Long-term Geomechanical Observation in the Jeroným Mine

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Abstract

Geomechanical measurements have been carried out in the medieval Jeroným Mine since 2001. At first quarterly observation and later also continual monitoring by distributed measurement network were used. The network includes a number of different sensors that have been installed in selected places of underground spaces. There have not been any manifestations documenting dangerous changes of stability during the period of monitoring (2001-2015). The results of accomplished measurements from all convergence profiles confirm the total stability of all underground spaces. However, a number of places have been documented as potentially unstable. Measured values of selected parameters are presented in the paper, namely, movements along fractures, changes of stress tensor and fluctuations in the level of mine water table.

Key words: abandoned mine, geomechanical observation, movements along fractures, stress tensor changes, mine water table fluctuation.

1. INTRODUCTION

The Jeroným Mine has been declared the National Cultural Heritage Site of the Czech Republic. Only small part of this medieval mining locality is open to the public in the present time. The Jeroným Mine was “forgotten and re-discovered” (historical documentation was destroyed during the fire in 1772). This mine is undoubtedly a technical monument of European impor-

tance. It is expected that the mine will be used for tourism. Therefore, a lot of experimental work began in 2001 to obtain more objective and specific information on stress-strain and on the state of stability of this shallow mine.

The beginning of underground mining of tin-tungsten deposits in granite in the area of the Slavkovský les Mts. dates back to the first half of the 16th century. A detailed description of mining history in the locality of Čistá was compiled by Bernard and Suček (2000), Žůrek and Kořínek (2004), or Kaláb *et al.* (2006, 2008a). All medieval mining methods (rock breakings) can be documented here, *e.g.*, manually made spaces using hammers of different sizes and the so-called bits, setting a fire, and/or blasting later.

Preserving underground spaces of the Jeroným Mine and securing the surface above the underground spaces is conditioned by the mine stability. Therefore, an extensive monitoring system is gradually developed and operated. The first observing (geological, hydrogeological, and geomechanical) was realized in a quarterly period. Since 2006, distributed monitoring network (below as DMN) has been implemented. Some sensors within the DMN have been in operation for 10 years; therefore, it is possible to evaluate selected measured data. In this paper, three curves have been evaluated, namely movements along fractures, changes of stress tensor and fluctuations on the level of mine water table. Vibration effect measured in the underground spaces will not be dealt with in this article as it is described in other papers (*e.g.*, Kaláb and Lednická 2011, Lednická and Kaláb 2013, Lyubushin *et al.* 2014, Kaláb *et al.* 2015). Results of all these measurements are important for assessing stability and predicting a possible risk in the future.

2. DISTRIBUTED MONITORING NETWORK

The concept, development process, implementation and current state of the DMN were described in the papers, *e.g.*, Knejzlík and Rambouský (2008). Therefore, only some brief information is given below. The instrumentation in the mine consists of PCM3 data acquisition system and an embedded single board PC, Advantech Biscuit PC PCM-3864 (Knejzlík and Kaláb 2002). Recording of seismological data in a triggered regime is a prime aim of the PCM3-EPC4 system. In the period when recording of seismic data is not triggered, the PC only decodes time normal information of the DCF. It means that free machine time is available in this mode. This free time is conveniently utilized for Master Unit functioning also for operating of distributed measurement network. The apparatus is telemetrically connected with the Institute of Geonics and enables a remote control of the station operation, any change in the setting of operating parameters and data transmission to the interpretation centre (Kaláb *et al.* 2008a, Knejzlík *et al.* 2011). The DMN allows more detailed evaluation of hydrologic, geomechanical,

and some other parameters from the first half of 2006. The DMN is especially important for sudden changes of measured parameters. Instrumentation is generally based on a commercial control kit and on commercial sensors.

