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VIBRATION EFFECTS IN THE MEDIEVAL JERONÝM MINE

VIBRAČNÍ PROJEVY V HISTORICKÉM DOLE JERONÝM

Abstract

The article describes a method employed to evaluate seismic load, using the medieval Jeroným Mine as an example. The evaluation is based on experimental measurements taken by seismic instrumentation located in underground workings. The records can be divided into the following groups: natural seismicity (micro-earthquakes in West Bohemia and manifestations of distant strong earthquakes); and technical seismicity (blasting work during the renovation of the mine's drainage adit and in quarries in the vicinity, traffic on the road above the mine).

Keywords

Earthquake, Kraslice Region, technical seismicity, seismic load, medieval Jeroným Mine.

Abstrakt

Příspěvek popisuje hodnocení seizmického zatížení na příkladu historického Dolu Jeroným. K tomu je využito experimentálního měření seizmickou aparaturou umístěnou v podzemí. Záznamy naměřené touto stanicí lze rozdělit do následujících skupin: přirozená seizmicita (mikrozemětřesení ze západních Čech a části vzdálených intenzivních zemětřesení) a technická seizmicita (trhací práce realizované při rekonstrukci dědičné štoly a v blízkých okolních lomech, doprava na silnici nad důlním dílem).

Klíčová slova

Zemětřesení, Kraslicko, technická seizmicita, seizmické zatížení, historický Důl Jeroným.

1 INTRODUCTION

The medieval Jeroným Mine in Čistá is a very important piece of evidence of medieval ore-mining operations. The book "1,000 Years of Ore Mining in the Slavkovský Forest (Kaiserwald) Mountains" (Beran et al., 1995) lists a number of mining sites, both relatively close to the mine and in its broader surroundings, but only the mine workings referred to above have been preserved till the present times. Examples of manual extraction operations, various types of stopes and pillars, extraction by fire and other relics illustrate how medieval miners used to work. Ore extraction operations in the "Old Mine Workings" part of the mine were terminated as early as during the medieval times; as to the "Abandoned Mine Workings" part of the mine; they were going on intermittently until the closure of the mine after World War Two. In 2008, the whole complex of the mine workings was declared a National Cultural Heritage Site. A fairly comprehensive collection of historical, geological and geomechanical information, including results of more than a decade of geomechanical monitoring performed on the site, can be found in various publications, e.g. Žůrek

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et al. (2008), or Tomíček (2010), as well as in a monothematic issue of the "Exploration Geophysics, Remote Sensing and Environment" journal (EGRSE No. 1/2011).

The medieval Jeroným Mine is now a complex system of adits, shafts and chambers situated at no less than three levels. Due to the mine's ventilated or unventilated atmosphere and the protracted action of both running and stagnant water found underground, "exposed" rocks have weathered. There are quite a few other negative factors affecting the rock mass and hence the stability of the mine workings; some parts of the mine are thus deemed unstable in the long run (according to Žůrek et al., 2001). One of the factors adversely affecting the rock massif may be represented by vibrations, either caused by earthquakes or man-made activities. The seismic monitoring of the mine working was launched in 2004, when the renovation of the drainage adit had begun. The tunnel-driving method employed in the drainage adit renovation project made use, inter alia, of blasting. The blasting was identified as a risk factor in the evaluation of the seismic load of the mine working (e.g. Kaláb, 2003).

In the Czech Republic, evaluations of seismic loads of buildings and structures are based on Eurocode 8 (natural seismicity) or the ČSN 73 0040 Standard (technical seismicity). There is a classification table dividing underground structures into Classes C to F, with Class C being represented by ceramic and stone tiles and pavement slabs in underground structures of subways or underpasses …, and Class D comprising brickwork, stonework and breeze block walling in underground structures. However, both standards deal with civil engineering structures only; insofar as atypical objects, such as underground mine workings, are concerned, the evaluation should be based on experimental measurements the results of which would be used to determine vibration limits for various damage levels. Acceptable values for a particular situation are determined by the engineering estimate, which is considered on the basis of the value from the standard reduced using multiple factor. This factor is based on the results of experimental measurements (e.g. from found structure damage, break of glass target . . .). This factor includes influences such as age of the object, the susceptibility of the reference element to resonance oscillations and others. The article uses the example of an old mine working the age of which exceeds 400 years to present various vibration sources and their underground manifestations.

