SEISMIC ACTIVITY IN MEDIEVAL JERONÝM MINE, WEST BOHEMIA, DURING PERIOD 2006 – 2009

Summary. The Jeroným Mine is declared as National Cultural Heritage Site of the Czech Republic. This medieval mining locality is not open for public in the present time but in connection with the assumed utilization of the mine for the purpose of tourism, in 2001, works started to obtain more objective and specific information about the stress-strain and stability state of this shallow mine. Integral part of this study is evaluation of seismic load of the Jeroným Mine and numerical modelling of underground spaces to verify the present stability conditions of the working.

1. Introduction

The beginnings of underground mining of tin-tungsten deposits in the area of Slavkovský les Mts. are dated back to the first half of the 16th century. The mining at Čistá – Jeroným Mine (Sokolov district, West Bohemia) – began much later than in the surroundings. Although the development of mining in this mine was rapid, it did not last long. However, the mining and sporadic exploitation continued with many interruptions until the beginning of the 20th century. Detailed description of mining history in the locality of Čistá was realized by Bernard and Suček [1], Žůrek and Kořínek [16] and Kaláb et al. [8]. All medieval mining methods (rock breakings) is possible to document here, e.g. hand-made spaces using hammers.
of various dimensions and so-called bits (Fig. 1), work done with fire (fire setting) and/or blasting (from 1774, Fig. 2). This mining locality is not open for public yet. To obtain more objective and specific idea about the stress-strain and stability state of this shallow mine, many experimental works started.

Observing of stability of underground spaces began in 2001 when quarterly inspection of selected parameters started (changes in mine water level fluctuation – 4 points, measurement of openings of joints – 10 points, measurement of horizontal and vertical directions of cross-section convergence – 21 points). Seismological monitoring has started together with the restoration of old drainage adit in 2004 because significant load by vibrations occurred (drilling and blasting especially). To have more detailed information about rock massif behaviour, distributed measurement network for evaluation of hydrologic, geomechanical and other parameters has been built up in the Jeroným Mine from the first half of 2006. Instrumentation is generally based on commercial measurement kit and sensors [11, 13]. Current monitoring points include sensors for measurement of changes in mine water level fluctuation (3 points), measurement of openings of cracks (aperture of cracks, 5 points), measurement of vertical cross-section convergence (two points with mechanical system, one with laser distance meter, measurement of temperature of mine atmosphere (2 points) and measurement of change of tensor stress state of rock mass in shallow horizontal boreholes (2 points). Design of distributed measurement network and partial results of this monitoring were published [7, 9, 10, 13, 15, 17]. Distributed measurement network system is integrated to the existing seismic recording station (equipped by data transmission via GSM network to registration centre in Ostrava). Described monitoring system is performed as modular to have possibility to change configuration of this system. At present, distributed network is tested with six different types of sensors (15 sensors are used now); however, up to 250 sensors are possible to append.

This paper deals with description of seismic activity in medieval Jeroným Mine during period 2006 – 2009 and numerical model of the greatest underground space. The results acquired by the numerical model may contribute not only for verification of the existing stability situation of the given locality, but they are also significant for selection of new measurement points.
Fig. 1. Jeroným Mine – rock breaking using traditional hand tool – hammer and bit
Rys. 1. Kopalnia Jeroným – ślady urabiania ręcznego

Fig. 2. Jeroným Mine – gallery exploited using blasting
Rys. 2. Kopalnia Jeroným – wyrobisko wydrużone przy użyciu materiałów wybuchowych
2. Seismological Monitoring

Seismic recording apparatus PCM3-EPC [12] with special modification for environment with high air humidity and drip water (inner and outer housing IP55) was realized. The seismic apparatus with three seismometers of SM-3 type and with telemetric transmission of data through the GSM net is used for triggered registration of events. The apparatus consists of data acquisition system PCM3 and a single board PC (Advantech Biscuit PC PCM-3864). Free machine time of PCM3 is advantageously utilized for control and data acquisition from distributed measurement network. The remote control of station enables a change in the setting of operating parameters of system and data transmission to the interpretation centre.

