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Vibration Effect of Near Earthquakes at Different Depths in a Shallow Medieval Mine

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Abstract

The shallow medieval Jeroným Mine is located at a distance of about 25 km southeast of the Nový Kostel focal zone where the most intensive seismic activity in West Bohemia (Czech Republic) has been documented. Permanent seismological monitoring has been carried out since 2004 in this mine. During the 2011 and 2014 seismic swarms, more than 1000 triggered records comprising almost 1500 earthquakes were recorded at the permanent station in the mine. Three short-term seismological experiments were accomplished during these swarms. Several temporary seismic stations were simultaneously placed in different parts of underground spaces which enabled comparison of vibration effect caused by near earthquakes in different parts of the mine. Although the depth of the lowest parts of mine is only about 60 m, a vibration effect generated by earthquakes from the Nový Kostel focal zone is not the same for the whole underground complex.

Key words: Jeroným mine, vibration, earthquake, seismic swarm, underground space.

1. INTRODUCTION

The Jeroným (Jerome) Mine is located near Čistá in the Sokolov Region, West Bohemia. This medieval mine was declared the National Cultural Heritage Site in 2008 and it represents a part of the European Mining Heritage

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Ownership: Institute of Geophysics, Polish Academy of Sciences;

Network. The oldest parts of the mine are related to the extraction and processing of tin during the second half of the 16th century. In the underground complex we can find mine workings made by different mining methods such as extracting by a picker and miner's hammer, fire-setting, underhand stoping or overhand stoping**,** chamber mining, *etc*. Nowadays, small part of the mine is opened to the public as a mining museum. Stability of the mine, the parts of which are more than 400 years old, is the priority both in the light of preserving the unique spaces for next generations and in the light of safety of people visiting the mine. Therefore, a detailed geomechanical monitoring has been performed there including a stability analysis of underground spaces especially of the critical ones. A dynamic loading evaluation of underground spaces is included in the stability analysis and therefore a seismological monitoring is also performed in the mine. Earthquakes from the Nový Kostel focal zone in West Bohemia represent the most significant seismic loading of this mine. According to Fischer *et al.* (2010), limited seismic potential of the focal zone would amount to an earthquake of $M_L \sim 5$.

Permanent seismological monitoring has been carried out since 2004 in the Jeroným Mine. A seismic pillar has been installed in the mine about 30 m below the surface in one of the largest chambers signed as K1. Three modified SM3 seismometers in geographical orientation are anchored on the concrete pillar; the seismic station is signed as JER1. The seismic recording apparatus PCM3-EPC4 (Knejzlík and Kaláb 2002) has a special modification for the high air humidity environment and drip water. Seismic recording is based on a trigger regime. Sampling frequency of digital signal is 250 Hz per channel and the frequency range is 0.5-30 Hz.

Since 2008, more than 2000 earthquakes from West Bohemia were recorded on JER1 station during three intensive seismic swarms in the years 2008, 2011, and 2014. The first analysis of vibration effect in the Jeroným Mine during these seismic swarms was described in the papers by Kaláb and Lednická (2011), Lednická and Kaláb (2013), Lyubushin *et al.* (2014), and Kaláb *et al.* (2015). According to the presented results, the measured vibration velocity values reached up to 0.8 mms^{-1} at JER1 station for an earthquake with local magnitude M_L 3.6. Based on the measured data and information about local magnitude of recorded earthquakes (according to database of WEBNET network; IG CAS 1991), maximum space component of vibration velocity in the mine of 13 mms^{-1} was extrapolated for an expected earthquake with local magnitude M_L 5.0. As it is mentioned in the performed studies, maximum vibration velocity expected in the Jeroným Mine should not reach limit values for the first damage underground, as stated in the literature (*e.g.*, Dowding and Rozen 1978). Therefore, it is possible to say that the Jeroným Mine as the whole complex of underground spaces should be stable from the viewpoint of damage caused by vibrations. Nevertheless, determined maximum space component of vibration velocity is valid only for the place of JER1 station. If there will be amplification of vibration effect in other parts of the mine compared to the effect at JER1 station, it will be necessary to perform other detailed studies of vibration effect at these parts and to determine corrected maximum of expected vibration velocity value for stability evaluation.

It is necessary to study vibration effect especially in critical places where movements along discontinuities may occur or places where a deformation of roofs may take place, especially in shallow underground workings. Some movements along discontinuities in the highest levels of the mine were detected within last years. These movements were detected by cracked glass targets installed across the discontinuities. These targets are checked visually, approximately five times per year during irregular inspections of the mine. At present we can only speculate about the time and reason of glass target cracking. Cracked glass targets were detected on the fissured residual pillar in the chamber K4 and on the roof in the highest part of the chamber K1.

During seismic swarms in 2011 and 2014, short-term seismological experiments were made in the mine, enabling to analyse a vibration effect at different parts of the mine caused by near earthquakes (epicentre distances up to 25 km). Five temporary seismic stations (signed ST1-ST5) were placed in three large chambers on different levels of the mine during the experiment in 2011 to cover the different parts of the whole underground system of mine workings. Seismometers had to be placed directly on the rock massif during the measurement to have possibility to compare vibration response of the rock massif (not the response of infilling rock material located in the chambers). Especially in sloping chambers K3 and K1, there is practically no uncovered rock massif at the bottom of the chamber suitable for placing a seismometer. The chambers are filled with the rock blocks from the collapsed roofs and pillars and with the weathered rock material; moreover, the lowest parts of these two chambers are permanently flooded. The lowermost temporary seismic station was situated in the lowest accessible part, which means, on the level of drainage adit. The highest placing of the seismic station was on the same level as the permanent station JER1 but in the different part of the chamber K1 – in a small niche (see Figs. 1 and 2 and Table 1). The difference in height of the lowermost and the highest station was 19 m. Based on the remarks resulting from the measurement in 2011, next experimental measurement was performed during 2014 seismic swarm with temporary seismic station (signed ST6) located in the highest accessible part of K1 chamber near collapsed roof and cracked pillar.

