Analysis of seismic events at the Velenje Coal mine

Analize seizmičnih dogodkov v območju Premogovnika Velenje

Milan Medved[1], Evgen Dervarič[2], Goran Vižintin[2], Jakob Likar[2], Janez Mayer[1]

[1]Premogovnik Velenje, d. d., Partizanska 78, 3320 Velenje; Slovenia;
E-mail: milan.medved@rlv.si, janez.mayer@rlv.si
[2]University of Ljubljana, Faculty of Natural Sciences and Engineering,
Aškerčeva 12, SI-1000 Ljubljana, Slovenia; E-mail: evgen.dervaric@ntf.uni-lj.si,
goran.vizintin@guest.arnes.si, jakob.likar@ntf.uni-lj.si

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Abstract: Complaints due to ground shaking and tremors were regularly addressed to the management of the Velenje Coal Mine. The micro-seismic monitoring system was set up on the surface in the nearby urban areas and also directly in the vicinity of mining activities. Results of these measurements were carefully analysed and openly presented to the public together with various safe vibration limit standards (national standards). The system for automatic publishing of measurements immediately after the event recorded was also set up. This resulted in a drastic reduction of complaints. Routine micro-seismic monitoring became part of the regular monitoring of mining activities as some patterns of seismic response to mass mining were revealed.

Izvleček: Na Premogovnik Velenje so se redno naslavljale pritožbe zaradi povečanega tresenja tal. Postavljen je bil mikroseizmični sistem za spremljanje tresljajev na površini, v bližnjih naseljih, pa tudi na odkopih. Rezultati meritev so bili detajlno analizirani in predstavljeni zainteresirani javnosti skupaj z raznimi standardi in predpisi za varno tresenje tal, ki veljajo v posameznih državah. Taki predpisi in standardi v slovenski regulativi ne obstajajo. Poleg tega je bil postavljen tudi sistem za avtomatsko zapisovanje podatkov o tresenju tal in objavljanje teh na spletnih straneh. Navedeno je imelo za posledico drastično zmanjšanje števila pritožb. Rutinske mikroseizmične nadzorne meritve tresenja tal so tako postale del obratovalnega nadzora, saj so se pokazala določena pravila pri seizmičnem odzivu okolne hribine na rudarska dela.

Key words: rockbursts, seismicity, coal mine, longwall mining, caving, Velenje, Slovenia, public response

Ključne besede: stebrni udar, seizmičnost, premogovnik, širokočelno odkopavanje, rušenje krovnine, odziv javnosti

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Introduction

The Velenje coal basin has very thick layer of lignite. Modern mining technology on big excavation plates assures viability of operation despite low combustion value. The main consumer is the nearby thermo power plant.

Mine tremors and even rockbursts follow the excavation, although the geological formation is soft. Seismic monitoring systems on the surface and in the mine gave us invaluable insight into the processes that took place at the excavation.

Geology of coal deposit

The lignite seam at the Velenje Coal Mine extends under almost the entire Šaleška Valley, its deposit being 8.3 km long and 2.5 km wide. The thickness of the coal ranges from 20 m to 160 m. The nearest coal is 60 m under the surface, in the seam, which is 10 m to 35 m thick. The greatest amount of the coal can be found at the depth of 290 m where the thickest seam has been confirmed. The coal layer is 100 m thick at the depth of 400 m. The north area of the coal seam inclines at the angle of 10° to 15°, and gradually becomes thinner in the depth from 100 m to 300 m, where in the south area it ends up abruptly at the depth of 150 m under the surface. The quality of the coal decreases from the hanging wall to the footwall of the seam. The lower calorific value for the coal seam still being exploited is down to 7.5 MJ/kg. The longitudinal section of the coal seam is shown in Figure 1.

