th 2015 rockburst, acquired at the Panewnicka street recording station.

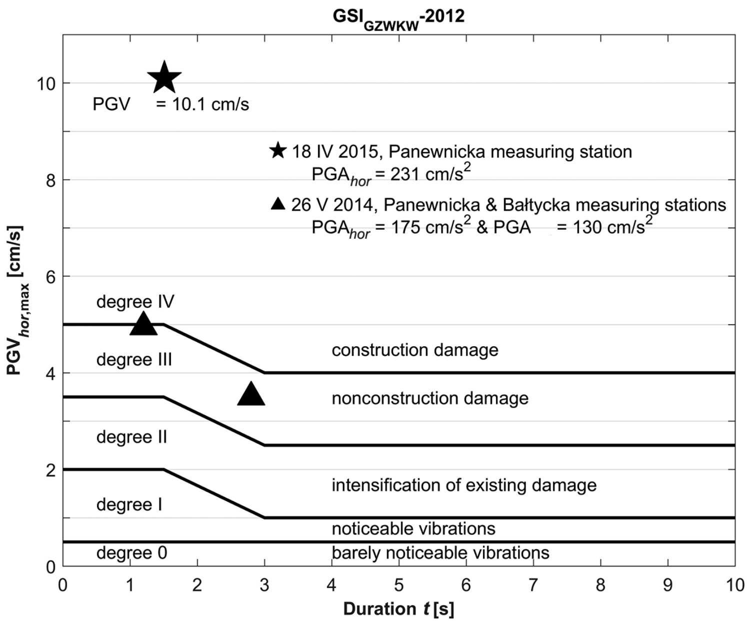

Fig. 1. GSI GZW KW – 2012 scale: Peak Ground Velocity vs. strong motion duration and three records of April 2015 and May 2014 rockbursts

Clearly, the value PGV_{hor} = 10.1 cm/s substantially exceeds the GSI scale. The image of spatial, horizontal ground accelerations is shown in the inset of Fig. 2 while in the upper part of this figure, a plot of horizontal accelerations along the *y* horizontal axis (the more intensive component) is shown together with the respective plot of velocity versus time (lower part). Note that 'hor' (horizontal) version of *PGV* it is its spatial horizontal maximum as obtained for any horizontal vector quantity $U(t) = [U_x(t); U_y(t)]$:

$$Peak_{hor}U(t) = \max\sqrt{\left[U_x(t)^2 + U_y(t)^2\right]}, \quad (1)$$

with U_x and U_y standing for respective two horizontal components of either acceleration, velocity or displacement . The term 'strong motion duration', as applied for the GSI scales, is defined in the next section of this paper.

About one year earlier than the previously mentioned incident, another strong rockburst took place in the same mining area on May 26th 2014. No destructive results were recorded either underground or at surface level in spite of what can still be described as a substantial local magnitude of m_L = 3.7 and an energy release of $E = 8\times10^8$ Joules. Values of PGV_{hor} versus duration are plotted in Fig. 1 as triangles. It can be seen that this time, the maximum values of the GSI scale were not exceeded, although the level of excitation was still very high.

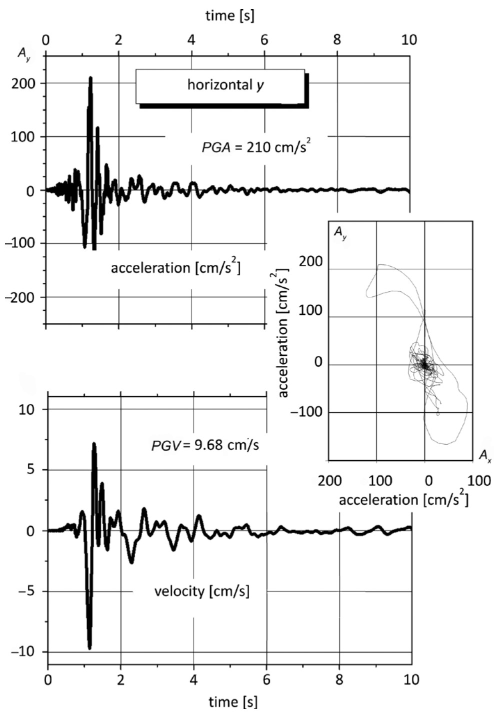

Fig. 2. Accelerations and velocities of the April 18th 2015 rockburst horizontal record as measured along the '*y*' axis of the Panewnicka Street recording station (inset: image of simultaneous spatial, horizontal *x* and *y* accelerations)