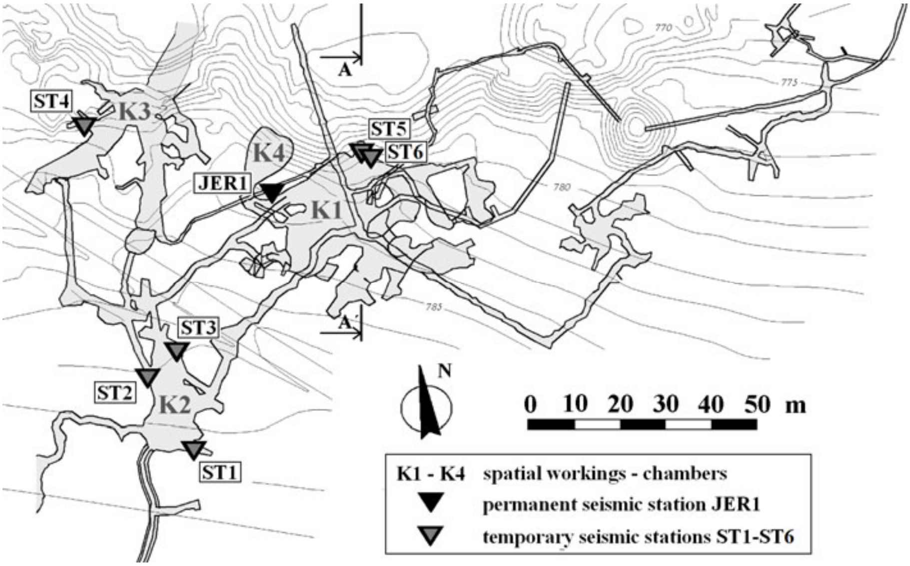

Fig. 1. Sketch of the Jeroným Mine and locations of seismic stations.

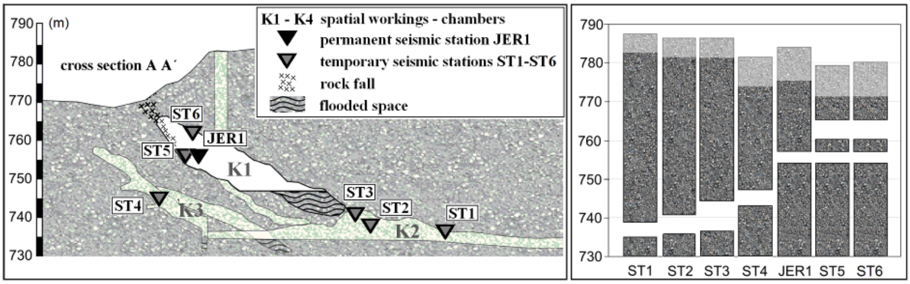

Fig. 2. General cross-section of the Jeroným Mine with position of seismic stations and detail cross-sections in the seismic station places. Light grey colour of near-surface layers on the right figure represents zone of low velocities indicated by geophysical measurement (according to Beneš 2011).

Table 1

Seismic stations

Seismic station	JER1	ST1	ST2	ST3	ST4	ST5	ST6
Altitude above sea level [m]	754	735	736	739	743	754	760
Depth below the surface [m]	30	53	51	48	37	24	20

2. LOCALITY DESCRIPTION

Some detailed information about the Jeroným Mine and mining history in this locality was described in the papers by, *e.g.*, Žůrek and Kořínek (2001/2002), Tomíček (2011). Geological and geomechanical descriptions of this locality can be found in numerous papers (according to Kaláb *et al.* 2006, 2008). From the geological viewpoint, the territory consists of metamorphosed rocks of the Slavkov mantle crystalline complex and of Variscian granites of the Ore Mountains pluton. Rock mass underground had been exposed to devastation and weathering for many years and places with lower stability were formed as a result of those processes (Lednická and Kaláb 2012). Some critical places underground are represented mostly by fissured and weathered supporting pillars or hanging layers on the roof in chambers. On the residual pillars there is probably an influence of recent tectonics induced by anthropogenic factors. These, most likely, tension cracks roughly trace directions of natural tectonics. Some other critical places are represented by ground deformations above the mine where a few collapses occurred due to broken sub-surface rock layers into shallow workings (Kukutsch *et al.* 2011). The sub-surface rock structure is possible to investigate, *e.g.*, through a seismic survey (Arosio *et al.* 2013). The refraction seismic survey was applied also at the locality of the Jeroným Mine and the results of the performed measurements have shown that the rock environment is to a great extent inhomogeneous. The overlying layers above the cavities are at heavily loosened places. This is shown by significant declines of the seismic velocities. The existence of unknown cavities was confirmed by the testing boreholes which were situated on the basis of the geophysical measurement results (Beneš 2011).

The Jeroným Mine consists of an underground system of workings, galleries, shafts, and chambers on at least three horizontal levels. The lowest level is permanently flooded (Fig. 2). Some parts of the underground space have so far been unexplored. All historical maps and documents were destroyed by the fire in the Bureau of Mines in 18th century. Therefore, there is no detailed information about any historical mining activities and a scale of subsurface and underground space in this location. At present, the lowest accessible part of the mine is on the dewatered level of about 55 m below the surface.

3. WEST BOHEMIA SEISMIC SWARMS

A weak seismic activity in the form of seismic swarms is typical for the West Bohemia Region. It means hundreds up to thousands earthquakes occurring over several days or months. An earthquake swarm activity in this area has been monitored by local seismic network WEBNET operated by the

Institute of Geophysics and the Institute of Rock Structure and Mechanics, both coming under the Czech Academy of Sciences, Prague (IG CAS 2000). The oldest observations of earthquakes in the region date back to the Middle Ages. The magnitude of the strongest earthquakes in 1824, 1897-1908, and 1985-2011 did not exceed M_L 4.5 (Fischer *et al.* 2014).

