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ACQUIRING ROTATIONAL GROUND MOTION FROM TRIGGERED SEISMIC EVENTS

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Abstract

This paper presents preliminary results of a program of collecting ground rotations from the surface stations of deep mining area of "*Ziemowit*" mine located in the Upper Silesian Coal Basin in Poland. A set of 51 rotations records acquired during the first 7 weeks of the recording program was analyzed. Three strongest records are discussed in detail in this paper. The program, in its longer perspective, aims at getting rotations of as intensive mine tremors as possible. So far the maximum measured rotational velocity reached 0.03°/s, while respective maximum rotational acceleration was equal to 2.53 $^{\circ}/s^2$ which was measured during mine tremor with local Modified Mercalli intensity of about IV. These rotations represent rockbursts of rather low magnitude, well below m_L=3, but stronger mine tremors are expected to be collected in near future. The time history records of ground rotations have similar durations like the translational records but their Fourier spectra are shifted in a characteristic way, predicted by theoretical analyses [5], [17].

Keywords: seismic ground rotations; mine tremors; ground motion; Fourier spectra

1. Introduction

So far only the translational surface ground motions excited by seismic activities along three Cartesian axes have been observed and applied in seismology and engineering. All the key geophysical information currently known about earthquakes and the structure of the Earth derives from respective translation records of accelerations or velocities. In seismic engineering it is the collection of strong translation accelerations, which started from the famous, benchmark, 1940 El Centro record and is applied to analyze structural response and shape design codes.

In addition however to the three translational components (horizontal $u(t)$, $v(t)$ along x, y axes and the vertical $w(t)$ along z axis) three rotations $\psi_X(t)$, $\psi_y(t)$, $\varphi(t)$ about each of these axes can be defined (Fig. 1).

It was probably Mallet in 1862, [1], who, for the first time, mentioned ground rotations as the effects of earthquakes. Later in 1927 Gutenberg [2], and Richter in 1958 [3], claimed with their strong authority, that such rotations would be too small to be of significant meaning. In spite of these early, intuitive counter arguments theoretical efforts to substantiate the origin of seismic ground rotations have been investigated e.g. as special, rotational waves radiating in close, epicentral areas of earthquakes (Teisseyre et al., [4]) or appearing as the effect of body wave reflections (Trifunac, 1982, [5]). However, direct or indirect observations of ground rotations, with very few exceptions (e.g. [6]), appeared to be very difficult, mainly because of the lack of suitable instruments. The situation has changed from the beginning of the 21st century when respective instruments were developed and tested for small, tele-seismic observations (e.g. Igel et al. [7]) as well as for the experiments at close distances (e.g. Nigbor [8]). Recently rotational ground motion became subject of an emerging branch of modern seismology, see e,g. the special issue of BSSA, [9], or J. of Seismology, [10], and the activity of respective working group dealing with rotational seismology: http://www.rotational-seismology.org/.

