Vibration response of the waste rock dump in open pit mine caused by blasting operation

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Analysis of slope stability is often solved when designing and realizing waste dumps. Vibration effect needs to be taken into account, especially when the waste dump is situated in close distance to the seismic loading source. In the open pit mine near Jarnoltowek (Poland), phyllite is excavated, and rock waste is deposited on the dump directly in the mine; that is at a distance of approximately 150 m from the quarry face. Blasting operations are used as mining technology here so the rock waste dump could be influenced by these vibrations significantly. The paper presents results of experimental seismological measurement performed on four levels of the rock waste dump in the discussed mine. One seismic station was also located in front of the dump on the rocky ground so that analysis of dump response in amplitude and frequency domains can be performed for example by the spectral ratio method. The spectral ratio is calculated based on the records obtained on rocky ground and the dump. Seismic noise data recorded at different levels of the dump were also analysed to obtain the resonant frequency of the dump.

Key words*: dump, vibration, blasting, seismic noise, spectral ratio, HVNR (horizontal to vertical noise ratio)*

Introduction

Waste rock dumps are geostructures consisting of waste rock originating in the mine that will not be processed any further. In general, stability analysis of this type of geostructure needs to be ensured during all phases of mine development, i.e. the phases of planning and designing, operation, decommissioning and post-closure. The safety of these structures is mainly related to long-term environmental impacts and social-economic issues. Estimating the dynamic response is one of the issues addressed in the frame of stability analysis of geostructures (including also earth dams, tailings dams, solid waste landfills, etc.). According to Gazetas (1987), several types of seismic damage have been observed in geostructures, e.g., slope instability, liquefaction flow failures, longitudinal and transverse cracks, piping failures due to cracks, etc. In several papers, different approaches estimating the dynamic response of geostructures are presented using theoretical methods, numerical modelling and in situ investigation and measurement (e.g. Haiwang and Wen, 2012; Psarropoulos et al., 2007; Lagaros 2009; Choudhury and Savoikar, 2009, Hrubešová and Luňáčková, 2006). As stated in the literature, it is necessary for the estimation of dynamic response to consider also parameters like geomorphic and topographic structure of the site, possible soil-structure interaction, parameters of input ground motion, the effects of local site conditions, etc. Knowledge of the fundamental frequency of the geostructure is important for seismic response analysis. Dakoulas and Gazetas (1985) present equations to compute the fundamental period for the given cross-section of the dam that includes a variation of shear modulus with depth. The next approach is to determine the fundamental frequency of the geostructure based on the in situ measurement of its dynamic response during seismic loading.

In this paper, evaluation of the dynamic response of the waste rock dump caused by the blasting operation is presented. Detailed analysis of vibrations recorded at different levels of the dump´s embankment is performed, and the fundamental frequency of the dump is determined. Subsequently, the approach to determine the fundamental frequency of the dump using seismic noise measurement on the dump´s embankment is also presented. Fundamental frequency was determined based on the HVNR (horizontal to vertical noise ratio) method (Nakamura, 1989), and it was compared to the fundamental frequency determined based on the records of blasting operations.

Locality

Seismological measurements presented below were performed in the year 2012 in a quarry, which is situated near the village Jarnoltówek in the Opole region, Poland. At that time, the quarry covered an area of 89,673 m² and it was mined on three levels. Phyllite is excavated in the quarry and rock is disintegrated using blasting operations. This rock is milled and sorted according to the requirements of further industrial processing, where this phyllite material is used as a filler and/or insulating compound. Waste rock is transported by trucks from the technological cleaning plant, and it is deposited on top of the internal dump without compaction.

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Only the mined out part of the quarry was at the disposal of waste rock deposit. The dump had four levels at the time of performed seismological measurement (Fig. 1, 2), the height of the dump was about 23 m, and individual level height varied from 4 to 8 m.

Fig. 1. Photo of the quarry near Jarnoltowek in the year 2012; on the left – part of the quarry face, on the right – embankment of the internal dump.