The analysis of the 2011 seismic swarm is presented in the study by Fischer *et al.* (2014). The hypocentre depths in the Nový Kostel focal zone range between 6.5 and 11 km with some clusters down to 13 km. Two sub-clusters, the northern and the southern one, are distinguishable. The 2011 seismic swarm took place in the northern sub-cluster of the Nový Kostel focal zone and the duration of the main swarm period (earthquakes with local magnitude $M_L \geq 2.5$) was only 2 weeks. Almost 1400 earthquakes were recorded at the seismic station JER1 within the phase from 23 August to 11 September. Maximum component vibration velocity recorded at JER1 station reached the 0.35 mms^{-1} during one of the most intensive earthquakes (4 September, M_L 3.3). Epicentres of earthquakes from the Nový Kostel focal zone, which were recorded at the JER1 station during the 2011 seismic swarm, are plotted in Fig. 3.

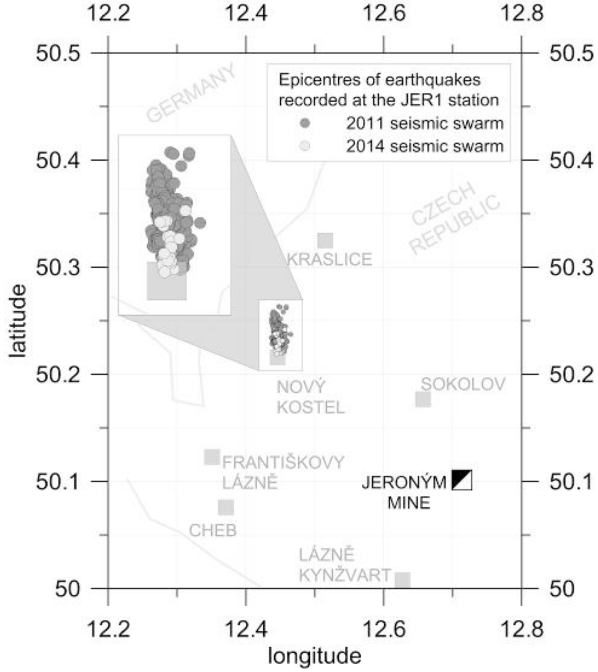

Fig. 3. Epicentres of earthquakes in West Bohemia region occurred during the 2011 and 2014 seismic swarms, which were recorded at the JER1 station; according to the WEBNET seismic network (IG CAS 1991).

The last intensive seismic activity was recorded in 2014 (according to http://www.ig.cas.cz/struktura/observatore/zapadoceska-seismicka-sit-webnet/aktualne-o-seismicke-aktivite-v-zapadnich-c-0). On 24 May 2014, intensive earthquake of local magnitude M_L 3.5 occurred in the Nový Kostel focal zone at a depth of about 9 km. On 31 May 2014, intensive earthquake occurred at 10:37:20 UTC in the same focal zone at a depth of 8.5 km with the local magnitude M_L 4.4. This earthquake counts among the two strongest earthquakes registered in this area over the last 100 years and is comparable to the earthquake in 1985. At night from 3 to 4 August 2014 next intensive earthquake of local magnitude M_L 3.6 occurred in the Nový Kostel focal zone. The depth of the epicentre was approximately 9 km. During this seismic activity, almost 100 earthquakes were recorded at JER1 station. Unfortunately, there was 10 day's gap in the seismic monitoring at JER1 station due to some reconstruction activities in the mine and the most intensive earthquake with M_L 4.4 was not recorded. Maximum component vibration velocity recorded at JER1 station reached the 0.76 mms^{-1} during the M_L 3.6 earthquake (3 August). Epicentres of earthquakes from the Nový Kostel focal zone, which were recorded at the JER1 station during the 2014 seismic swarm, are plotted in Fig. 3.

4. MEASUREMENT

Analysis of short-term measurements (signed as A, B, and C) performed in the mine during the 2011 and 2014 seismic swarms is presented in this paper. Periods of these measurements are illustrated in Fig. 4. The permanent seismic station JER1 was simultaneously in operation and more than 1000 triggered records comprising almost 1500 earthquakes were recorded at this station within these two swarms. The values of maximum component vibration velocity for all recorded earthquakes during the evaluated periods of the seismic swarms in 2011 and 2014 are plotted on the graph in Fig. 4. During one of the strongest earthquakes (25 August 2011, M_L 3.5), the maximum amplitude range of seismic channel ($\pm$ 0.25 mms^{-1}) was exceeded so the maximum component vibration velocity was not possible to be determined for this earthquake.

A short-term measurement A was performed in the Jeroným Mine in order to evaluate a vibration effect in different parts of the mine complex. Five solitary seismic stations (signed as ST1-ST5) with three component sensors were installed in three large chambers of the mine on different levels (Figs. 1 and 2). Some detailed information about the location of individual seismic stations is given in Table 1. This experiment was performed within the period from the afternoon of 30 August to the morning of 1 September 2011. Unfortunately, during this short-term measurement there was a gap in seismic activity and only a few weak earthquakes with local magnitude $M_L \leq 2.5$