At present, the distributed measurement network has been tested by means of ten different types of sensors (about 25 sensors have been in use). However, it is possible to append up to a total of 250 sensors. Sampling frequency for our experimental operation was set to 1 hour. Current continuous monitoring points include the following sensors: measuring the movements along natural fractures in the rock mass (KD), measuring vertical direction of convergence (mechanical sensor (KK), laser sensor (LS)), measuring fluctuations of the level of water table in the mine (KV), measuring resistivity (RZ) and pH (PH) of mine water, measuring the temperature of mine atmosphere and the temperature of mine water (KT), measuring changes in the tensor of stress state in the rock mass (CCBM), and measuring the concentration of radon activity (RA). Measurement of a seismic load (SM3) runs in a triggered regime as mentioned above. Location of the sensors is shown in Fig. 1.

Special expansion of distributed measurement system in Jeroným Mine was realised in 2013; it was a continuous measurement of radon activity concentration (sensor was located near KD3). First short-time measurement

Fig. 1. Sketch of the Jeroným Mine and location of the DMN sensors (for abbreviations see the text).

of this parameter was made in 2009; the second one was made in 2012. Measurements were realized both in upper level of the mine and drainage level. Temperature and moisture measurements in the underground spaces were supplement of the radon activity concentration measurement. Resulting values are in range from 2.6 kBq m^{-3} in bottom of shaft up to 39.8 kBq m^{-3} in gallery in the drainage level.

3. MOVEMENTS ALONG FRACTURES

Rock massif in the Jeroným Mine contains at least two basic systems of discontinuities. By means of tectonic measurements, it was concluded that the tectonic system, presented by Cloos fissures, has the most important significance. Main systems of fissures are in the direction NEE-SWW and perpendicular direction NNW-SSE. Both systems have high values of inclinations, namely from 70° to 90° . Fissures oriented roughly horizontally with a slight dip (5° - 35°) are the third system. These systems of fissures are unambiguously endogenous discontinuities. Fissures detected on residual pillars are of a different tectonic system that is also under investigation. We assume that these fissures are of a recent tectonic system, which is probably generated by anthropogenic influences. These fissures, probably tensional, roughly follow natural tectonic direction. Those fissures are predominantly represented by rough, discontinuous or even pinnate fissures with a significantly higher frequency of occurrence (3-5 per meter). Some fissures are considerably wide open (1-5 cm) and fresh, usually without any clay coating (*e.g.*, Žůrek and Kořínek 2004).

Continuous measurement of opening (closing) of natural fissures (KD) in the rock mass started again in 2006. Distance inductive sensors were used at that time. However, the inductive sensors were destroyed due to overvoltage after a stroke of lightning during strong storms. These sensors were gradually replaced by sensors of strain gauge type. The range of measured distances is usually $\pm 5 \text{ mm}$. In order to evaluate results of the measurement, temperatures have to be measured in observed places, especially, if the distance sensors are in places where the air moves. It is possible to document the dependence of measured distances on the temperature using a long time sequence. The ventilation of underground spaces changed in May 2011 and it significantly influenced the shape and character of some curves, especially the KD4 curve (Fig. 2). Anomalous values at this curve represent electrical errors; shifts of segments are an effect of the DMN configuration changes.

Temperature corrected curves of measured distances document that significant movements on measured fissures do not exist. It is necessary to add that broken glass targets on two fissures have been detected in last three years. These targets were installed in very shallow workings (no more than 15 m below surface). There are often tree roots in these fissures.

Fig. 2. Curves of measured distances using strain gauge sensors (KD1, KD4) with measured temperature (KT3) for the selected period from 1 August 2010 – 1 March 2012.

Distance measurements in the mine are carried out using mechanical and laser distance sensors. Analyses of long-term data from laser sensor showed some interesting results; this sensor measures a height of the chamber K2 (e.g., Kaláb *et al.* 2010, Telesca *et al.* 2011, Lyubushin *et al.* 2012).

4. CHANGES OF STRESS TENSOR

Several methods are used to monitor changes of stress tensor in the rock massif. The CCBO method (Compact Conical-ended Overcoring) that was developed by Sugawara and Obara (Nakamura *et al.* 1999) is one of those methods. Using this principle, a prototype of the CCBM (Compact Conical-ended Monitoring) for long-term monitoring has been developed and applied in the Jeroným Mine. The probe contains, among others, six pairs of measuring strain gauges and one compensation strain gauge inside the probe. The aim of monitoring was to verify the use of the CCBM probes in distributed measurement networks and to test both their reliability and long-term stability. Two probes were built and installed in two 3 m long horizontal boreholes. Obtained data are now being analysed to eliminate any structural defects of the CCBM prototype probes and to optimize their design for the use in distributed networks. While testing the optimum thermal compensation and the structural design of compensation strain gauge, there was found a significant effect of moisture content on the expansion of porous rocks and therefore on the measured values (Knejzlík *et al.* 2013).