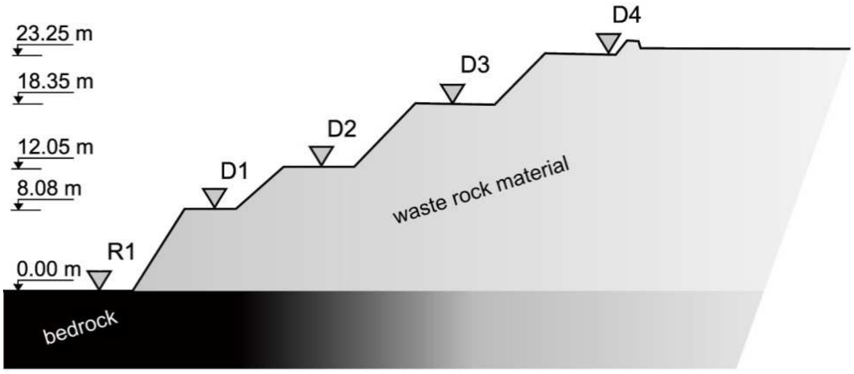

Fig. 2. Sketch of the dump cross-section in the year 2012 (according to Slovák, 2013).

The analysis of the geotechnical parameters of waste rock samples was performed in the laboratory of the Technical University of Ostrava (Suchyňa, 2012). Two types of rock samples were analysed: crushed rock and fine-grained rock (rock grains smaller than 0.06 mm). It was documented that the content of fine-grained fraction for each sample is in the range of 10-15 % and the content of the sand fraction is in the range of 85-90 %. The density of this material is 3.28 $g.cm^{-3}$, Poisson number 0.3, porosity 0.47 and bulk density 1.84 $g.cm^{-3}$.

Experimental measurement

To evaluate the effect of blast-induced vibrations on the waste rock dump, experimental seismological measurements were performed in the year 2012. Seismic recorders GAIA Vistec with three-component sensors ViGeo2 were used. The frequency range of seismic channel was 2 Hz – 200 Hz; this range was sufficient for the measurement of blast-induced vibrations and the resonant vibration of the dump. The measurement was performed on four levels of the embankment of the dump (seismic stations marked as D1 – D4) and one seismic station (marked as R1) was located in front of the dump on rocky ground of the quarry. Distribution of seismic stations is plotted on the map in the fig. 3. To obtain good contact of D1 – D4 sensors with the ground, they were placed in shallow holes.

The GAIA Vistec recorders enable the wide possibility of setting of records. In the described measurement, sampling frequency of the digital signal was set to 500 Hz. Horizontal components of the ViGeo2 sensors were directed to radial (R) and transversal (T) directions; the third component was vertical (V).

Blasting operations are used as mining technology in the discussed quarry. Two blasts were initiated during the measurement. One blast was located at the lowest mining level (below marked as BLAST1) and the second blast was located on the higher level on the opposite site of the quarry face (marked as BLAST2). The distance between the location of blasts and the R1 seismic station was approximately 150 m. Technological parameters of performed blasts were not at disposal.

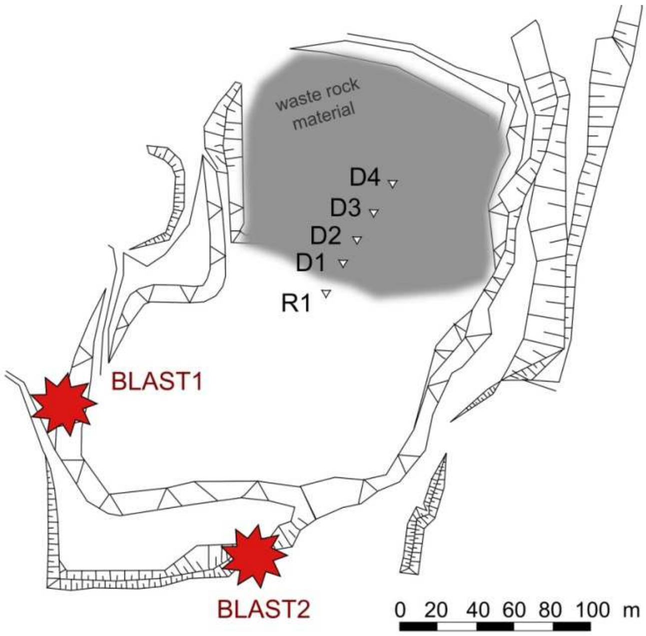

Fig. 3. Map of the quarry with the position of the internal dump, positions of blasts and the distribution of seismic stations during the measurement.