2 SEISMIC RECORDING APPARATUS

The Institute of Geonics of the Czech Academy of Sciences developed a seismic recording apparatus designated PCM3-EPC3 with the IP64 ingress protection, which is necessary to be installed in underground with high humidity spaces (see, for example, Kaláb et al., 2006). The instrumentation set-up is conceptually based on the PCM3-EPC2 described by Knejzlík and Kaláb (2002); it is a three-channel digital recorder with an embedded recording PC. Triggered regime is used for the data recording; the current seismic signal amplitude has to exceed a preset trigger level. Every seismic event is recorded in a separate file. The time base of apparatus is synchronized using the DCF time normal signal.

Remote access to the PC built into the seismic recorder apparatus via a serial port and a suitable modem is provided by Symantec's pcAnywhere software. The seismic station located in the Jeroným Mine makes use of a Siemens TC35 Terminal GSM modem. The remote access to the PC provides for flexible checks of the apparatus functionality and status manner, which is always a problem with far measurement sites, as well as for telemetric transmissions of recorded seismic data (with the addition of a distributed system in 2006, the system is also capable of transmitting files containing geomechanical data – see, for example, Knejzlík, 2006, Knejzlík and Rambouský, 2008).

The design of the seismic apparatus the maximum possible use of CMOS components was used to minimize the power consumption and to maximize the operating life of the back-up battery. Similarly, the PC used in the unit is the very simple, single-board PCM3864 model by Advantech. Its hard disk is a 512 MB Compact Flash card. This arrangement helped achieve very favourable power consumption, around 20 W, with a reduced heat in covered apparatus.

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Reliable operation of a remote seismic recording apparatus requires a sufficient capacity for stored data, the longest possible operating life of the back-up source and, above all, an automatic restart when the power supply is restored after the back-up power source has gone completely flat, or when the control programme stopped. Protection against adverse effects of atmospheric electricity is equally important. This is why the mains supply and all input and output connectors of the units have been equipped with transient over voltage protection circuitry, and the aerial lead of the GSM modem with a coaxial surge arrester.

The seismic recording apparatus PCM3-EPC3 installed in the mine was put into permanent operation in June 2004 (Fig. 1). The frequency limit of its seismic signal amplifiers is 60 Hz, the sampling frequency of the analog-to-digital conversion is set at 250 Hz. Measurement intervals can be set in binary degrees from 0.25 $mm.s^{-1}$ to 32 $mm.s^{-1}$, depending on the current situation. As a rule, the lowest interval is set to capture enough quantitative data even for the weakest seismic events. The interval is adjusted whenever an increased load of the site due to technical seismicity is expected, or after an occurrence of a seismic swarm in the nearby region of Kraslice.