The chart in Fig. 3 represents the data of the CCBM1 for the period from 16 November 2007 until the beginning of 2013. The initial period of meas-

Fig. 3. Curves of measured strain of the CCBM1 probe for the selected period from 16 November 2007 to 1 January 2013.

urement until 2009 was analysed and interpreted from the geomechanical viewpoint by Knejzlík *et al.* (2011).

The recorded data can be allocated to the period before and after July 2010. That month was a long period of exceptionally intense strokes of lightning during which the DMN was interrupted and the CCBM2 probe was damaged after the lightning the surface near the shaft of the Jeroným Mine. A stroke of lightning is an extraordinary risk for the probes (and other sensors as well) because the probes are installed at a shallow depth (mostly up to 30 m) in the rock with a relatively high specific resistance.

A rapid increase in the value of the compensation strain gauge TC in the CCBM1 probe was detected after repairing the DMN (end of July 2010). At the same time, there was an increase in values of the strain gauges signed as T6T and T6L outside the measurement range. Other values were stabilized to the original trends after approximately 1 month. The data since that time cannot be used for geomechanical interpretation, and may only be used to assess trends and unusual behaviour of each strain gauge. At the beginning of the year 2012, measured values of the other five gauges increased rapidly. However, these changes are not quick jumps; therefore, they are not attributed to the immediate failure of strain gauges. These changes may occur due to the corrosion of the gauge. Long-term positive trends of measured values could also be caused by diffusion of ions through a porous potting material of a probe body, and as a consequence emerging DC potentials.

It is possible to point out an interesting effect. Two significant seismic swarms from the Nový Kostel area occurred during a monitoring interval (about 30 km away from the Jeroným Mine). After both swarms (October

2008, August 2011), some significant changes of character (trends) of measured values on the CCBM1 probe were detected. But, no other changes on other sensors of the DMN were documented.

At present, long-term data from the CCBM probes (more than 5 years) cannot be used for the geomechanical interpretation of the rock massif state as mentioned above. However, firstly, the obtained knowledge has confirmed the possibility of including this type of instrumentation into a distributed system with telemetrically transferred data. Secondly, the measured data are not influenced by signals from the other sensors, and thirdly, this type of probe is possible to use for a long-term monitoring because the electronic system is fully functional (original probes were possible to use for short/time overcoring only). Using all these facts, a new design of the CCBM probe has been made (Knejzlík *et al.* 2013).

5. FLUCTUATIONS IN THE LEVEL OF MINE WATER TABLE

Measurements of the water table fluctuation in the mine are most frequently covered in papers about geomechanical observations in the Jeroným Mine (*e.g.*, Kaláb *et al.* 2008b, Lednická *et al.* 2012). Two locations for this measurement are situated in the upper part of the mine near the Jeroným shaft (signed as V1 and V2); one position is located in a narrow vertical shaft (V5); the two others are approximately on level of the drainage adit (V3 and V4) – see Fig. 4. This quarterly monitoring started in 2001. Strain-gauge sensors were used for continual hydrogeological monitoring of water table fluctuation at the location V2 in March 2006 (the location is now signed as KV2) and at the station V3 (KV3) in April 2006. Continuous monitoring at the V5 position (KV5) was realized later. The sampling time is again one hour.

Fig. 4. Cross-section of the Jeroným Mine with locations of mine water accumulations; K1, K2, and K3 – large chambers.

It is evident that water gets to the mine solely by seeping surface water as gravity water. The drainage of the mine is done via the reconstructed drainage adit. A part of mine workings below the drainage adit level of the Jeroným Mine as well as some small mine workings above this level are permanently flooded by accumulated mine water. In addition to known underground spaces, other spaces may exist in the massif that could be closed by caved areas already existing. Of course, these spaces may be also flooded.