Methods

Three-component records of vibration velocity were analysed in the amplitude and the frequency domains. To evaluate the vibration effect on the dump´s embankment during the performed blasts, maximum values of component vibration velocity were determined for both mentioned blasts and they were plotted depending on the elevation of measuring point above the rocky ground. The maximum vibration effect measured on the dump´s embankment responds directly to the seismic waves caused by blasting; it means that the maximum vibration effect is in the higher frequencies than the expected fundamental frequency of the dump. To also evaluate the fundamental frequency of the dump during the resonant vibration, frequency analysis of recorded vibrations was performed separately for two selected parts of the measured signals. First part marked as "A" corresponds to the blast-induced waves with the maximum values of vibration velocity and higher frequency range and the second part marked as "B" corresponds to the resonant vibration of the dump when the blast-induced waves of higher frequency are attenuated. Part A and part B were determined based on time-frequency spectral structure of recorded vibrations (Lyubushin 2007). The continuous wavelet Morlet transform was used because it allows thinner resolution of time structure than e.g. estimating power spectra in short moving time window (e.g. Lyubushin et al., 2015). Morlet wavelet diagrams are presented in Fig. 4 for the reference station R1 and the station D4 on top of the dump. At the reference site R1, short vibration effect was detected only during the blast lasting 1 – 2 seconds. While on the top of the dump, gradual attenuation of higher frequencies and stabilizing at the fundamental frequency lasting for several seconds were detected. Harmonic vibration at the frequency of 16 Hz detected during BLAST2 was caused by the technology used in the mine for rock disintegration. This harmonic frequency differs from the fundamental frequency of the dump, so the record obtained during BLAST2 can also be used for the frequency analysis of vibration response on the dump.

Selected parts A cover the direct effect of blasting operation with the duration of 1.5 s and 1.8 s for BLAST1 and BLAST2, respectively. Parts B cover the record, where the higher frequencies are attenuated, and the response of the dump is still significant compared to the level of seismic noise. The duration of the part B is 5 seconds for both blasts (Fig. 4). Amplitude spectra were calculated for individual components using Sigview software for elaborated parts A and B, and the results are presented in the next chapter.