First evaluation of seismic loading of the Jeroným Mine was published by Kaláb (2003). Experimental measurement contributed evaluation of ambient seismic noise during common activities in the underground spaces; maximum velocity values does not exceed \(2 \times 10^{-5}\) m.s\(^{-1}\) on vertical component and \(5 \times 10^{-6}\) m.s\(^{-1}\) on horizontal ones. Seismic effect of heavy traffic on road above the mine represented the most significant manifestations that time.

Nevertheless, the building operations during restoration of old drainage adit (2004 – 2006) significantly increased the seismic load. After opening of this restoration, seismic monitoring was started. Particular aims of seismic monitoring were:

- to maximize breakup without failure of rock in the surroundings,
- to minimize seismic effect in underground spaces,
- to use the most value of boreholes with explosives and specific timing.

In June 2004, seismological monitoring was started by means of a station installed directly in the mine working – three one-component sensors in geographical organization are anchored on concrete pillar. Main aim of the monitoring was to avoid damages of the historical parts in the mine. Using the Czech technical standard 73 0040 and an expert opinion, the limit value of maximum oscillation velocity in the working was fixed to 0.1 mm.s\(^{-1}\). It was necessary to regulate parameters of blasting operations when this value was exceeded; it was performed at the end of restoration – October, 27, Dec. 11 and Dec. 16, 2005). Maximum measured velocity value, i.e. 0.16 mm.s\(^{-1}\), was detected at the vertical component (component Z, see Fig. 3). More than 250 events of blasting operations were recorded during restoration of the adit. The wave patterns consisted of several wave groups that represent individual stages of blasting (Fig. 3).
Interpretation of seismic events recorded during period 2006-2009 shows that set is possible to divide into following groups:

- blasting operations from adjacent quarries,
- traffic – road above the mine,
- earthquakes – intensive distant,
- microearthquakes from North-West Bohemia,
- other seismic events – e.g. mining induced seismic events from Lubin.

Two quarries are situated in surroundings of the Jeroným mine – Vítkov and Krásno. Maximum oscillation values are in range $10^{-3} - 10^{-2}$ mm.s$^{-1}$, rarely higher value. This seismic loading has not significant influence on stability of underground spaces. Wave patterns have specific shape representing explosion of explosives.

There is a road from Krásno to Sokolov situated on the surface above the Jeroným Mine (approximately 7 – 20 m). More significant maximum amplitudes of velocity vibration are generated by heavy trucks, especially in case when velocity of trucks was changed. Number of these records depends on number of trucks, maximum generated amplitudes of vibrations and also value of triggered level in seismic apparatus. This type of seismicity was significantly decreased after partial restriction of truck traffic. Maximum oscillation
amplitudes reached up $10^{-2}$ mm.s$^{-1}$ during test measurement (passages of heavy truck loaded by rock material) and during following seismological monitoring.

Parameters of seismic path, especially frequency range, and triggered regime for recording enable to record very short (generally unidentified) parts from wave patterns of intensive distant earthquakes. Maximum oscillation velocity do not reached up $10^{-2}$ mm.s$^{-1}$.

The North-West Bohemia/Vogtland is the nearest region with natural seismicity [14] that is located about 25 km to the west from the mine. The 1985/86 swarm (December – February) ranks among the largest in the whole region under discussion. Seismic loading of underground spaces of Jeroným mine in 2008 was very low until 6 October 2008. From this date, significant seismic loading occurred because of a very intensive seismic swarm that started in West Bohemia, Nový Kostel area near Kraslice [2]. In sum 451 earthquakes from Nový Kostel area were recorded in seismic station Jeroným within 6 Oct. – 10 Dec., 2008. The most intensive shock occurred on 14 Oct (21:00); maximum value of component velocity reached 0.435 mm.s$^{-1}$ (Fig. 4). Damages of underground spaces (i.e. cracking of pillars, opening of observed fissures and discontinuities, more significant breaking off rock from the ceilings and walls ...) were not visually observed during quarterly experimental geomechanical monitoring in autumn 2008 and spring 2009 [6].