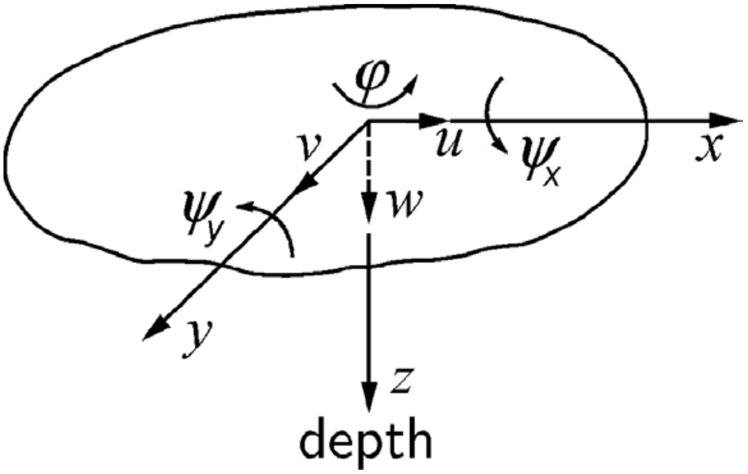

Fig. 1 – Six components of seismic surface ground motion

The collection of tele-seismic records of ground rotations is growing fast and leads to interesting and fruitful geophysical studies. From engineering point of view rotations $\psi(t)$ about horizontal axes could be particularly important as these rotations may lead to substantial excitations of slender, high structures like tall buildings, TV-towers, industrial chimneys etc. Including rotational effects may dramatically change their seismic design loads. The added torsional effects from direct ground torsion $\varphi(t)$ can be important for structures extended in horizontal plane. First proposals of the respective codified approaches already appeared (see e.g. [11]), still however the credibility of these models may be questioned because there are no rotational strong motion data behind respective load models. Waiting for records of strong ground rotations would require locating enough number of such instruments in the potential epicentral areas of strong earthquakes, which will take long time. A partial remedy for this is to try to measure strong rockbursts, which resemble original earthquakes. Some of the rockbursts met in the areas of deep mining can reach magnitude of 4 (see e.g. [12, 13]) or can even exceed 5 (e.g. [14]) making this phenomenon a source of good quality, strong seismic signals yet, in some places, expected with return periods of 2-5 years.

In what follows early results of a program of collecting ground rotations from the surface measuring stations located in the mining area of “Ziemowit” mine, located in the Upper Silesian Coal Basin (USCB) in Poland, will be reported. At this moment (after 2 months) the measurements are collected only from minor quakes of magnitude below 3 – however, as the time passes by, stronger rotation records are expected to be acquired.

2. Description of field monitoring site at Coal Mine "Ziemowit"

The Coal Mine “Ziemowit” (CMZ) is situated in the Upper Silesia Coal Basin and it is characterized by high induced seismic activity. The largest recent seismic events have reached at this mine local magnitude exceeding m_L 3.2. The two R-1 electrochemical, tri-axial, rotational velocity seismometer and two tri-axial, translational accelerometers EA-120 were mounted in close surroundings of the coal mine. The rotational R-1 sensor and EA-120 translation sensors were deployed on the ground surface in special vault, similar in shape and depth to the vault used by Liu et al. [15]. The second pair of these sensors was installed on the foundation of a nearby small building.

The R-1 instrument response is flat from 0.1 to 20 Hz and its noise is lower than 10^{-6} rad/s (see e.g. paper by Nigbor et al. 2009 [16]), so it meets well parameters of induced seismic events recorded in the USCB. Portable seismic recorders DR-4000 were linked to each pair of sensors. The measuring equipment, which was mounted in the building, started registering the data at the end of October, 2015. The second set started recording on December 11th, 2015. In this paper, only the data recorded in the vault will be presented and discussed, (Fig. 2).

Fig. 2 – Instruments deployed in the vault

3. Results of monitoring

The 51 analyzed local seismic events occurred from 11th of December, 2015 to February 2nd, 2016. The seismic activity was induced by mining of two longwall panels, no. 101 and no. 102 at depths from 670 m to 700 m. The periodically high seismicity at field monitoring site resulted from zones of stress concentration near edges, remnants of old shallower exploitation and presence of local fault zones. The magnitude of recorded events changed from 1.7 to 2.7 (Fig. 3). The epicentral distances of the collected records varied from about 520m to 1320m.

During seven weeks of registration reported here, the Peak Rotational Velocity (PRV) of ground motion reached maximum level of about 0.5 mrad/s (0.029 degree per second) while maximum Peak Ground Acceleration (PGA) equaled 0.8 m/s^2 (with the corresponding maximum translation velocity of about 2cm/s). The rotational velocities at our (CMZ) field site are comparable to those acquired by Liu et al., [15], at the HGSD Station in Taiwan, while respective recorded PGA usually were a little higher at the CMZ monitoring site. The quakes recorded at CMZ site were weaker, yet they were recorded with a much closer epicentral distance. High ratios of PGA/PGV are characteristic for low intensity surface records of tremors from deep mining (see e.g. [12]).