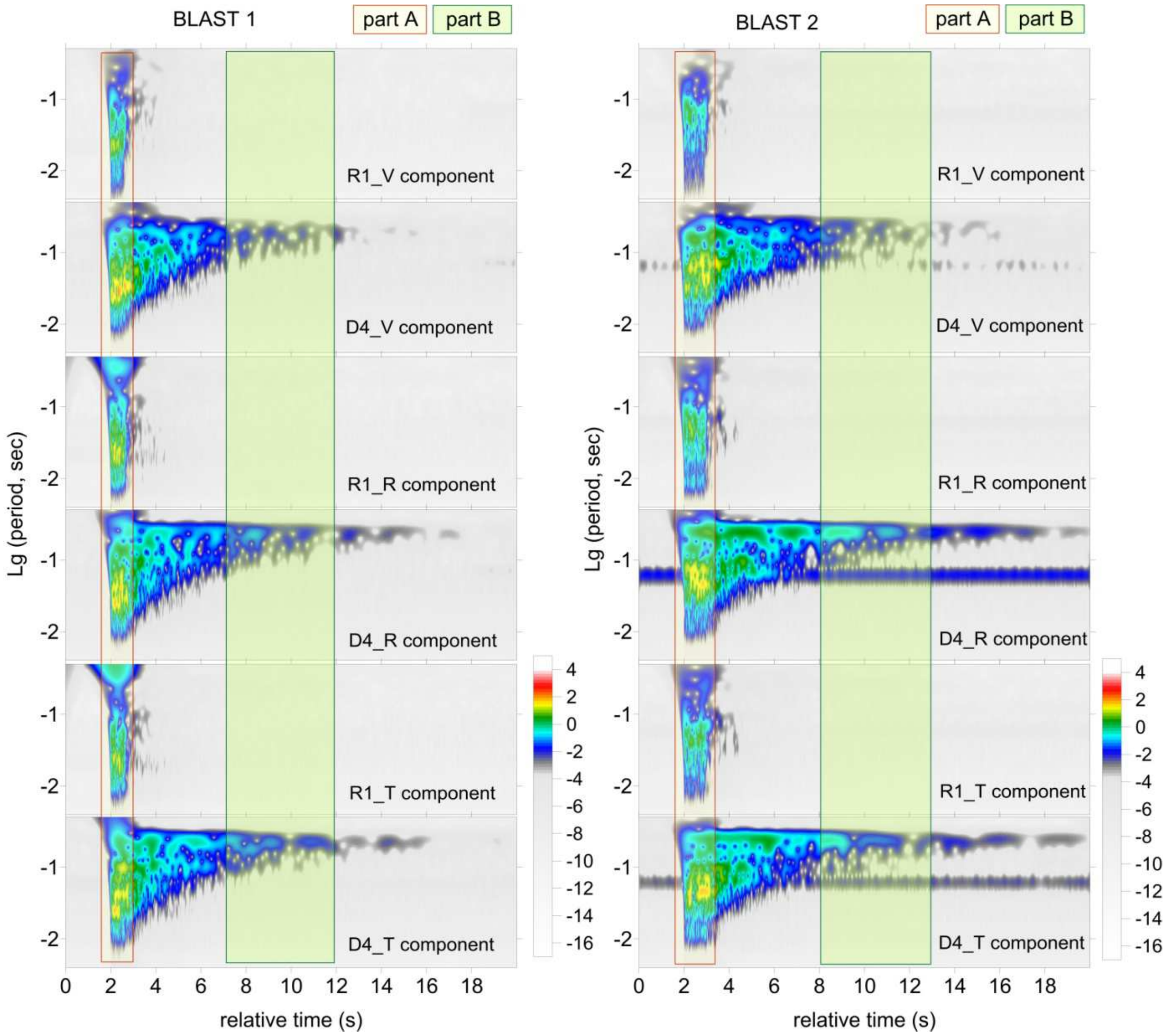

Fig. 4. Morlet wavelet diagrams for the reference station R1 and station D4 on top of the dump. Part A and B are also displayed (for details, see the text).

Records of seismic noise were used for the computation of spectral ratio curves using the HVNR method (Nakamura, 1989). This method uses the noise as a seismic input, and it computes the horizontal-to-vertical spectral ratio (below H/V ratio) between the horizontal and vertical components of the motion. Fundamental frequency and amplification of the motion may be derived from the resulting spectral ratio curve. This method is widely used in seismic engineering studies for site effect evaluation, microzonation studies and seismic hazard assessment (e.g. Ansal (ed.), 2004; Bard (ed.), 2008; Ansal et al., 2010; Panzera et al., 2013). But it is also used in other branches, e.g. study of response to buildings and the determination of fundamental frequencies together with determination of possible soil structure interaction (e.g. Gallipoli et al., 2010; Lednická, 2014), amplification of ground motion in the vicinity of different seismic loading sources (e.g. Driad-Lebeau et al., 2009; Motazedian et al., 2012; Lednická et al., 2015) determination of thickness of sediments (e.g. Gosar and Lenart, 2010; Nehmé et al., 2013), geotechnical site investigation, including e.g. assessment of quality of compacted ground (Harutoonian et al., 2012), etc. Resonant frequency of sedimentary layers depends mainly on shear-wave velocities and the thickness of sedimentary layers; the amplitude of fundamental resonant peak depends on the impedance contrast between surface soil layers and underlying bedrock (e.g. Pitilakis, 2004). The impedance contrast between “soft” and “hard” layer causes that the seismic energy, propagating through the soft layer downwards to the bedrock, is reflected back to the soft layer. Due to this effect, the soft layer behaves as a resonator for a certain frequency, which leads to the amplification of ground motion in this soft layer (Nehmé et al., 2013).

The discussed dump is a geostructure constructed of soil layers placed on a rocky ground so that resonant effect may be expected here. Records of seismic noise measured before the realization of blasting operations were used for the computation of the spectral ratio using the HVNR method. The data were analysed using Geopsy software (Wathelet et al., 2011). A minimum of 50 windows of the length of 15 s was elaborated in each record. Before computing the spectral ratios, Fourier spectra amplitudes of three components were smoothed with the Konno-Ohmachi smoothing function at a smoothing constant equal to 40. The resulting spectral ratio curves at all measured points are presented in Fig. 6.