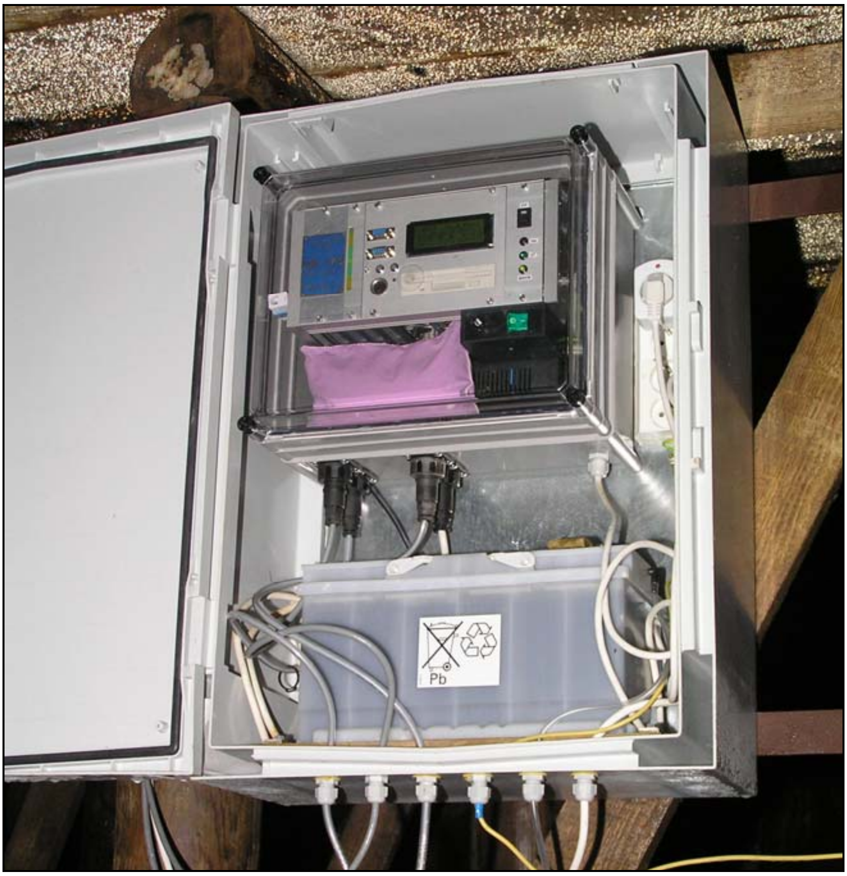

Fig. 1: The PCM3-EPC3 seismic recording apparatus with a back-up battery, installed in a double-walled waterproof case.

The apparatus is connected to three single-component seismometers SM3 in geographical order (three-component recording of wave pattern). Seismometers are anchored to a concrete pillar in one of the underground chambers about 30 m below the surface (Fig. 2). Additional autonomous seismic stations are used at the time of experimental measurements.

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Fig. 2: Seismometers SM3 are anchored to a concrete pillar.

3 SEISMIC ACTIVITY IN THE VICINITY OF THE JERONÝM MINE

When determining the seismic load of any site, it is necessary to consider all seismicity types, i.e. natural local and distant seismicity and technical seismicity (e.g. Kaláb, 2003). The nearest focal area of natural earthquakes is located approximately 30 NW of the Jeroným Mine; however, a few sporadic foci have been identified even closer. Young tectonic movements accompanied by volcanic activity influenced the geological setting of the region as early as in the Tertiary period. Relatively weak earthquakes can be detected in West Bohemia and Germany even now, the strongest of them being felt by local people or causing weak damages to buildings. The seismic hazard map of the Czech Republic (an annex to the Eurocode 8 National Application Document) shows the West Bohemian earthquake area can be expected to host earthquakes the macro-seismic intensity of which is between 6° and 6,5°. High-intensity European earthquakes have also been detected in the area under study. Most of these events can be traced down to Alpine seismic zones (Austria, Switzerland, Italy), and also to Slovenia and the Rhineland (Germany, the Netherlands). These earthquakes seem not to make a major contribution to the seismic load in the area under study, one of the reasons probably being the proximity of the Kraslice source area.

It is obvious the strongest vibrations can be expected to have their source in the nearby region of Kraslice. The strongest West Bohemian earthquake swarms that have so far been recorded by instruments occurred in 1908, with the strongest event achieving the magnitude of 5.0 (on the Richter scale value 5). The second half of the 20th century saw several recurrences of the seismic activity; relatively significant earthquake swarms that could be felt by local people occurred in the autumn of 1962, 1985 – 1986 winter periods, 1997, 2000 and 2008. The strongest earthquake on December 21, 1985, read 4.6 on the Richter scale. The strongest earthquakes caused damage to buildings and panic among the population (please refer to www.ig.cas.cz; Horálek et al., 2009, Fischer et. al., 2010).