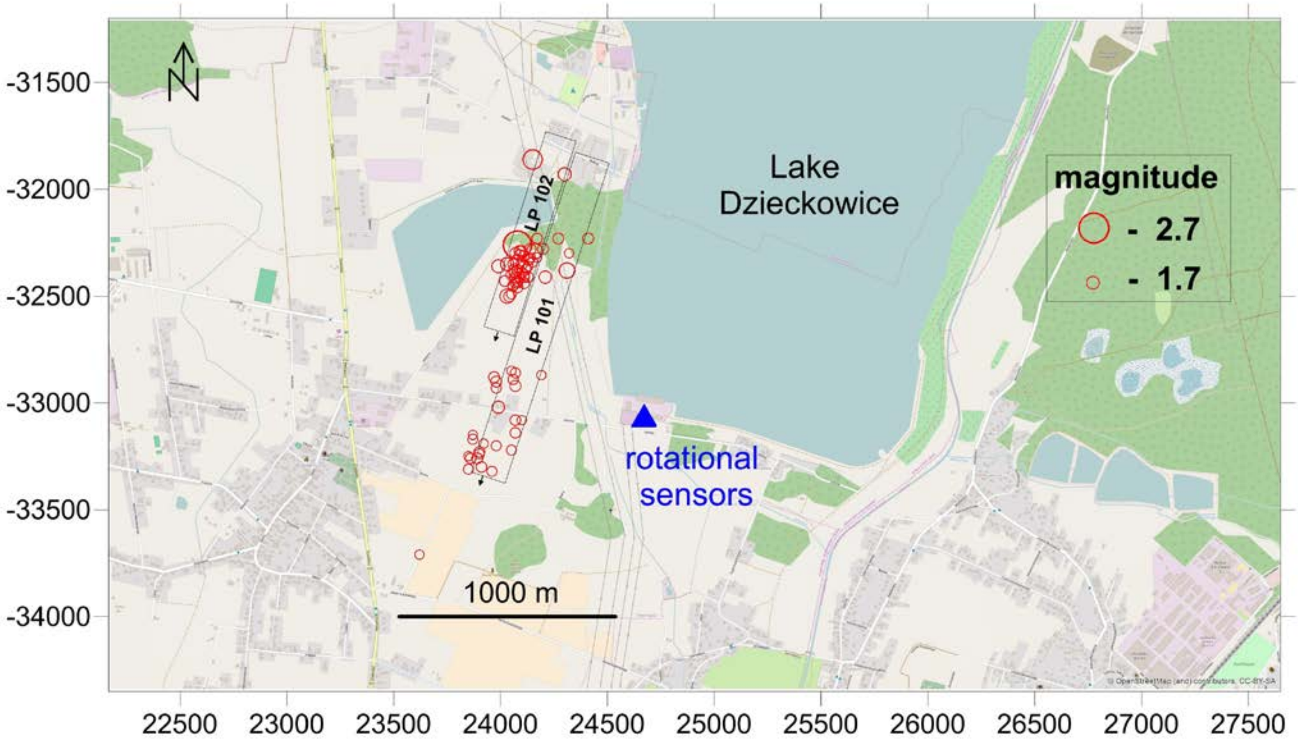

Fig. 3 - Locations of epicentra of mining seismic events and the R-1 rotational sensors at the site of Coal Mine Ziemowit. The seismic events were monitored from December 11th, 2015 to February 2nd, 2016. The size of the circles is proportional to the magnitude of the event.

In Fig. 4 the rotational velocities about vertical axis are plotted vs. PGA for all the acquired records. It can be seen that the smaller the intensities, the more clearly linear relationship between PRV and PGA becomes.