Results and discussion

The results are presented for both blasts. The maximum values of component vibration velocity are plotted depending on the elevation of measuring point above the rocky ground (Fig. 5). At all measuring points, vibration effect was higher during BLAST1 compared to BLAST2. The maximum value of vibration velocity was equal to 8 $mm.s^{-1}$ on the R component at the station D2. Similarly, the maximum measured value during BLAST2 was recorded on the R component at the station D2. Three-component records of vibration velocity during both blasts are presented in Fig. 6 for the station R1 (input ground motion on the bedrock) and for the station D2 (maximum vibration effect on the embankment of the dump).

Part A of measured signals was used for the determination of the amplitude spectra during maximum vibration effect. Amplitude spectra of all components at all measuring points are plotted in Fig. 7. The spectral content of these parts of records for the dump and the rocky ground is similar. Spectral analysis proved a difference in the prevailing frequency range of measured blasts, i.e. 40-50 Hz during BLAST1 and 15-25 Hz during BLAST2. This difference may be caused by different parameters of performed blasting operations (e.g., Pandula and Kondela, 2010). Moreover, the blasts performed were realized in different parts of the quarry face and on different levels, so the seismic waves propagated through different paths between the blast and the stations.

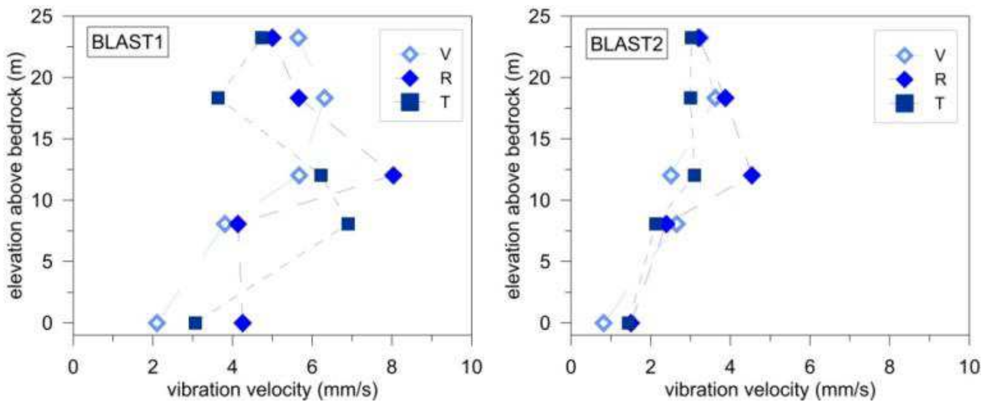

Fig. 5. Graphs of maximum values of component vibration velocities for individual measuring point (elevation above bedrock).

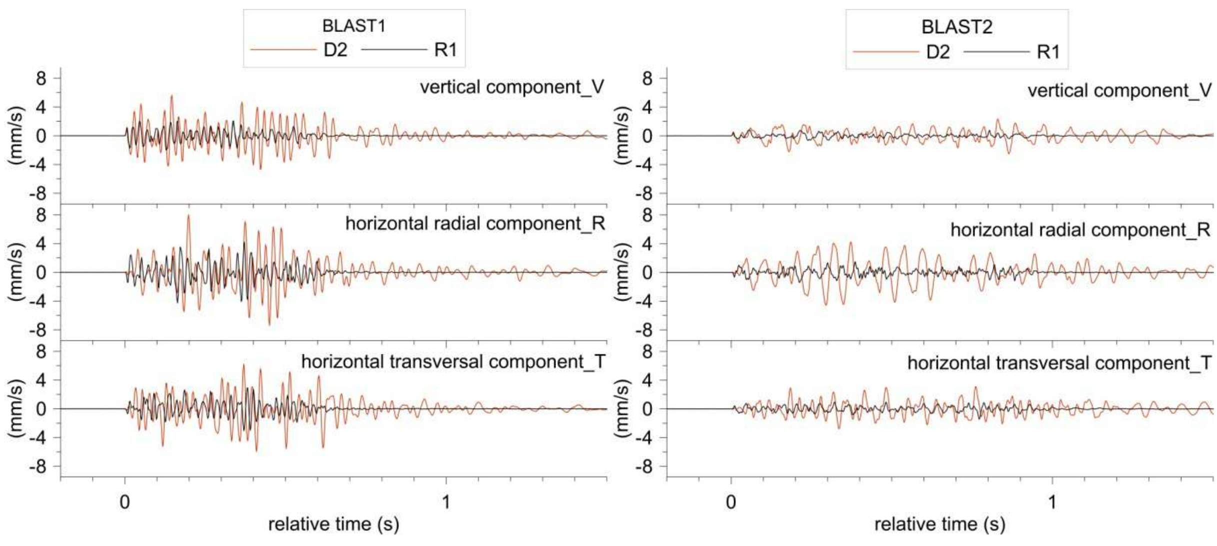

Fig. 6. Comparison of vibration effect recorded on the R1 station (black colour) and D2 station (red colour).