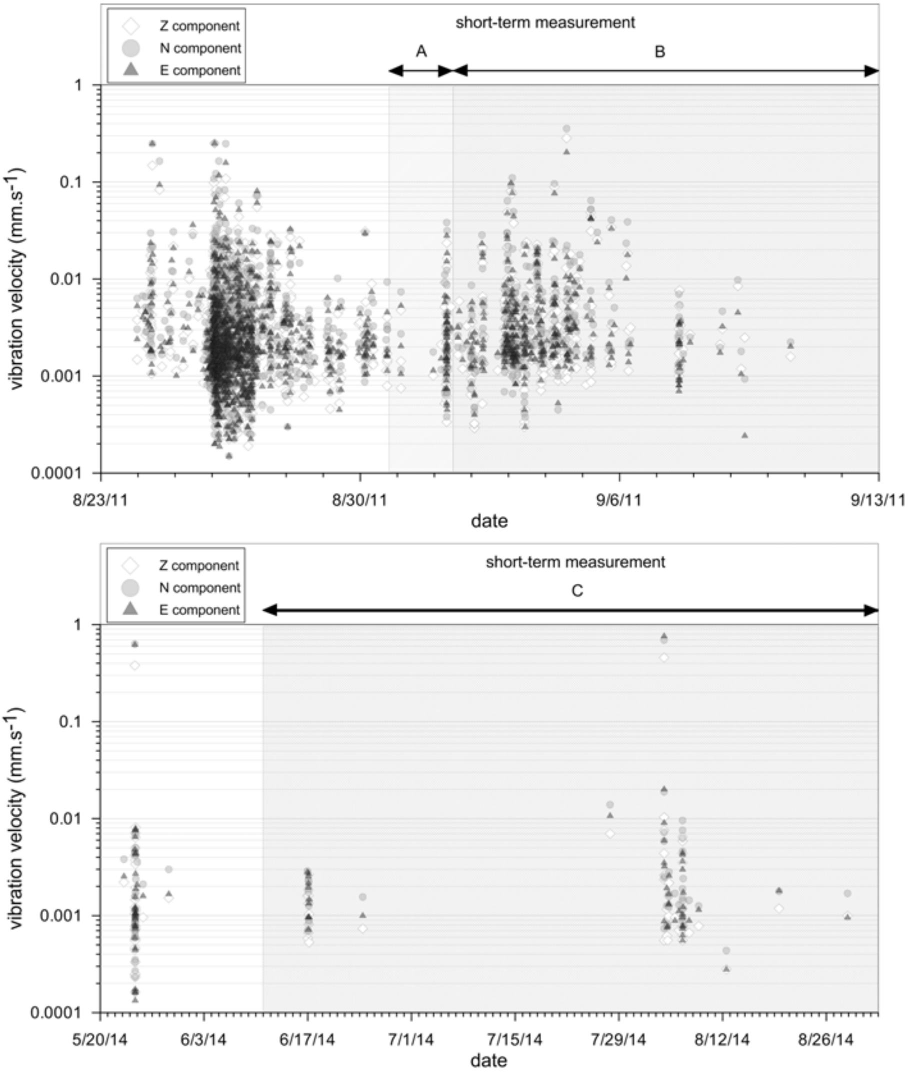

Fig. 4. Chronology of peak ground velocities for all recorded earthquakes at the seismic station JER1; A, B, C – periods of short-term measurements.

were recorded. Only 10 earthquakes (data set A) were possible to be used for elaboration out of this measurement. After this short-term experiment, the station ST1 was kept at the lowest level for subsequent monitoring (measurement B). On 1 September 2011 the next phase of seismic activity started in the Nový Kostel focal zone and within the phase from 1 to 11 September 2011 more than 200 earthquakes were recorded in the mine with local magnitude $M_L \leq 3.3$ (data set B). Third short-term measurement, C, was performed in the mine to extend the knowledge about the vibration effect in the highest parts of the mine. One temporary seismic station (signed as ST6) with three component sensor was placed at the higher level in K1 chamber at a depth of 20 m below the surface; the difference in height of the ST6 and JER1 station was 6 m. This measurement was performed within the period from 11 June 2014 to the beginning of October 2014 and almost 50 earthquakes from the Nový Kostel focal zone were recorded with the local magnitude $M_L \leq 3.6$ (data set C).

5. DATA ANALYSIS

As mentioned above, first analysis of the data recorded at the permanent station JER1 during the seismic swarm in 2011 was presented by Lednická and Kaláb (2013) and the data analysis was focused especially on the evaluation of influence of near earthquakes on the stability of discussed mine. Data from the 2014 seismic swarm are still analysed. In order to summarize main results from the above-mentioned paper we can say that extrapolated values of the component vibration velocity at the station JER1 are in the range from 3.5 to 7.5 mms^{-1} (space component 13 mms^{-1}) for expected local magnitude M_L 5.0. It is necessary to mention that determined equations are derived only for earthquakes from the Nový Kostel focal zone and only for location of the station JER1. Other relations will be necessary to determine if the vibration effect will vary in different parts of the mine, especially for the places where the vibration effect can be higher compared to the effect at the place of the station JER1. Permanent station JER1 was selected as a reference station for all calculations performed in next sections and ratios of peak ground velocities (PGV) from the given station to the reference station were calculated.

5.1 Short-term measurement A

Only 10 weak earthquakes (see Fig. 4) were elaborated with local magnitude $M_L \leq 2.5$ from the Nový Kostel focal zone. The PGV during the phase of *S*-wave (almost all of recorded earthquakes have the maximum value of recorded vibration velocity during the phase of *S*-wave) was determined for each recorded earthquake at each station. PGV ratios from the given station to the reference station were then calculated and elaborated by using box-whisker plots. The results show the lowest vibration effect at the station ST1 on the adit level (Fig. 5), *i.e.*, half the effect at JER1 station. It is possible to detect a slight increase of the vibration effect at the ST2 and subsequently at the ST3 station in the chamber K2. The vibration effect in the central part of the chamber K3 is approximately 1.3 times lower than on the JER1 station and it is slightly different for all three components. At the station ST5 in the

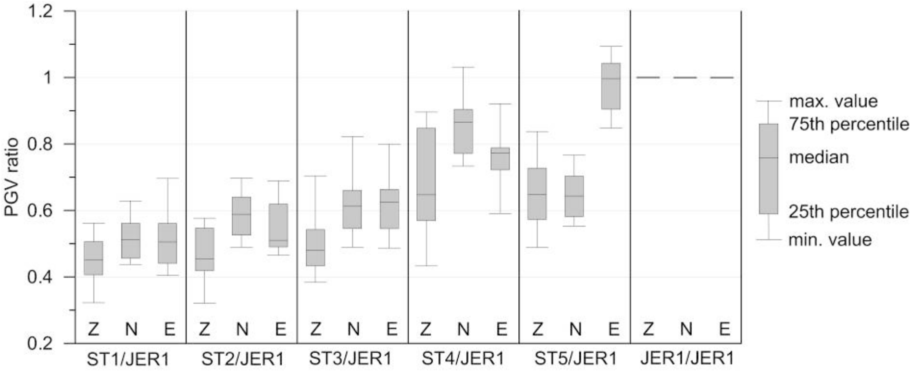

Fig. 5. The PGV ratios of the given stations to the reference station calculated for each component (data set A).