3. Surface ground motion of mine tremors and their measures

Surface records of natural earthquakes are characterised by their peak values of acceleration (PGA), velocity (PGV) and displacement (PGD), each value being along one of two horizontal directions, for example, for accelerations PGA_x and PGA_y, and vertical for PGA_z. If one wants the horizontal peak values to be independent of the instrument directions, a spatial maximum should be used according to equation 1. Another important parameter of seismic ground motion is the duration of strong motion. A proposal based on the gradual energy release rate based on the Arias intensity concept [15], defined by Trifunac & Brady [16], is widely accepted and tested [17].

In 2004, the surface ground motions of rockbursts were divided onto two types [5]:

- type I – substantial accelerations, low velocity and short duration resembling quarry blast records;
- type II – moderate accelerations, substantial peak velocity and longer durations, similar to small, shallow earthquakes.

This classification is in good agreement with the seismological classification of rockbursts based on their mechanism [18]. Type II rockbursts are similar to so-called 'regional mine tremors' characteristic of the Silesian coal basin which are usually induced on pre-existing faults by long term mining activities.

Examining the Panewnicka Street record, as shown in Fig. 2, one can note the characteristic pattern of a near surface ground motion which is also characteristic of natural small earthquakes i.e. clear velocity pulse [19], seen in the time record (lower plot) and in the form of well-pronounced directivity, as seen in the spatial plot of accelerations (see the inset of Fig. 2).

Consider the following formulas for time-dependent cumulated Arias intensity defined for vertical and horizontal accelerations [15, 7]:

$$I_A^{hor}(t) = \frac{1}{2}\int_0^t \left[A_x^2(\tau) + A_y^2(\tau) \right] d\tau \tag{2a}$$

$$I_A^{ver}(t) = \frac{1}{2}\int_0^t A_z^2(\tau) d\tau \tag{2b}$$

Plots of normalised Arias intensities, as given by equations (2), are called Husid plots (see, for example, [5]) and are used to calculate strong motion duration [16]. Strong motion duration is defined as a the duration of time between 5% and 95% of cumulative, normalised Arias intensity. In Fig. 3, the Husid plot of the Panewnicka Street station record from Fig. 2 is shown together with the strong motion duration. It can be seen from this plot that the horizontal duration (eq. 2a) equals, in this case, 1.51 seconds. As for the type II tremor, it is of a rather short duration (see e.g. [5]). The Fourier spectrum reveals, however, a clear domination of energy within the bandwidth of 0 to 5Hz (see Fig. 4). From this point of view, this is the classic, low frequency ground motion described in reference [5] as a type II record.

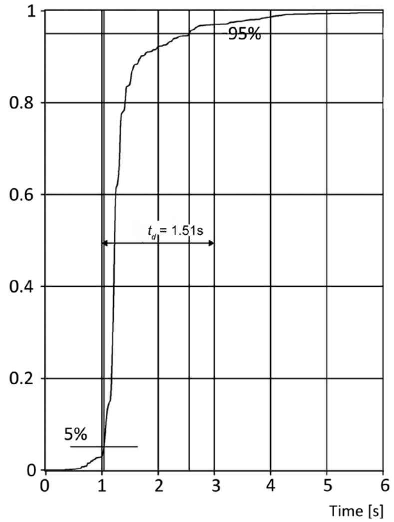

Fig. 3. Normalised Arias intensity versus time (Husid plot) for the Panewnicka Street station horizontal records of April 18th 2015 rockburst (Fig. 2)

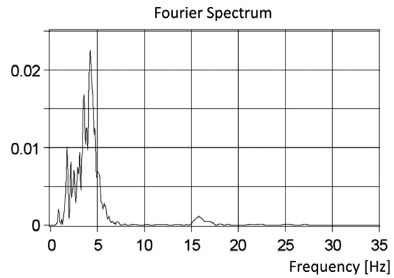

Fig. 4. Fourier spectrum of the acceleration component the Panewnicka Street station horizontal '*y*' record of April 18th 2015 rockburst

4. Re-assessment of seismic risk

The building stock of the Katowice Region belonging to KHW S.A. KWK Wujek – Ruch – Śląsk mining area consists of typical low-rise residential buildings, four ten-story panel buildings, two churches and an industrial plant [14].