River and lake alluvia consisting of sand and clay, whose thickness totals 460 m at the most, represent the hanging wall of the seam. Immediately above the coal seam

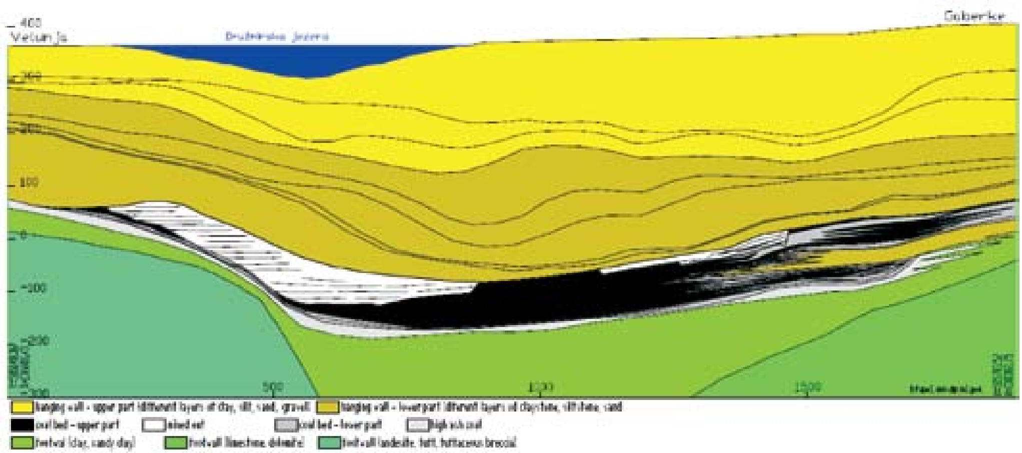


Figure 1. Longitudinal section of the coal seam (geomechanical interpretation)
Slika 1. Vzdolžni prerez skozi sloj premoga (geomehanski profil)

Table 1. Geomechanical properties of different layers
Tabela 1. Geomehanske lastnosti različnih slojev

	Density (kN/m^3)	Moisture content (%)	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Young modulus (MPa)	Poisson modulus (/)	Cohesion (MPa)	Friction angle (°)
Hanging wall – upper part	20.9	24.4	0.85	0.08	140	0.35	0.4	15
Hanging wall – lower part	19.2	32.6	2.5	0.23	430	0.2	0.7	17
Coal bed upper part	12.6	39	8.4	0.92	480	0.25	0.7	30
Coal bed – lower part	13.6	35	5.4	0.59	480	0.3	0.7	30
High ash coal	17.7	25.6	1.6	0.17	375	0.35	-	-
Footwall	23.6	10	4.9	0.44	2917	0.3	1.4	21.6

there are clay layers ranging from a few hundred meters to minimum of six meters. They prevent water inflow into haulages.
The footwall of the seam consists of clay and marl lying on triassic limestone and dolomites. In a hydrological sense, the depression is extremely water bearing, especially in the Pliocene area.
The coal seam, in whose hanging wall and footwall most roadways can be found, is tectonically not much cracked, and the fractures caused by sinking of the seam are mostly of local character.
The whole formation is soft with low values of geomechanical properties. Brittle failure of coal can be expected based on experiences with laboratory compressive strength tests. Geomechanical properties are collected[11] in Table 1.

MINING METHOD

The mining method used in Velenje Coal Mine is known as Velenje Mining Method and is unique in world mining technology. The basic principle of work on the faces was based on winning the lower and the upper excavation part of the face at the floor level height of 10–15 m.
The cracking of roof influences considerably further mining. The first floor level advances only with the lower excavation part, and crushes the hanging wall and the coal to the extent that efficient excavation from the upper area is made possible with the following floor level.
With the Velenje mining method the length of longwalls amounts from 80 m to 210 m and the length of panels varies from 600

m to 800 m. Maximum face inclination in the direction of advancing totals 15° and 7° inclined along the face.

Technological coal mining procedure is divided into:

- winning the lower excavation section of the coalface and
- winning the upper excavation section of the coalface.

The double-drum shearer excavates the coal in the lower section of the longwall face.

The coal in the upper section of the face is excavated by winning the coal through the gate in the shield, or over the canopy of the shield of the section.

Working cycle is completed when all the coal from the upper excavation part is extracted. The coal from the upper excavation part is mined systematically after a certain number of cuttings in the lower part. The number of cuttings in the cycle depends on:

- working height,
- coal face length,
- slope and inclination of the face,
- number of sectors in the upper excavation section along the face and
- degree of coal crushing in the upper excavation section of the coalface.

The sequence of working phases is changed with regard to what was stated above. They can also be carried out simultaneously, in case of favorable conditions.