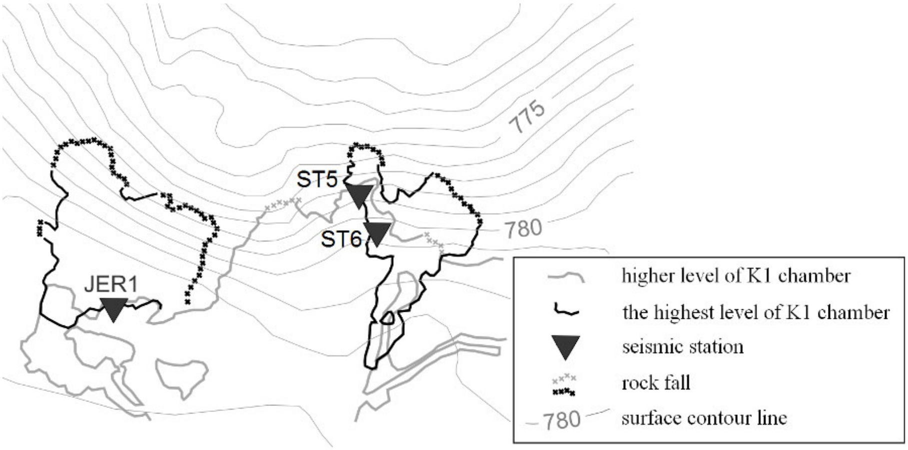

Fig. 6. Detailed situation in the surroundings of the ST5, ST6, and the JER1 stations.

chamber K1, the PGV ratio is much more different for all three components in comparison with PGV ratios at the other stations. The median of calculated PGV ratio is 1.0 at E component and only 0.65 at N and Z components. The station ST5 was situated in the part of the chamber K1, where a complex structure of pillars and hanging roofs is located. Above the station ST5 and in its surroundings there are located rock-falls leading from higher collapsed parts of the mine (Fig. 6). It may cause this specific character of the vibration effect in this place. One example of wave patterns for N components recorded during measurement A is in Fig. 7.

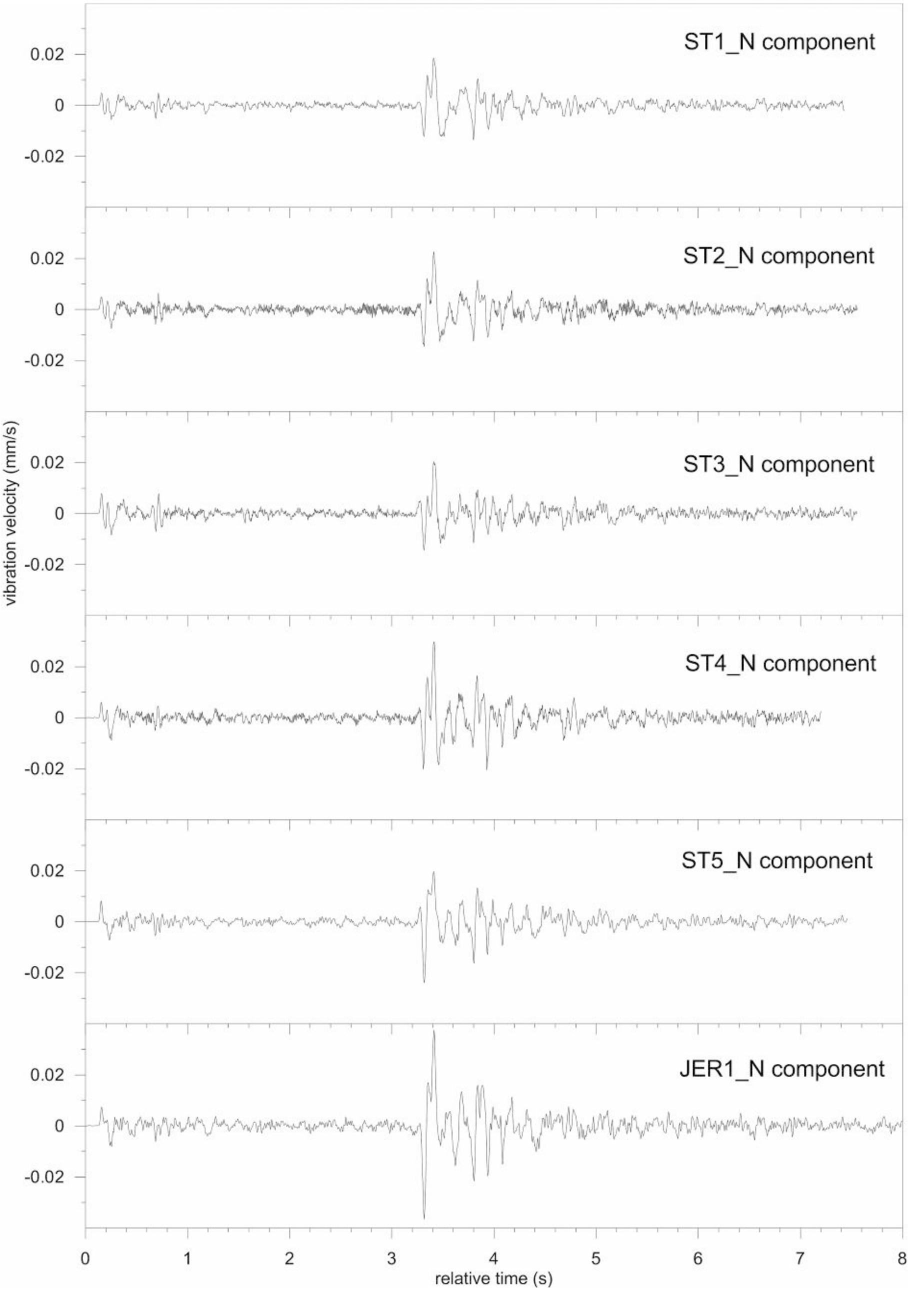

Fig. 7. Example of wave patterns of recorded earthquake (1 September 2011, M_L 2.5) for N components simultaneously measured on six seismic stations during short-term measurement A.