Detailed analyses of the damage occurring to buildings on the ground after the rockburst of April 18th 2015 were routinely carried out by the surface protection services of the Mine. They revealed that all of the detected damage only fitted the category of 'cosmetic' or non-structural damage. Similar, or even lesser, post-tremor damage was noted after the rockburst of May 26th 2014. Moreover, the GSI scale classifies the rockburst of May 26th 2014 as belonging to degree III (see Fig. 1).

During these two events, the buildings were subjected to horizontal ground velocities reaching 10 cm/s in some places. Thus, a key observation is noted that **the two events may**

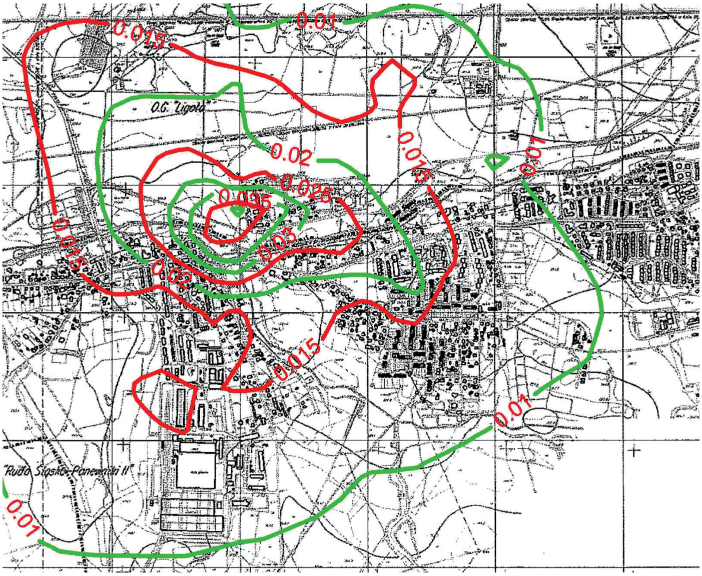

Fig. 5. Map of the Wujek – Ruch – Śląsk mining area marked with areas of expected maxima of horizontal velocities [m/s] forecasted for the years 2015–2017

serve as real-life seismic tests of the resistance of the existing building stock to mine tremor effects.

The Wujek – Ruch – Śląsk mine prepared exploitation plans for the years 2015–2017 in a new coal bed (no. 409). In the light of the recent two strong rockbursts, a question was formulated regarding the safety of the surface infrastructure and building stock during the planned exploitation. For these reasons, new forecasts of mining seismicity for the years 2015–2017, was undertaken by the Central Mining Institute. The results of these forecasts were given as maps of maximum peak horizontal velocities expected until the end of 2017. In Fig. 5, a section of such a map is presented. This map was compared with another map presenting horizontal ground velocities of the two rockbursts obtained by the Central Mining Institute when analysing ground motion records of the two rockbursts of 2014 and 2015. Overlapping these three maps gave an answer to the question if expected seismic intensity does not exceed the past seismicity so far safely sustained by the buildings. Since horizontal peak ground velocity is "most appropriate" single measure of destructiveness of the seismic excitation effects on buildings so far (see, for example, [5, 6, 8, 9, 11, 12, 17]), a procedure can be established which allows the exploitation of the underground mine if the area was already subjected to excitations from rockbursts leading only to minor, 'cosmetic' damage when peak horizontal velocity levels do not exceed the earlier measured PGV_{hor}.

5. Concluding remarks

This paper presents an analysis of an exceptionally strong mine tremor of April 18th, 2015, its strongest record and respective surface effects. A decision making procedure is described how to decide whether to allow safe deep mining exploitation with respect to the safety of surface infrastructure and building stock in terms of its dynamic response. The procedure consists of following three stages:

a) analyse existing rockbursts and provide maps of generated horizontal peak ground velocities and their effects on buildings;
b) prepare a map of forecasted mining seismicity in terms of the peak ground horizontal velocity using well-established methodology of mining seismology described in detail in, for example, references [3, 4];
c) localise eventual places where the expected future peak ground velocities exceed what the building stock already carried on;
d) decide if the resistance of the building stock to past seismicity makes it possible to allow deep mining exploitation.

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