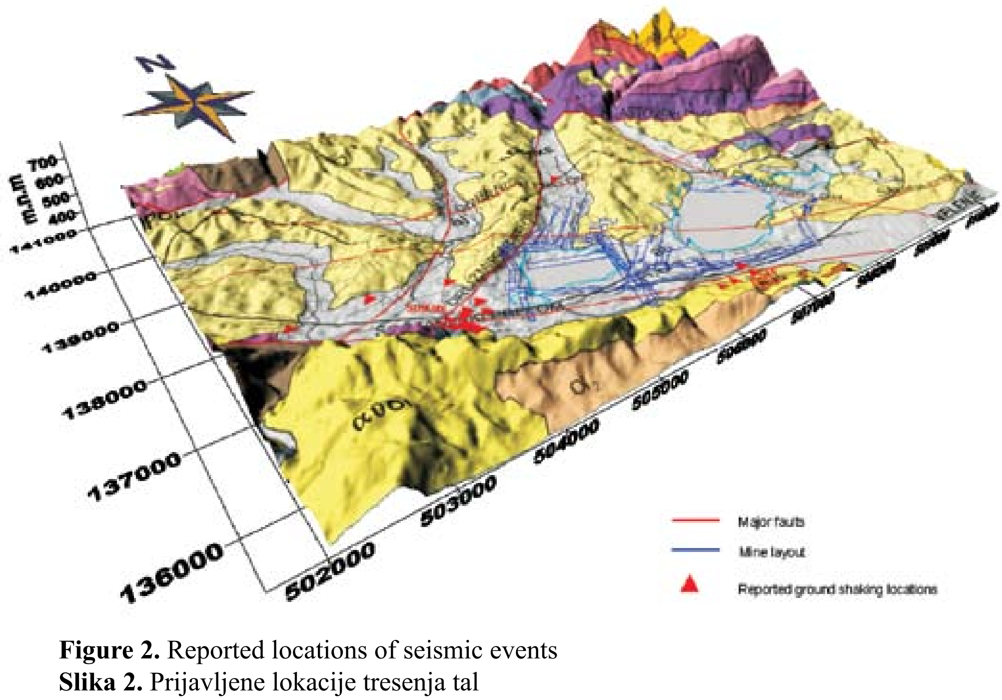


Figure 2. Reported locations of seismic events
Slika 2. Prijavljene lokacije tresenja tal

Tremors and mining

Tremors regulary accompany longwall mining. They are felt by local inhabitants of the nearby town of Šoštanj and village Pesje which is only few hundred meters away measured in horizontal distance from longwall faces (Figure 2). Most of the tremors that were felt by local inhabitants were not observed in the mine and also did not cause any damage to the mine infrastructure. But the local community has organized and started strong media campaign against the mine authorities, which was from time to time very disagreeable. Regularly new minor superficial cracks were reported to the mine and damage compensation was claimed. After careful examination of reported damages it was found out that cracks were not to ascribe to tremors and were rather ascribed to other causes like uneven settlements of foundation, changes in humidity and constructional reasons.

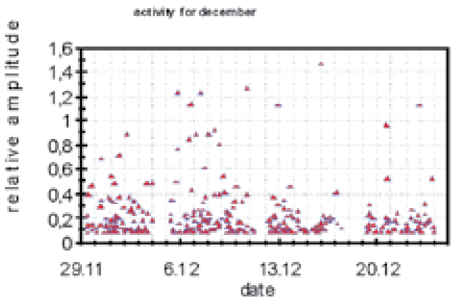
It was very difficult to explain to local inhabitants that these cracks were not caused by mining. The approach to the problem was very systematical. First we started to collect public response on a toll free phone line, where every caller was asked to report the location of event felt and the description of event. Then all locations were summarized and plotted on a map with relation to the mine layout. In the centre of the areas with greater density of complaints – in area of Šoštanj and Pesje - ground vibration monitors were installed. The system is trigger based. The trigger is set to 0.1mm/s which is about 5 times less than the human sensitivity to ground vibrations. This means that we make sure that we do not miss an event which can be felt by local inhabitants.

Results of micro seismic monitoring

The results of measurements soon revealed that at most seismic active days three to five seismic events were recorded with maximum peak particle velocities from 2–3 mm/s at frequencies of 7–10 Hz. Typically recorded values were from 0.7 mm/s to 1.1 mm/s at same frequencies. So most of the tremors were weak which could not cause any damage to the buildings.