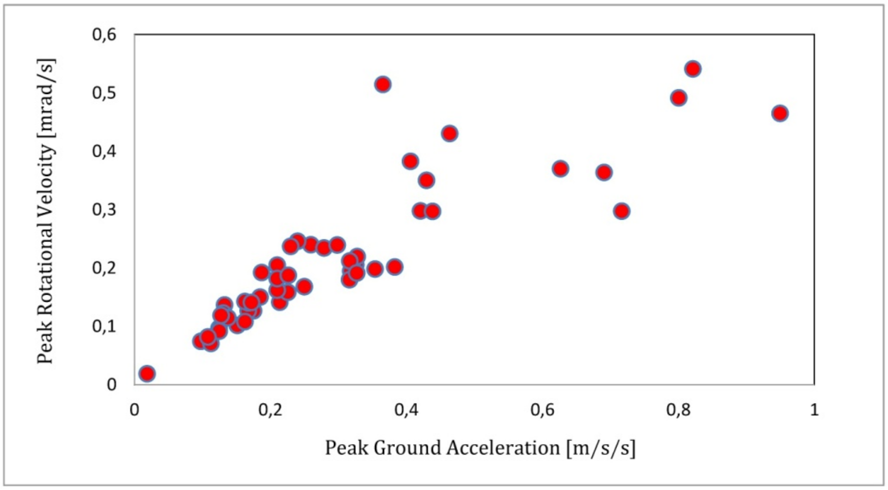

Fig. 4 - PRV (rotation about vertical 'Z' axis) versus PGA (horizontal) for the seismic data set from 11.12.2015 to 02.02.2016

4. Time histories and spectral data

From all 51 records 3, the most intensive ones, were selected for more detailed analyses. In Tab 1 their basic data are shown. The PGV_{hor} shown in the second column of this table it is horizontal, spatial maximum of ground velocity $\sqrt{(PGV_{E\text{-}W}^2 + PGV_{N\text{-}S}^2)}$ and is shown here as an approximate measure of ground motion intensity. The horizontal peak velocity proved to be particularly appropriate intensity measure for the mine tremors [12]. It is also important to note that while peak velocity is much better measure of mine tremor intensity than peak acceleration, such defined spatial maximum makes the intensity approximation also not dependent on the exact orientation of horizontal, measurement axes.

Table 1 – Detailed data of the translation and rotation records of three, selected events

No.	Description		PGA $[m/s^2]$	f_C [Hz]	PRV= PGV_{rot} [rad/s]	PGA_{rot} $[rad/s^2]$	f_C [Hz]
1	Event: „*IMI_20151212_043336*” PGV_{hor}= 0.0203 m/s	E-W	0.800	7.05	0.000513	0.040733	13.51
		N-S	0.490	6.82	0.000527	0.032348	12.97
		Z	0.210	9.42	0.000491	0.027061	12.60
2	Event: „*IMI_20160123_011352*” PGV_{hor}=0.0083 m/s	E-W	0.365	12.05	0.000425	0.033030	16.20
		N-S	0.244	12.79	0.000298	0.025041	16.61
		Z	0.214	13.01	0.000514	0.044210	16.90
3	Event: „*IMI_20151214_071053*” PGV_{hor}=0.01380 m/s	E-W	0.438	8.55	0.000276	0.022619	12.89
		N-S	0.462	9.16	0.000500	0.037887	14.21
		Z	0.163	9.43	0.000430	0.026207	13.79

In Figs. 5-7 the complete set of records of the event *IMI_20151212_043336* from December 12th 2015 is plotted in detail. Each figure shows translation velocity and acceleration along specific direction as well as respective rotational velocity (rotation rate) and rotational acceleration about the specific direction (‘*E-W*’ - Fig. 5, ‘*N-S*’ - Fig. 6 and ‘*Z*’ - Fig. 7). It should be noted that while the translation velocities were obtained from original acceleration signals by numerical integrations, respective rotational accelerations were obtained by numerical differentiations of the original rotation velocity signals (rotation rate). The three events described in Tab. 1 represent typical mine tremors. The ground excitations level with PGV of about 1 to 2cm/s results in ground vibrations at the site with Modified Mercalli intensity III to IV (see e.g. Trifunac, Brady [18], [12]). It can be seen from Figs. 5-7, that the Fourier spectra of translational accelerations are slightly moved to higher frequencies compare to natural earthquakes i.e. they could be classified as type I rockbursts (see e.g. Johnstone [19] or Zembaty [12]). Particularly rather small contribution of the lowest part of the spectrum (frequency range 0-5Hz) is characteristic for the type I rockbursts [12]. The frequency shifts of the ground motion Fourier spectrum can roughly be measured by a single number i. e. position of the center of the area f_C of the Fourier spectrum $S(f)$:

$$f_C = \frac{\int_0^\infty f S(f) df}{\int_0^\infty S(f) df} \qquad (1)$$

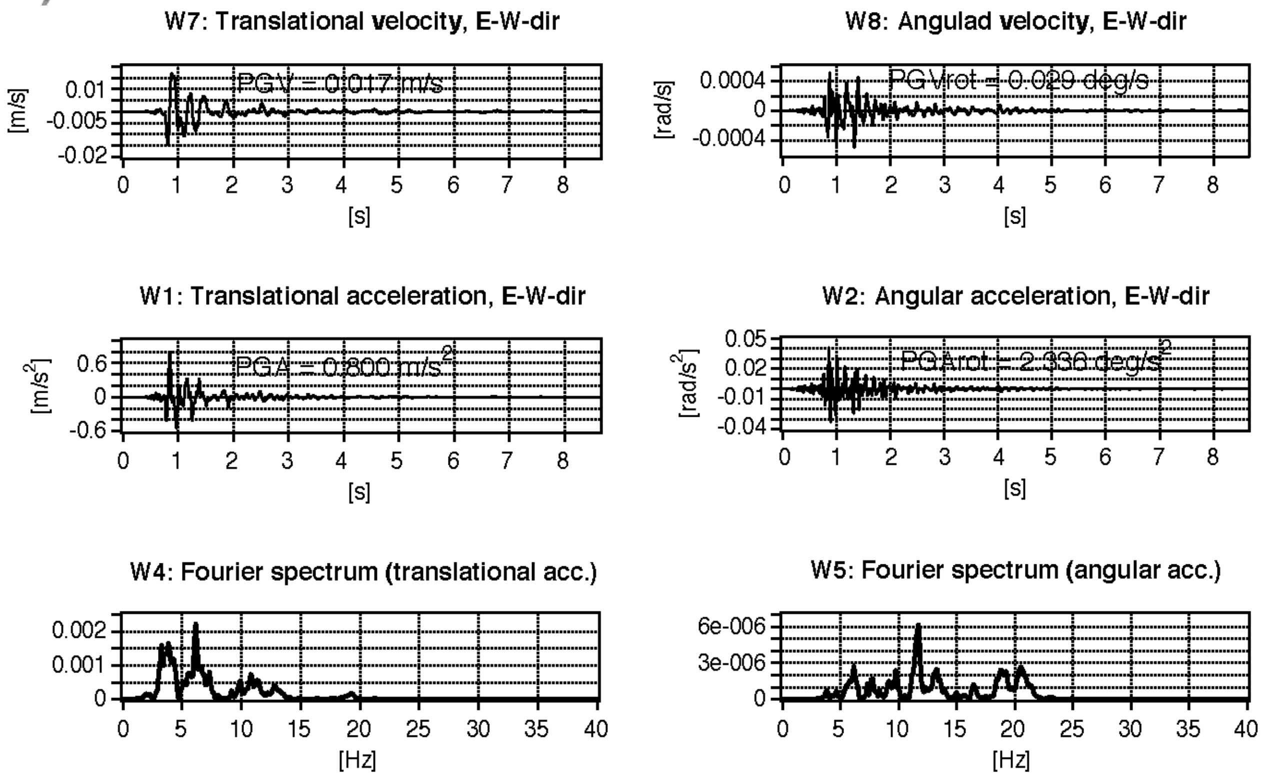

Fig. 5 – Translation and rotation records of the event ‘IMI_20151212_043336’ from December 12th, 2015, axis E-W