This chapter summarizes information about seismic loading on medieval Jeroným mine during 2006 – 2009. The source area of Nový Kostel swarm is about 25 – 30 km far form the mine workings and it represents the most significant source of seismic loading. Using map of seismic risk of the Czech Republic from Supplement of Eurocode 8, earthquakes with macroseismic intensity up to 6.5 degree can be predicted in the area under discussion.

Numerical model of K1 chamber

The K1 chamber is the largest underground space of Jeroným mine. Simple plane finite element model (Plaxis programming system), with limited possibilities of respecting real discontinuous environment, enables to obtain basic idea about the stress-strain and stability situation in the area of interest and also enables the realization of parametrical computations. Together 16 transverse sections and 12 longitudinal ones passed through the chamber were made with the use of the 3D scanner and appropriate interpretation software.
Now, only two transverse sections were modelled (signed as section 7 and 8). The results of the model document the stability of the present status – the degree of shear strength abstraction in the case of section 7 reached the maximum value of 0.26, the value of 0.46 in the case of section 8 and these are concentrated in the area of sharp transitions [4]. Overall
displacements in the roof part of the chamber reach maximum values of approx. 2 mm in both sections (for example see Fig. 5).

![Displacements in the roof part of the chamber](image)

**Fig. 5.** Total displacements in the section number 7 ($u_{\text{max}} = 2$ mm)

Rys. 5. Sumaryczne przemieszczenia na przekroju 7 ($u_{\text{max}} = 2$ mm)

The results acquired by the numerical model may contribute not only for verification of the existing stability situation of the given locality, but they are also significant for creating an idea of development of the stable situation in connection with anticipated construction work, the variation of form of mining areas and the fluctuation of underground water level in certain parts of the mine. The results of modelling are also very substantial in light of optimization of geotechnical monitoring with regard to distribution of monitoring stations aimed at covering the most questionable locations and reaching the highest predicative value of the results acquired from this monitoring. Last but not least, the appropriate numerical parameter calculations make it possible to consider the change of the rock massive parameters in connection with degradation processes which have been taking place in the given locality, in space and time, since the excavation of the historical mine working in the 16th century and which may have unfavourable influence on the stability conditions of the working.

### 3. Conclusion

Methodology of evaluation of seismic load of historical mining monuments has to respect strict protection of conserved parts, careful installation of instrumentation and individual evaluation of measured data. Current evaluation of seismic load of the Jeroným Mine
documents slight effects of vibrations in underground spaces. However, the seismological measurements described above are very important for detailed assessment of rock stability. The acquisition of information for predicting the stability of underground spaces is the main aim of geotechnical monitoring and iterative geophysical measurements in historical mines. These data are evaluated in relation to knowledge about the current state of underground spaces, especially fracturing and degradation of the rock mass. Results obtained by mathematical modeling of selected parts or of the whole complex of workings form the foundation of expert opinions on stability [3]. Information obtained by geotechnical monitoring is essential for the creation of a reliable mathematical model. One site at which geotechnical monitoring has been implemented for this purpose is the medieval mine of Jeroným where measurements in the section named the Abandoned Mine Workings are the basis for the case study described above.

A most important conclusion based on the measurements obtained from the distributed measurement network is that the mine workings are stable. Thanks to this, it is possible to continue preparations for opening of the Jeroným Mine heritage site to the public.

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Omówienie

Kopalnia Jeroným jest uznana za Obiekt Dziedzictwa Narodowego Republiki Czeskiej. Ta średniowieczna kopalnia nie jest dostępna dla zwiedzających, ale od 2001 roku prowadzone są prace mające na celu jej udostępnienie dla ruchu turystycznego. Obecnie trwają prace m.in. nad rozpoznaniem stanu naprężeniowo-odkształceniowego i stateczności wyrobisk. Integralną częścią tych prac jest określenie zagrożenia sejsmicznego dla stateczności wyrobisk oraz numeryczne modelowanie wyrobisk podziemnych dla celów weryfikacji obecnych warunków
ich stateczności. W ramach artykułu omówiono wyniki badań prowadzonych w zakresie monitoringu sejsmicznego i modelowania numerycznego stateczności wyrobisk. Wyniki badań pozwalają sądzić, że istnieje możliwość prowadzenia dalszych prac mających na celu udostępnienie kopalni dla ruchu turystycznego.