When the results were presented to the public, lot of skepticism and disbelief among local inhabitants was present. Up to date measurements were collected for period of more than one year and sent to independent and internationally acknowledged blasting techniques and vibration expert. In his "Experts opinion" it was officially confirmed, that damage due to vibration in terms of a reduction in utility values is unlikely to have occurred. The vibrations at recorded levels were not able to damage buildings in a causal manner according to standard DIN 4150[2]. However already existing damages could change. If damages are found, it is to be assumed that other causes are responsible for this damage.

We openly presented the conclusions from "Experts opinion" and analyzed measurements to the public. In the meantime we also set up a system for automatic measurements and publishing of results on company's web pages – which was the most convincing proof that we are ready to assist local inhabitants with information. In the first months we received lots of calls immediately after the tremor from people asking where the results of measurements could be seen. So instead of complaint calls we are now receiving calls from people who



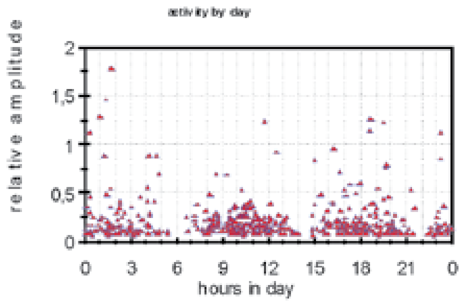


Figure 3. Activity for December 2004 (a) and its display by hours in day (b)
Slika 3. Aktivnost decembra 2004 (a) in prikaz po urah (b)

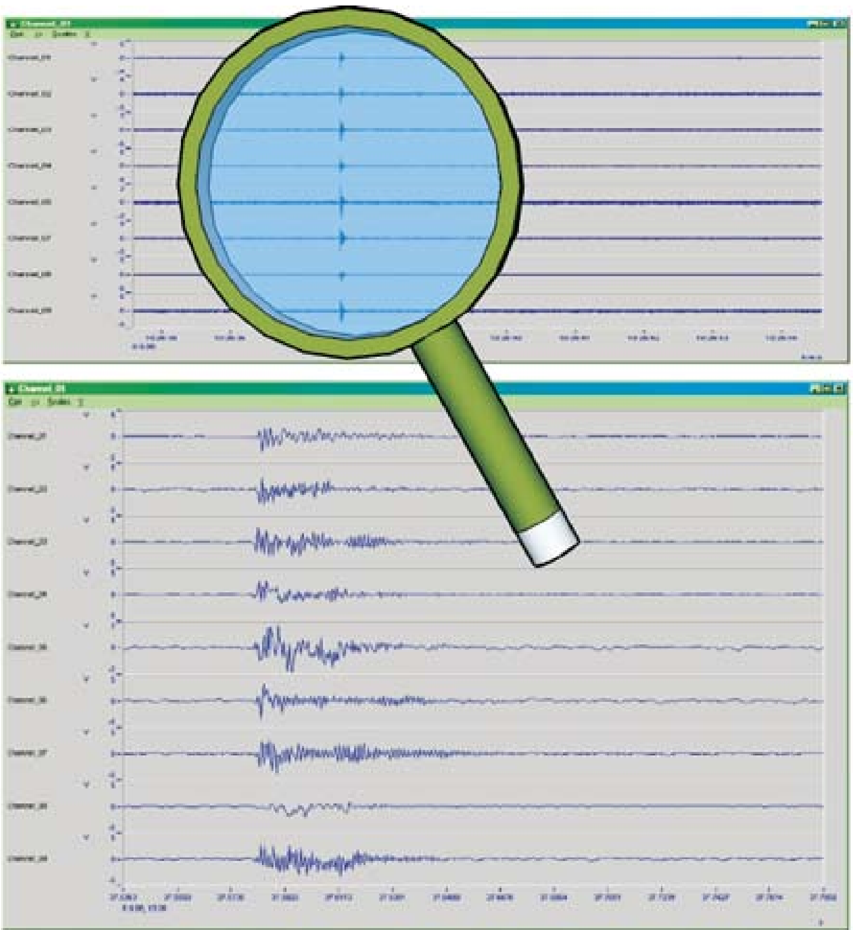


Figure 4. An example of the accelerogram recorded by the in-mine system. Time is in seconds, amplitude in Volts.
Slika 4. Akcelerogram, zapisan z jamskim mikroseizmičnim sistemom. Čas je v sekundah in amplituda v voltih.

are interested in things like "What are safe vibration limits", "What are mm/s", "What other can cause cracks in my house". To answer these and other questions we have supplemented web pages with answers to these frequently asked questions. These measures resulted in a drastic reduction of complaints.