5.2 Short-term measurement B

More than 200 earthquakes with $M_L \leq 3.3$ were recorded at the permanent station JER1 and temporary station ST1 within the phase from 1 to 11 September 2011. The PGV ratio was calculated and analysed using box-whisker plots (Fig. 8). This graph demonstrates that the vibration effect is similar for all three components. The vibration effect at the adit level is also approximately half the effect at the station JER1. These results correspond to the re-

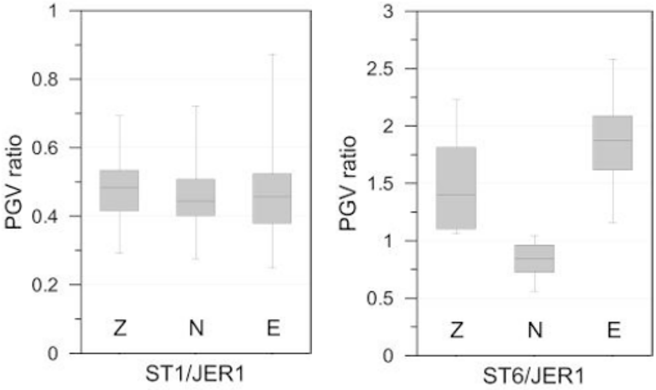

Fig. 8. The PGV ratios ST1/JER1 and ST6/JER1 for all components (data set B – left and data set C – right).

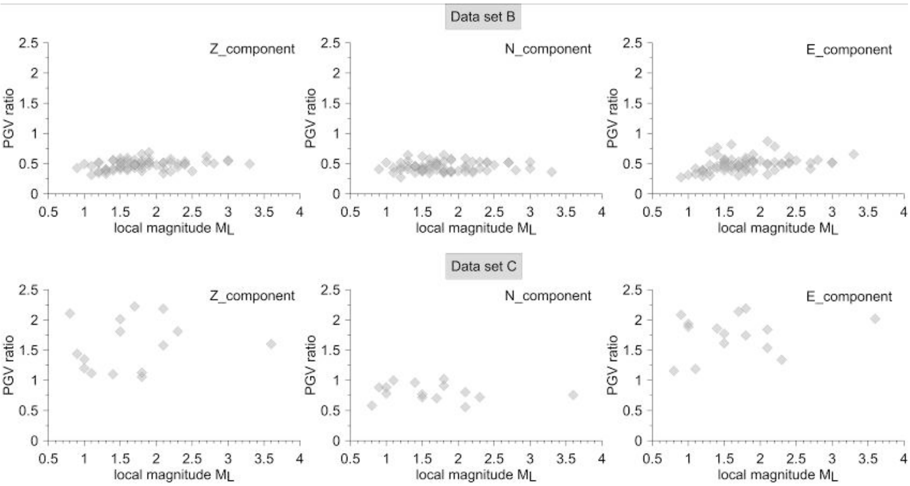

Fig. 9. The PGV ratios ST1/JER1 and ST6/JER1 for data set B and C depending on local magnitude.