Several manifestations of seismic activity in the region of Kraslice have been recorded during the Jeroným Mine seismic monitoring project. The strongest of them was caused by the earthquake produced by the seismic swarm that occurred in 2008. The current seismic swarm (autumn 2011) is probably coming to an end now.

3.1 The 2008 Seismic Swarm

In 2008, the recording apparatus installed in the mine took a total of 722 records in the triggered regime (according to Kaláb et al., 2011). Until October 6, 2008, the seismic load had been relatively low, but the situation significantly changed after the occurrence of the swarm. The swarm's epicentres were situated near the village of Nový Kostel, at a depth of about 10 kilometres (for details see www.ig.cas.cz). The earthquake swarm resulted in a significant increase of the number of recorded seismic events and of the seismic load of the mine working. As the maximum velocity

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amplitude of the strongest earthquake of October 9, 2008, exceeded the maximum limit of the current measurement interval (i.e. 0.25 mm.s^{-1}), the measurement range was increased to 0.5 mm.s^{-1}. Than, the strongest earthquake, the local magnitude of which was 3.9, occurred on October 12, at 9:44 CET, and was felt even by people living far from the epicentre, e.g. in the western part of Prague. Another major earthquake with the same magnitude of 3.9 was recorded on October 14, at 21:01 CET, and yet another, whose magnitude was 3.7, on October 28, at 9:30 CET. In addition, several dozens of events with local magnitudes exceeding 2.0 could be felt in the epicentre area. The seismic swarm was the highest-intensity earthquake event in West Bohemia since 2000.

Throughout the duration of the 2008 swarm, the seismic apparatus installed in the Jeroným Mine recorded a total of 451 earthquakes. The most intensive earthquake produced by the abovementioned swarm was recorded on October 14, at 21:00 CET (e.g. Kaláb et al., 2011), with its vibration component velocity reaching 0.435 mm.s^{-1} (maximum acceleration – 43.7 mm.s^{-2}); the approximate duration of the intensive vibrations was 5 seconds. The maximum values were observed over a short period of time in the S-wave group. Visual inspections of accessible parts of the mine, conducted as part of quarterly geomechanical measurements in the autumn of 2008 and in the spring of 2009, did not identify any damage caused by the vibrations produced by the seismic swarm referred to above (flaking-off, fissure opening, pillar cracking …).

3.2 The 2011 Seismic Swarm

The latest significant seismic activity appeared on August 23, 2011, in the area of Nový Kostel, and the seismic swarm is now (September 15) probably about to end. The local Webnet network has so far recorded several thousands of earthquakes, often following each other very rapidly (www.ig.cas.cz). Fig. 3 shows an example of the chronological sequence of the events from the "live seismograph" website. The "live seismographs" show records of the vertical component of seismic vibrations taken by national network stations (Institute of Geophysics of the Czech Academy of Sciences). Blue and red lines alternate every 30 minutes to make the recording easier to find one's way in. The "live seismographs" use the global time (UTC).