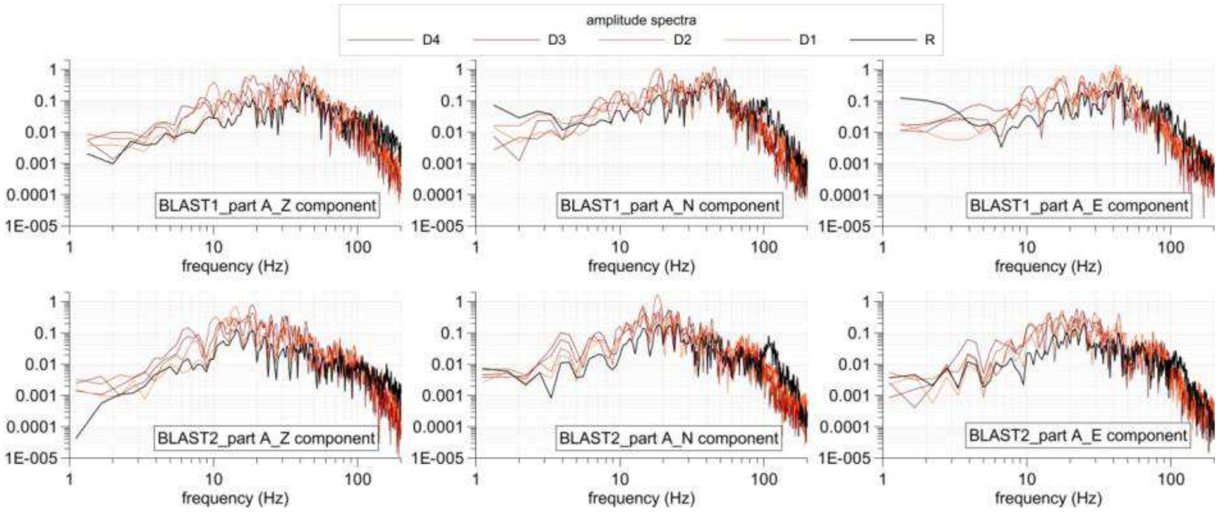

Fig. 7. Amplitude spectra during the maximum vibration effect; part A of measured signals.

Amplitude spectra calculated for part B, comprising resonant vibration of the dump, are presented in Fig. 8. At all presented spectra of individual stations, there is a significant difference between the spectral content of vibration effect on the rocky ground (R1) and on the dump´s embankment (D1-D4). It is caused by the resonant vibration of the dump lasting several seconds while the vibrations recorded on the rocky ground are quickly attenuated.

Results show that the prevailing frequency range at stations D1-D4 is decreasing with an increasing elevation above the rocky ground and that the maximum spectral amplitudes increase with increasing elevation above the rocky ground. For station D1, the prevailing frequency is in the range 7 - 10 Hz for horizontal components while for station D4 the prevailing frequency is in the range 3.5 - 5 Hz.

During BLAST2, the clear peak at the frequency approximately 4.0 Hz also appears at the stations at the lower elevation and also at station R1 on rocky ground in front of the dump. This is probably caused by the resonant vibration of the dump reflected back to the rocky ground.