CHARACTERISATION OF EVENTS

Seismic monitoring system on the surface and in the mine gave us invaluable insight into the processes that took place.

Figure 3 displays seismic activity for December 2004 by days and by hour in day. Stronger events occur in the beginning of week and are connected with the cracking of the console in the hanging wall that is built for the weekend. With the constant and not too fast progress of longwall the level of activity decreases and the number of events increases. The accumulated energy is released in smaller amounts[1]. We can see the decrease of activity in the time of shifts in Figure 3b (6, 14 and 22 o'clock). Relative amplitude shown on figure 3 was used to calculate energy of seismic events by considering distance and depth difference from seismic event to seismic station.

Caving is the most critical process at coal extraction. There have been studies of the caving processes associated with the longwall mining, for example HATHERLY et al[3]. Accurate location of the mine tremors is possible only with the use of in-mine seismic system. We have deployed also a mine wide seismic system consisting of accelerometers and signal transmission to the surface[10]. An example of accelerogram is displayed in Figure 4.

Values are measured in Volts and a factor of sensitivity $1/G = 9.684$ m/(V s^2) should be used to convert values to ground vibration accelerations. The locations of events are usually above the level of excavation[10]. The process of caving is taking place in that area. High stresses fracture the coal. The process can be improved by destress blasting or preconditioning (TOPER et al [4]).

ANALYSIS OF FOCAL MECHANISM

Even if the shaking tremors were now better described, some uncertainty still remains. Especially the question, if all big events are originated because of mine works, or their natural origin still remains unsolved. For these purposes the analysis was widened and also the national seismological station was used for analyzing the tremors (Figure 5). The question has its reasons in facts that some stronger tremors were also registered on the Slovenian seismological stations and some were not. Another reason was that only for the national seismological stations sensors orientations data are provided well enough for the first motion analysis. Because of these reasons, the selection of events registered on mine and Slovenian seismological observations network was needed. In fact there were just few events which we were able to prove that their origin was in the area of mining works. For better understanding of governing mechanism we decided for an analysis of a fault plane solution. A fault plane solution (or focal-mechanism solution) is a method to identify the type of an earthquake (COX[8], 1986). The fault plane solution is constructed from the detected signals of different stations and