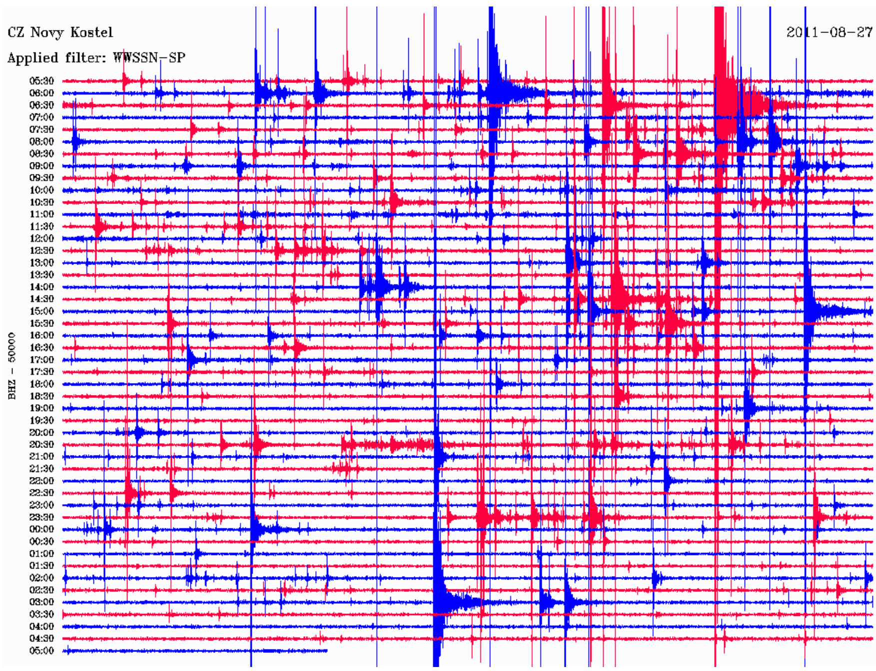

Fig. 3: An example of a recording of the vertical component at the Nový Kostel seismic station, August 27, 2011 (www.ig.cas.cz).

The seismic recording apparatus installed in the Jeroným Mine registered more than 800 events attributable to the above mentioned swarm. The maximum vibration component velocity was recorded on August 26, 2011, at 01:33 (magnitude equal to 3.5, www.ig.cas.cz); the vibration velocity measured in the mine did not exceed the maximum value recorded in 2008. Example of wave pattern of one of the strongest earthquake is presented on Fig. 4. Detailed information from measuring in Jeroným Mine will be published later.

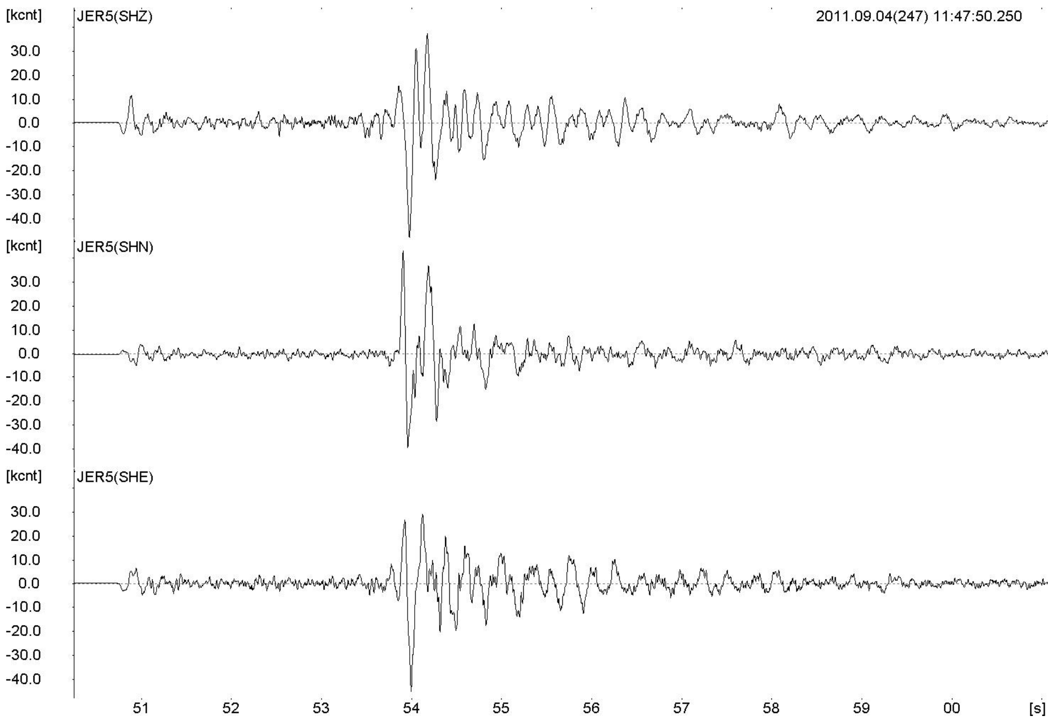

Fig. 4: Example of a wave pattern of one of the strongest earthquake recorded on the Jeroným Mine during the 2011 seismic swarm (local magnitude 3.3 according to www.ig.cas.cz); the maximum vibration velocity is 0.15 $mm.s^{-1}$ (in the figure at sampling units).