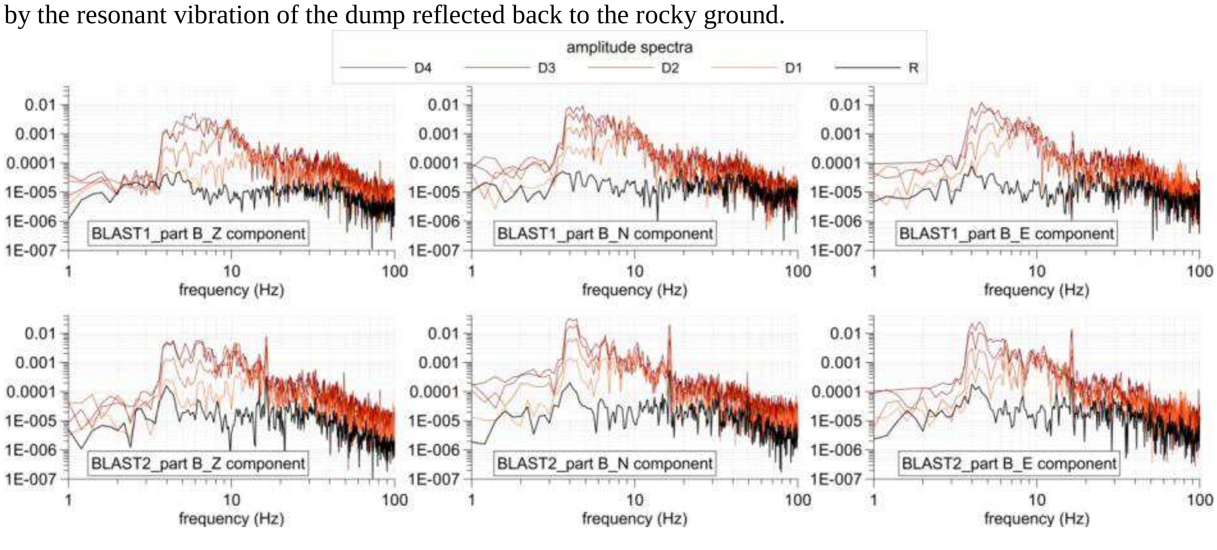

Fig. 8. Amplitude spectra during the resonant vibration of the dump; part B of measured signals.

According to the Morlet wavelet diagrams presented in Fig. 4, the resonant vibration of the dump at the frequency of 4 Hz is more significant during BLAST2, even though the input ground motion at station R1 has lower amplitude of vibration velocity than during BLAST1 (see record of both blasts at station R1 in Fig. 6). It is probably a consequence of the prevailing frequency content of input ground motion that has a significant influence on the dynamic response of the dump because the prevailing frequency of BLAST2 is much lower than during BLAST1.

Results of H/V ratio computation are presented in Fig. 9. At the station R, the spectral ratio curve has a flat shape with H/V ratio equal to 1 that is typical for the rocky ground with no amplification effect. At all points located on the embankment of the dump, the spectral ratio curve exhibits a dominant peak with the amplification up to 3.0. The fundamental frequency determined from the curve starts at the value of 8 Hz for the elevation 8.08 m, continuing with the value of 6 Hz for the elevation 12.5 m, at the elevation 18.35 m the spectral ratio curve exhibits two close peaks in the frequency range 4-5 Hz and on the top of the dump´s embankment, a clear peak is detected at the frequency of 4 Hz. It is necessary to add that the dump consists of several layers of waste rock material with different compaction and different age, so there could be more than one impedance contrast between these layers, and it can result in two or more peaks in the spectral ratio curves. The thicker is the waste rock layer, the lower is the fundamental frequency, which responds to the theory about the resonant vibration of soft layers above hard rocky ground. Determined resonant frequencies correspond to the results based on spectral analysis of resonant vibration of the dump caused by blasting operations.