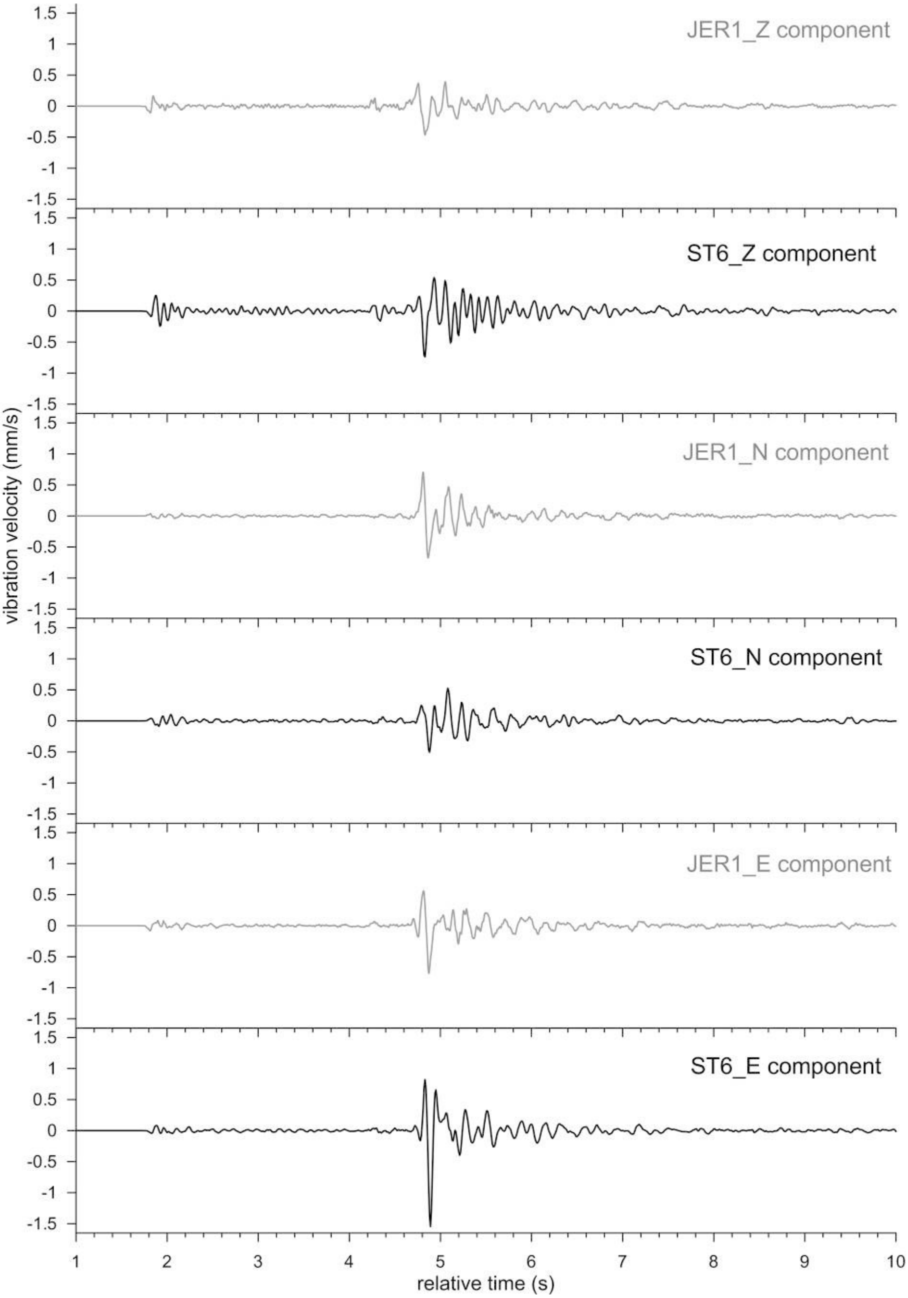

Fig. 10. Example of wave patterns of the recorded earthquake (3 August 2014, M_L 3.6) for Z, N and E components simultaneously measured on two seismic stations during short-term measurement C.

sults of a short-term measurement A, when only 10 earthquakes were elaborated. In order to be able to find out whether the calculated ratios are the same for earthquakes with different magnitudes, we have plotted the PGV ratio depending on local magnitude (Fig. 9). The information on local magnitude of earthquakes was possible to find in the map "Epicentres of earthquakes in the West Bohemia – Vogtland region" (http://www.ig.cas.cz/en/structure/observatories/webnet/map-of-epicenters/). This analysed data set contains 65 earthquakes ($M_L \leq 3.3$). The PGV ratio calculated for the stations JER1 and ST1 is generally the same for the whole evaluated range of local magnitudes M_L from 0.9 to 3.3.

5.3 Short-term measurement C

Almost 50 earthquakes with $M_L \leq 3.6$ were recorded at the permanent station JER1 and temporary station ST6 within the phase from 16 June to 28 August 2014. As well as for previous measurement, B, the PGV ratio was calculated and analysed using box-whisker plots (Fig. 8) and plotted depending on local magnitude (Fig. 9, selected data are presented here). The results in graph in Fig. 8 demonstrate that the vibration effect in the place of ST6 station is not the same for all three components compared to the JER1 station. PGV ratio is 1.4 and 1.8 for the Z and E components, respectively, but the PGV ratio is only 0.8 for the N component. The PGV ratio is generally the same for the whole evaluated range of local magnitudes. An example of wave patterns of all three components recorded simultaneously at JER1 and ST6 seismic stations is presented in Fig. 10 (earthquake with M_L 3.6).

6. DISCUSSION

According to the results of analysis, we can state that the vibration effect in the Jeroným Mine caused by earthquakes from the Nový Kostel focal zone is different for individual investigated parts of the mine complex. The lowest vibration effect was determined at the lowest accessible part at the adit level in the K2 chamber, *i.e.*, 53 m below the surface (ST1 seismic station). The most intensive vibration effect was detected on temporary seismic station ST6 in the higher part of K1 chamber, *i.e.*, 20 m below the surface.

It is known that the vibration effect underground is less than at the surface and that it decreases with increasing depth. Evaluation of vibration effect in different depths is often made, for example in geotechnical engineering, earthquake engineering and/or speleoseismology (Bokelmann and Gribovszki 2015, Szeidovitz *et al.* 2008). Hu and Xie (2004) investigated the variation of ground motion with depth for three different site conditions. They concluded that peak ground acceleration, velocity and displacement decrease with depth and the decline extent is more dramatic in shallower layers than that in deeper ones. In the paper, fitting curves calculated for subsurface/surface amplitude ratio are presented for investigated sites. For rock site, for example, the PGA (peak ground acceleration) on the surface is 1.2 times higher than at a depth of 100 m. For soil site, PGA on the surface is 1.8 times higher and for soil/rock site PGA is 3.3 times higher than at a depth of 100 m. They also found that the reduction of amplitude with depth is affected by the magnitude and site geology. Iwasaki *et al.* (1977) analysed acceleration measured in the boreholes at the different depths. Acceleration, with respect to depths, changes considerably with the change of soil conditions near the ground surface. Ratios of the surface acceleration to that at the deeper layer (110 to 150 m) are about 1.5 at a rocky ground, 1.5 to 3.0 at sandy ground and 2.5 to 3.5 at a very clayey ground.

Above the Jeroným Mine, no seismic station was placed on the surface during the measurements and, therefore, it was not possible to calculate PGV ratio between places underground and on the surface. Permanent station JER1 was used as the reference place, so the PGV ratio is equal to 1.0 at a depth of 30 m under the surface. Amplification and/or decreasing of vibration effect at other places were compared with this reference depth. The PGV ratio (median value from the data set A and C) depending on depth under the surface is presented in Fig. 11. The PGV at a depth of 53 m is approximately half of the PGV at a depth of 30 m below the surface. The PGV ratio calculated for the stations ST2, ST3, and ST4 is increasing with decreasing depth under the surface and it seems that the data are in linear correlation. Conversely, the PGV ratio calculated for the ST5 and ST6 stations is not in correlation with results from other stations. This effect may be caused, for example, by the local geological and geomechanical conditions at the place of ST5 and ST6 stations where complex structure of supporting pillars is situated and collapsed overburden is located (details on Fig. 6). It means that anomalous vibration effect may be regarded as a response of geological element in the mine. Therefore, it is necessary to perform detailed geomechanical evaluation of this place.

The results obtained from these seismological experiments provide important basis of seismic loading evaluation of this medieval mine. Damage to mines is more insignificant when they are located in highly competent, unweathered rock; the greatest damage occurs in mines found in loose unconsolidated or incompetent material. This is due to the effect of decreased vibration in competent rock; unconsolidated sediment is much more susceptible to damage caused by vibration. Large displacements occur primarily along pre-existing faults and fractures. Usually, more detailed analysis is required before seismic criteria can be formulated for the safety of people visiting the mine.