4 TECHNICAL SEISMICITY

Effects of technical seismicity recorded in the Jeroným Mine can be divided into the following categories: vibrations during the renovation of the mine working; vibrations caused by blasting in quarries in the vicinity of the mine; and vibrations attributable to traffic on the road above the mine. The vibration effect of these events is low and can in fact be neglected in the assessment of the seismic load of the historical mine workings (with the exceptions presented below). As a rule, the maximum vibration velocity values fall between 10^{-3} – 10^{-2} $mm.s^{-1}$, and do not have a significant impact on the stability of the mine (Kaláb et al., 2011).

Insofar as the seismic load is concerned, it will be necessary to carefully monitor the vibrations produced by renovation work in the mine and in its neighbourhood. These activities include, for example, an adit that will connect the two parts of the mine, which are separated at the moment. These vibrations, in particular those produced by blasting, may achieve relatively high levels. Between 2003 and 2006, the mine's drainage adit, which runs south of the historical parts in a length of about 500 meters, was renovated. Records of blasts during the renovation typically show a sharp onset, fast attenuation and high vibration frequencies (e.g. Kaláb and Knejzlík, 2004).

The highest recorded vibration velocity amplitude was 0.17 $mm.s^{-1}$ (the measurement took place on a seismic pillar mentioned above, not in the closest distance). If this value is compared to the amplitude of the highest-intensity earthquake of 2008, i.e. value 0.43 $mm.s^{-1}$, we can see the latter is approximately three times higher. However, one must bear in mind that these two seismic loads are not fully comparable, as the related vibrations are different, in particular insofar as their duration and frequency range are concerned; similarly, the distribution of the load produced by a close-proximity source also differs considerably.

Fairly significant vibrations are produced by vehicular traffic on the road above the part named Old Mine Workings. The passage of vehicles produces weak resonant vibrations (component values only up to 5.10^{-2} $mm.s^{-1}$). A description of experimental measurements of this effect can be found in an article by Kaláb et al. (2010). The cause and origin of these resonant vibrations have not been verified in a reliable manner yet; there are speculations they may be caused by hitherto undiscovered underground cavities. Surface geophysical survey has already indicated some of them (Beneš, 2011).

Several measurement using autonomous apparatuses were performed in the mine workings to determine values of vibration velocities generated by technology using in underground spaces. As is mentioned above, this was primarily blasting explosives during the reconstruction of drainage adit (e.g. Kaláb, Lednická, 2006). Furthermore, such measurements were realized also during drilling of holes for measurement of stress changes in the massif. With the exception of the effect of blasting no increased load of mine was detected. Observing of the movement of convergence and measurement of movement of blocks along cracks provided no information about this influence.

5 CONCLUSION

Seismic load must be also takes into account for assessment of the stability of the underground structure in question, i.e. medieval mine. An analysis of the seismic load of surroundings of the Jeroným Mine and its underground spaces was prepared prior to the commencement of the renovation of the drainage adit in 2003. The analysis showed that the mine working might be affected by higher-intensity earthquakes occurring in the Kraslice area, while generally technical seismicity levels would be very low. However, events induced by vibrations would have to be monitored during the renovation very carefully. These vibrations, in particular those produced by blasting, may achieve relatively high levels. The most significant segment of the seismic load of the site is represented by local earthquakes in the nearby focal region of Kraslice. The strongest earthquake recorded so far was produced by the seismic swarm in 2008 (vibrations component velocity value of 0.435 $mm.s^{-1}$).

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