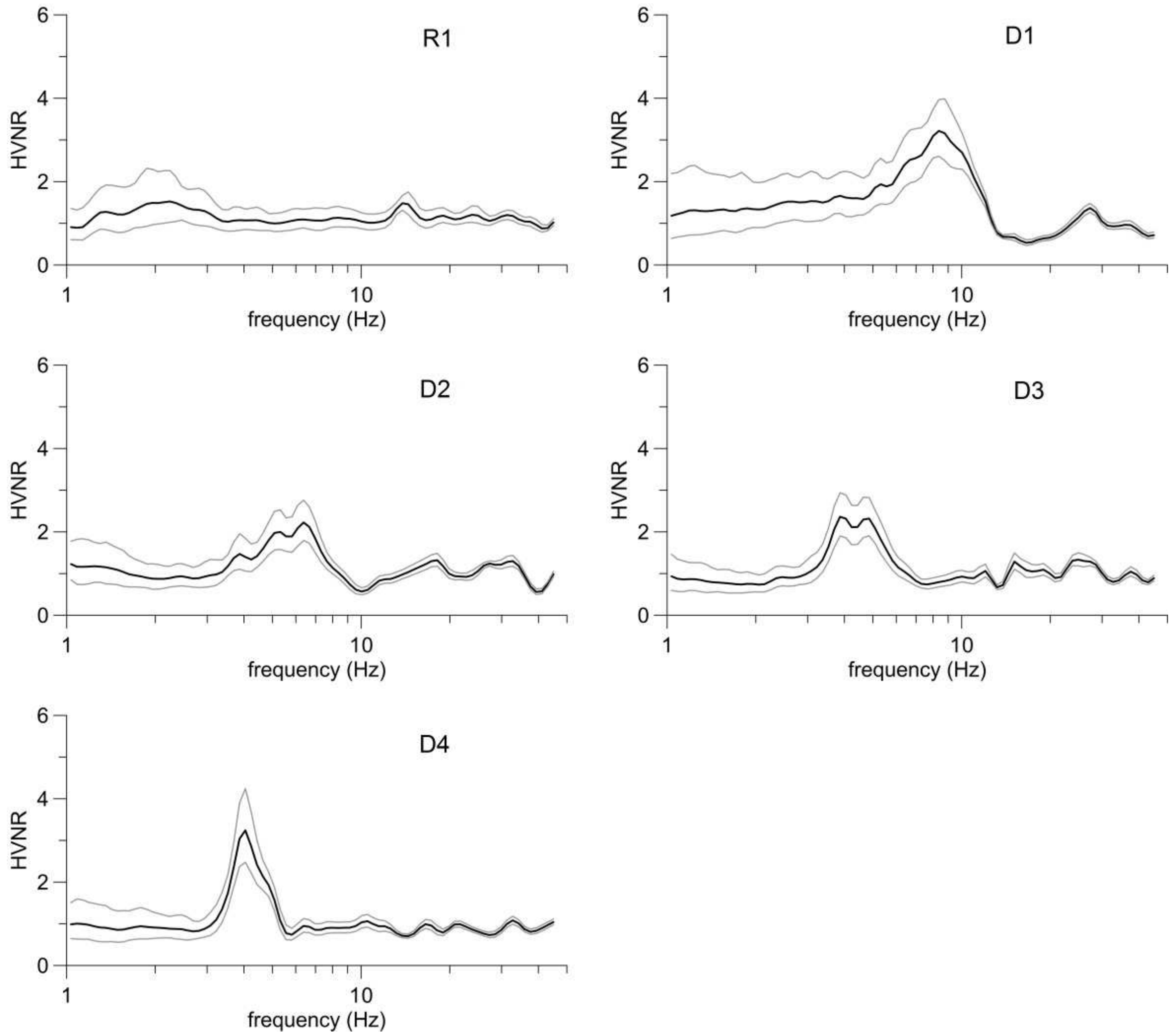

Fig. 9. The H/V spectral ratio curves for individually measured points R and D1-D4. Each H/V spectral ratio curve shows the averaged curve and its standard deviation computed for all selected windows.

Conclusion

This paper describes an experimental measurement of the vibration response of the waste rock dump caused by blasting operation. The aim of this measurement was to provide a detailed interpretation of wave patterns recorded at different levels of the dump´s embankment of the height of 23 m. The maximum value of vibration velocity during blasting reached 8 $mm.s^{-1}$ on the radial component at the embankment´s height of approximately

12 m. Spectral analysis proved a difference in the prevailing frequency range of two measured blasts, i.e. 40 - 50 Hz during the first blast and 15 - 25 Hz during the second one. It was also found that the prevailing frequency content of the input ground motion probably influences the dynamic response of the dump, especially in the phase of the dump´s resonant vibration.

To evaluate the fundamental frequency of the dump, two different methods were used. Detailed frequency analysis together with continuous wavelet Morlet transform were performed using records of a resonant vibration of the dump after the blast-induced vibrations were attenuated. Next analysis was performed using the spectral ratio HVNR method applied to records of seismic noise measured at different levels of the embankment. Both methods proved that the resonant frequency determined at different level of the embankment is decreasing with the increasing elevation of the embankment, which means that the thicker is the waste rock layer, the lower is the fundamental frequency. The maximum amplitude of resonant vibration was detected at the top of the embankment with the resonant frequency equal to approximately 4.0 Hz.

Results presented in this paper provide significant information about the behaviour of the waste rock dump and some additional information for possible numerical modelling.

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