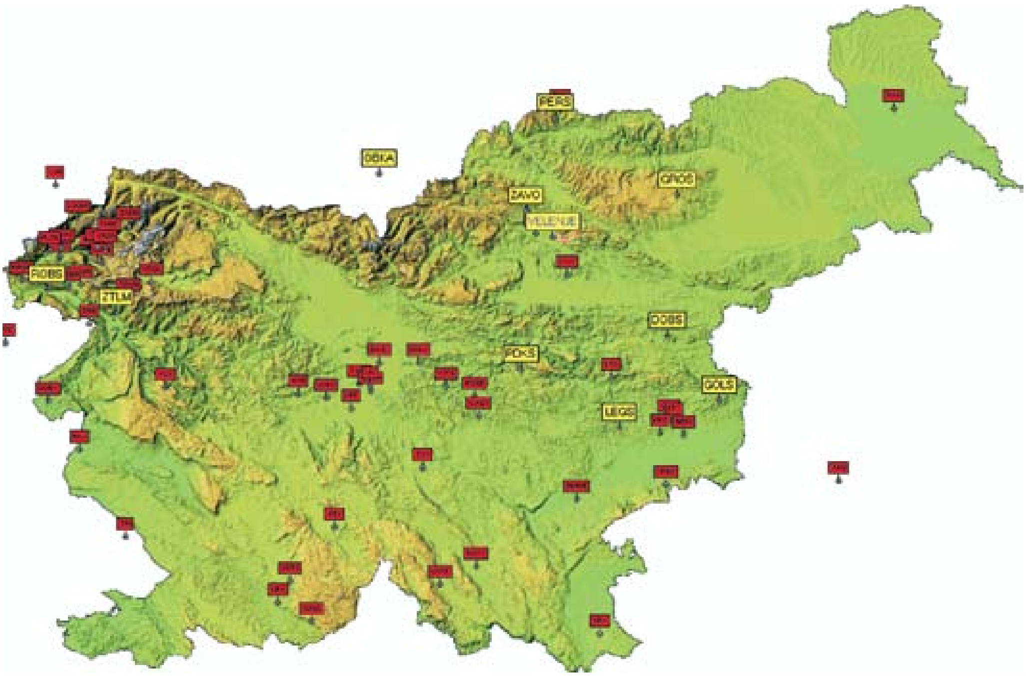


Figure 5. Seismological stations used for the analysis of focal mechanisms. Yellow stations had enough good signals for making the analysis.
Slika 5. Seizmološke opazovalnice, uporabljene za analizo žariščnega mehanizma. Rumeno označene opazovalnice so dale dovolj dober signal za analizo.

gives insight into the type or the source of the earthquake (normal fault, thrust fault or strike slip). To accomplish a fault plane solution, the azimuth as well as the angle of incidence and the type of the first wave (compression or dilatation), which reaches the detecting station, is necessary. The lower hemisphere projection of data is used in the way that the azimuth is taken as an angle and the angle of incidence is taken as the length of a line. At the end of the line a mark is placed depending on the type of the wave.

Our aim was to identify, if the events observed on the mine and national observations nets have manly their origin in normal fault movements or there are also components of thrust fault movements. If they would have their origin in thrust fault movements their origin would be unlikely due to the mining works. The events were first compared on the basis of their frequency and calculated seismic moments. Seismic moment is a quantity used to measure the size of an earthquake (Aki[9], 1966). The seismic moment of an earthquake is typically estimated using whatever information is available to constrain its factors. For earthquakes, moment is usually estimated from ground motion recordings of earthquakes (Westway[5], 1992). In 1970 Brune[6] set up this relation of dislocation along the fault:

$$u = (\sigma / G)\beta \cdot t'' \quad (1)$$

Where
σ - effective stress (difference in effective stress on a fault before and after dislocation)
G - shear modulus
β - velocity of shear waves
R - distance between the hypocenter and seismological station
r - fault plane distance
t'' - t-R/β
$f = (S/0.8)^{1/2}$ where S is a conversion factor of shear waves in compression waves

Using a Fourier transformation on the equation (1) a equation (2) can be found (STANKOVIĆ[7], 1988):

$$u(\omega) = R_{\Theta\phi} f (r/R)(\sigma\beta/G)(\omega^2 + \alpha^2)^{-1/2} \quad (2)$$

The equation (2) is describing amplitude spectra of dislocation on the free distance from the fault plane. In the equation (2) a factor ($R_{\Theta,\varphi}$) is defining a seismic waves we are observing. The α and f are very well known factors, usually $f = 1$ when $S = 0.8$ and $\alpha = 2.21\ \beta/r$. If we are calculating the specter of dislocation movement along fault using the equation (2) and putting the calculated values on abscise composed of log(ω) and ordinate of log(u (ω)) we are getting the diagram presented on the figure 6.

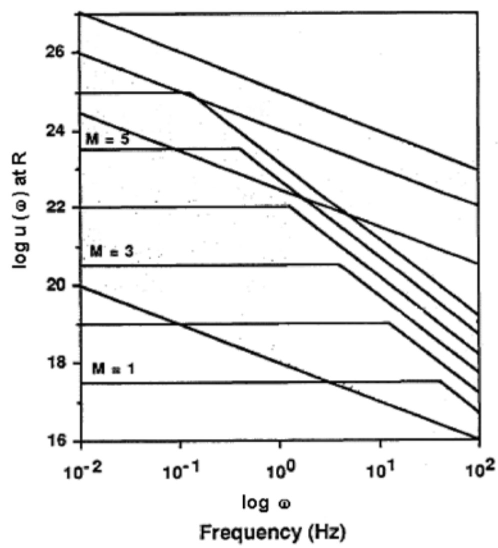


Figure 6. Displacement spectra (BRUNE[6] 1970)
Slika 6. Spekter po Bruneju

Looking at the equation (2) and taking in consideration well known expressions for seismic moment $M_o = (18/7)\sigma r^3$ and $\sigma^2 = (14\pi/9)\ (\beta/r)^2$ (BRUNE[6], 1970) and sending ω to 0 we can get the following equation:

$$u(\omega) = R_{\Theta\phi} M_o \eta (4\pi\rho\beta^3)^{-1} \quad (3)$$

From the equation (3) we can see that the seismic moment is depending on the spectrum of dislocation at low frequencies. This implicit that the using the low spectrum frequencies we are able to compare the events registered on the mining seismological nets with those on the Slovenian seismological net.