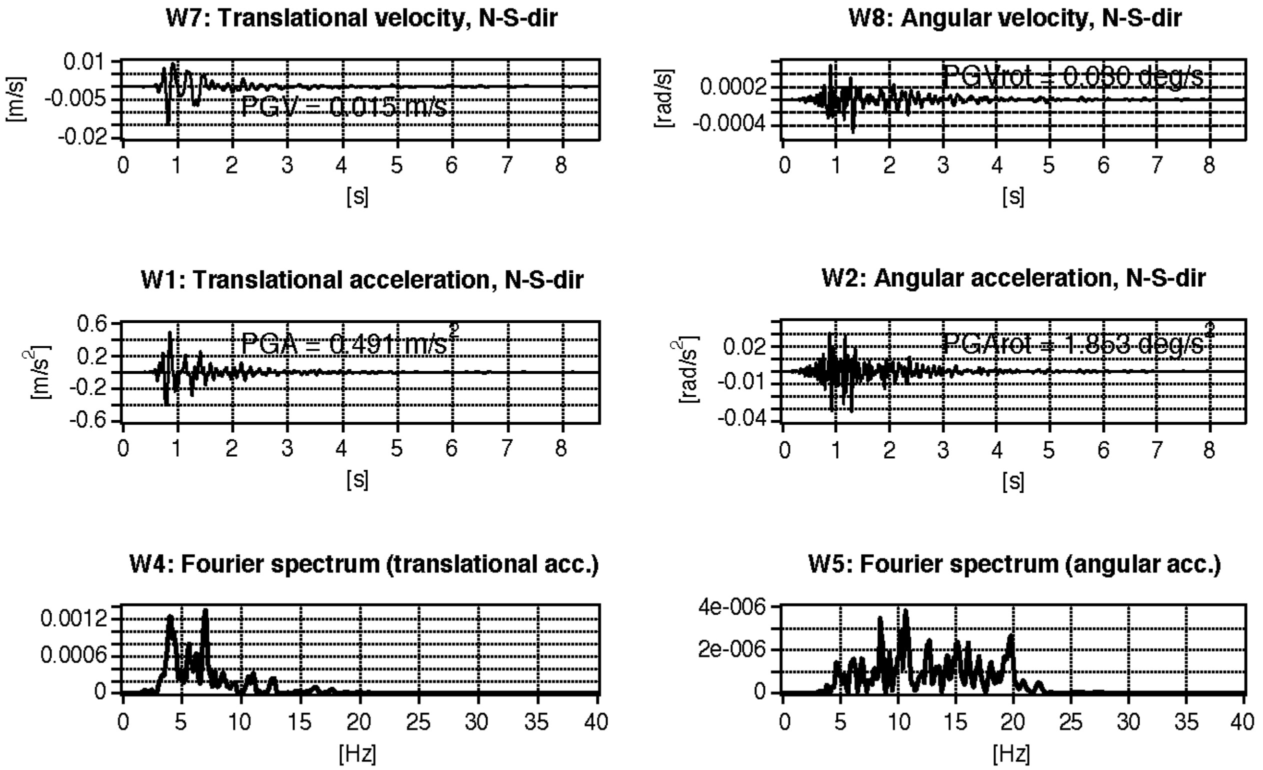

Fig. 6 – Translation and rotation records of the event ‘IMI_20151212_043336’ from December 12th, 2015, axis N-S