Fluctuation is detected at the KV2 location situated at the bottom of chamber K1 at lower part of the mine. Measured changes range up to 1 m. Mine water fluctuation was compared with the amounts of daily precipitation. External temperature measurements on the surface were used as some additional information in spring when snow quickly melted. Data from the weather-station at Krásné-Údolí, which is located about 15 km away from the mine, were used. The following conclusion has been determined: Sudden and significant increase of mine water table is obviously related with marked changes of surface water amount (spates or snow-melt). Gradual and long-term fluctuation of mine water table does not exhibit any significant relation with daily precipitation amounts on the surface.

What is interesting about fluctuation on the level of mine water table has been measured at the KV3 location. The KV3 position is located on the drainage level and mine water flows out through the gallery and drainage adit out of underground spaces. This mine water is accumulated in a down part of the K3 chamber and on the unknown flooded lowermost level (the entrance to the flooded gallery is possible to see). The surface area of accumulated water is large (about 25 m²) and 7 m deep minimally (but there is a rock cone at the bottom). The KV3 is about 50 m below the surface.

This accumulated water has a permanent overflow, as it is mentioned above. A few of separate periods represent anomalies during which more or less significant decreases occur (Fig. 5). The authors have published several papers about possible reasons of this phenomenon. It has been documented that the Jeroným Mine is a complex system of different underground spaces and also a complex system of an affluent of rain water and groundwater, spaces with accumulated mine water and also drain channels. It is necessary to add that so far there has not been any information about flooded spaces. Therefore, several hypotheses have been discussed. The following explanation is accepted as the most probable one: decreasing mine water table is in relation with decreasing underground water table in the surroundings of the mine, which might be derived from further hydrogeological wells (e.g., Gaždová *et al.* 2011).

The maximum decrease of mine water table occurred in 2003 and value almost 2.8 m were derived from quarterly observations. Subsequent decrease was monitored using the DMN in 2008, 2009, 2011, 2012, 2013, and 2014

Fig. 5. The fluctuation of mine water table at the KV3 location in 2001-2015; value of “0” represents an overflow to drainage adit.

with values of 1.7, 0.7, 0.2, 2.7, 0.3, and 0.9 m, respectively. The mine water table started decreasing in the second part of year (in late summer) and refill followed in the beginning of winter.

Using data from the DMN, it is possible to document that the decreasing and refilling periods have both almost smooth curves. Therefore, velocities of fluctuations have been calculated. For the KV3, three significant decreases, mentioned above, were used (2008, 2009, and 2011). The velocities of fluctuations were calculated using linear parts of monitored curves; values of decreasing water table of 0.021, 0.025, and 0.013 m.day⁻¹ were obtained and so were the values of refilling of 0.216, 0.049, and 0.051 m.day⁻¹. More detailed description of this analysis was presented by Lednická *et al.* (2012).

6. CONCLUSION

Underground spaces of the Jeroným Mine represent a very complicated structure. It is possible to say according to current measured data, using quarterly and continuous monitoring, that the whole historical underground space is stable as one system. It is a very important finding. Thanks to this fact, it is possible to continue the preparation of the opening the monument to the public. However, it is possible to derive from the obtained results that the values of some measured parameters are not quite stable so it is necessary to pay more attention to them.

Therefore, the installation of the distributed monitoring network at the Jeroným Mine has led to many applied and scientific benefits. In this contribution, long-term observations of three parameters have been presented.

Measurement of movements along fractures is a common method used to detect instability of the rock massif. The importance of this measurement will rise, especially when driving of new gallery (a plan for future) will be realized. On the other hand, using the CCBM probe for monitoring changes of stress tensor is a typical example of basic research. Obtained results will enable to design a new prototype of the CCBM probe that might be used for a long-term monitoring. A new interpretation methodology, changes of rock massif parameters (*e.g.*, moisture content and temperature) taken into account, are necessary to develop for detailed explanation of monitored data. The last presented long-term observation was a fluctuation of mine water table. The most important data have been measured near the accumulated water on the drainage level. The detailed analysis of these data also includes the evaluation of mine water table dynamics.

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