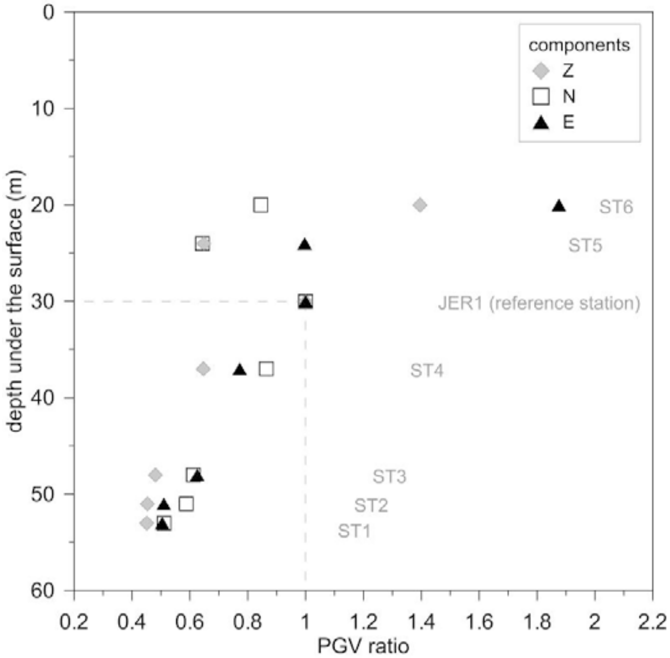

Fig. 11. The PGV ratios depending on depth under the surface; depth of 30 m below the surface represents the reference depth for PGV ratio calculation.

As it was mentioned above, maximum vibration velocity of 13 mms^{-1} expected in the Jeroným Mine at the place of JER1 station for an earthquake with local magnitude M_L 5.0 should not reach limit values for the first damage underground as stated in the literature (*e.g.*, Dowding and Rozen 1978). Nevertheless, this extrapolated value is valid only for the place of station JER1 at a depth of 30 m below the surface. Considering the results presented in Fig. 11 and the fact that the PGV decrease is more dramatic in shallower layers, especially in the weathered and collapsed parts of rock massive, the vibration effect can be more intensive in the highest levels of the mine and the expected maximum vibration velocity could reach the limit values for the first damage. Measurement on the station ST6 in 2014 confirmed this idea and it was documented that the vibration effect at the higher measured parts of K1 chamber is almost two times higher than the effect at the JER1 station in the east-west direction. Looking at the N component, the PGV value is lower than value measured at station JER1 (Fig. 11). This effect documents that the vibration field in underground spaces of the Jeroným mine is complex and anomalous vibration effect with increasing maximum PGV may occur at some places, especially in the highest levels near the collapsed parts and cracked pillars. It is not possible to perform the evaluation of vibration effect in this type of underground structure based on measurement at only one point. To confirm this idea, next measurement is necessary to be made at other places too, especially at the highest parts of the mine.

On the other side, results confirmed that the maximum expected vibration velocity will be approximately half the value of JER1 for chamber K2 and consequently all galleries and other workings at the adit level. The maximum expected vibration velocity values underestimate significantly limit values for the first damage caused by vibrations at these places. This information is very important from the stability point of view, because all the important galleries are located at the adit level – galleries for the entering all chambers, galleries for ventilation and dewatering of all accessible and/or inaccessible workings.

On the contrary, at the highest levels of the mine, it means chambers K3, K1, and K4, expected vibration velocities could be higher than the maximum expected PGV value of 13 mms^{-1}. This is very valuable information for stability assessment and also for planning of next geomechanical, geotechnical, and also seismological monitoring in this mine (Kaláb and Lednická 2016).

7. CONCLUSION

The paper presents the results of vibration effect evaluation in different parts of underground mine complex. Vibration effect was measured in different parts of shallow medieval Jeroným Mine, which is located in West Bohemia, Czech Republic. About 25 km from the mine, there is located the Nový Kostel focal zone, which is known as an area with weak seismic activity in the form of seismic swarms. During the 2011 and 2014 seismic swarms in the Nový Kostel focal zone, more than 250 earthquakes with local magnitude $M_L \leq 3.6$ were recorded in the underground spaces during performed short-term seismic measurements. One permanent and six temporary seismic stations were used for the measurement and data analysis. These stations were placed in different parts of the mine at the depth ranging from 20 to 53 m below the surface. Permanent station JER1 installed 30 m below the surface has been used for the seismic monitoring, for the evaluation of vibration effect in the mine and for the stability analysis since 2004. Results of experimental measurements performed using temporary seismic stations enabled to compare vibration effect at different parts of the mine. It was confirmed based on the obtained results that the vibration effect is higher at the highest places of the mine in comparison with vibration effect at the permanent station JER1. Based on previous studies, maximum vibration velocity for maximum expected earthquake of local magnitude M_L 5.0 was extrapolated based on long term monitoring at the permanent JER1 station that underestimates limit values for the first damage underground caused by vibrations.

Nevertheless, results obtained based on presented experimental measurement at different parts of the mine confirmed that new analysis has to be performed at the highest places of the mine where cracked and weathered supporting pillars and collapsed overburden are located. At these places, anomalous vibration effect can be estimated and the maximum expected vibration velocity could reach the limit values for the first damage underground.

From the stability point of view, it is necessary to add that the Jeroným Mine, as the whole complex of underground spaces, should be stable from the viewpoint of damage caused by vibrations. Maximum expected vibration velocity at the lowest parts of the mine at the adit level underestimates significantly the limit values for the first damage underground. But according to the results, at selected critical places, it is necessary to perform specific measurement and to analyse these places individually from the stability point of view, especially at shallow depths and near the collapsed parts. This information is very important for safety of people attending underground spaces and also for assessing the stability of these places and for subsequent stabilization of the most hazardous parts.

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