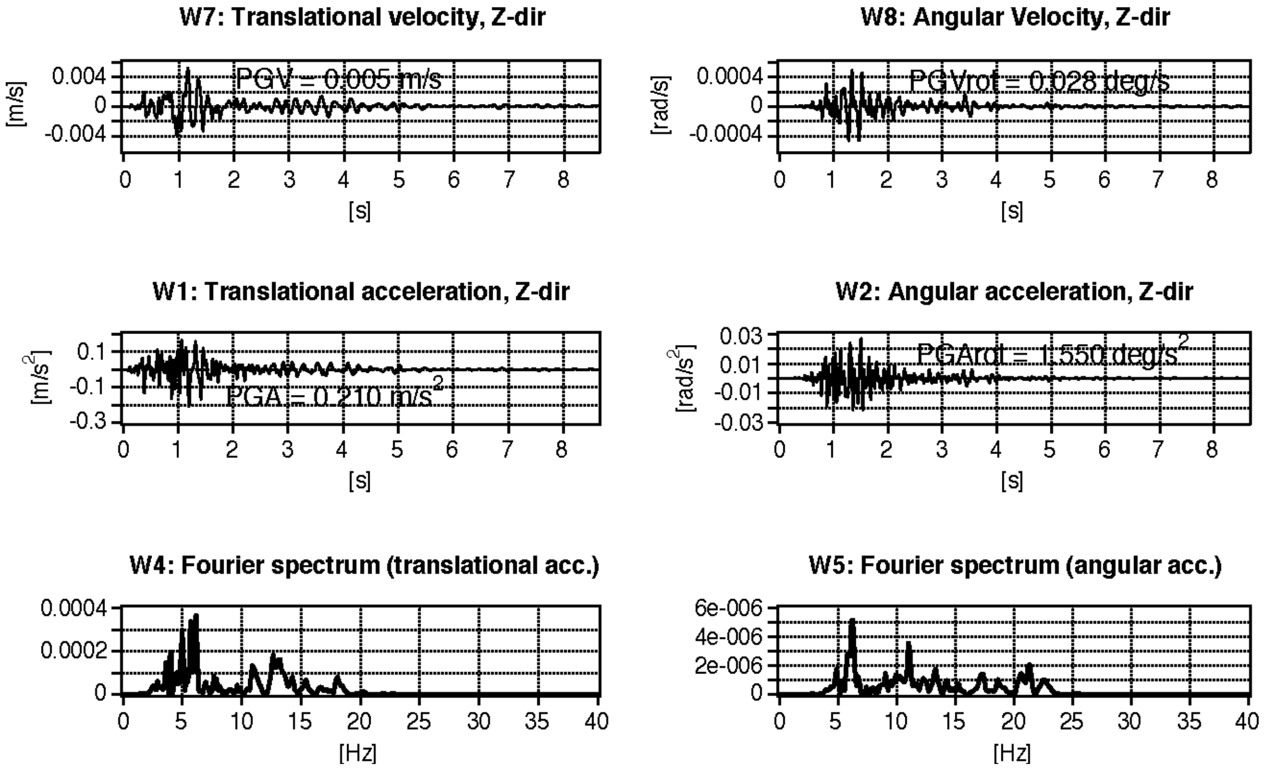

Fig. 7 – Translation and rotation records of the event 'IMI_20151212_043336' from December 12th, 2015, axis Z

In Tab. 1 the values of f_C are given for the Fourier spectra of 6 acceleration records of each of the three strongest, recorded signals. Rotational ground motions as combinations of derivative or respective translational components (see e.g. [5], [17]) should be shifted in to higher frequencies. Indeed a clear frequency shift of the rotational spectra can be observed in Tab.1 and Figs 5-7. Such the frequency shifts of the rotational ground motion components are described in detail by most of the theories of the origin of rotational ground motion (see e.g. papers from the special issue of BSSA [3] or J. of Seismology [10]).

5. Summary and conclusions

Selected early results of a program of collecting ground rotations from the surface measuring stations located in the deep mining area of "*Ziemowit*" mine located in the Upper Silesian Coal Basin is reported. A set of 51 rotations was recorded during the first 7 weeks of the program. These rotations represent still rather low intensity of ground motion, but stronger mine tremors are expected to be collected soon.

Three, most intensive records were analyzed in detail. Maximum, recorded rotation rate reached $0.03^o/s$ with respective maximum peak rotational acceleration was equal to $2.53^o/s^2$. This rotation corresponds to approximate ground motion *MM* intensity IV (PGV_{hor}=2cm/s). The rotation records resemble similar duration as the translation ones while their Fourier spectra are shifted to higher frequencies as predicted by most of the theoretical models.

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