On the basis of theory shown before, only few events could be identified on both observation networks. The uncertainty was even greater if we looked at the first arrivals on the seismological stations. So at the end only four events had data good enough (ŽIVEC[12], 2005) for first motions analysis (Figure 7).

It seems that in the four analyzed events the normal movements are present in the governing mechanisms of the tremors. This can be associated with the dilatations occurring due to the excavations of coal seam. Because of data uncertainty we can not for sure associate all big events with the mining works but on the basis of first analysis as some indications are strong

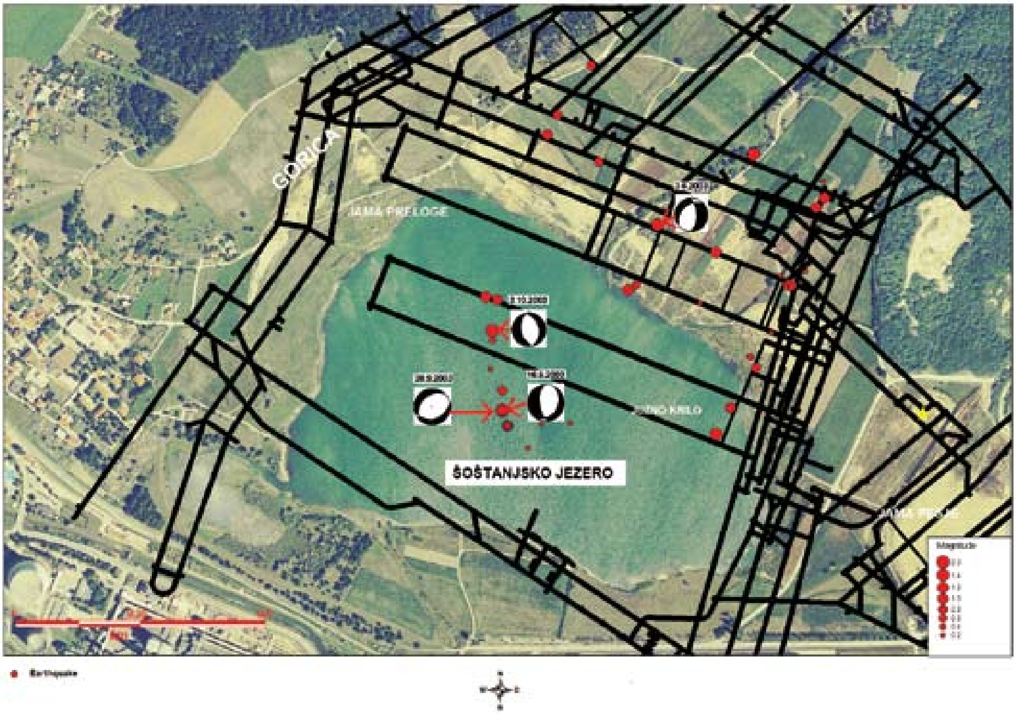


Figure 7. Focal mechanisms of four events which were good enough for the first motion analysis
Slika 7. Žariščni mehanizem štirih dogodkov, katerih signal je bil dovolj dober za analizo prvih premikov

enough that further work in this direction will be done.

Conclusions

Mine wide seismic monitoring system became essential part of mining surveillance monitoring systems especially for mines operating near urban areas. It serves with data about time and intensity of recorded seismic events at the locations where most of complaints are coming from.

The surface station in the nearest village Pesje and town of Šoštanj convinced us that the mine tremors don't cause damage to the buildings, as they are much smaller then allowed values according to the DIN 4150 standard. Independent experts opinion confirmed that statement on the basis of measurements for a period of more than one year. A first motions analysis was also made with the aim of better knowing of tremors governing mechanism. It seems that some big events had also the origin in the mining works rather than in the natural geological events.

We openly presented the conclusions and made the results of on-line measurements available to the public. So instead of complaining calls we are now receiving calls from people who are interested in things like "What are safe vibration limits", "What are mm/s", "What other can cause cracks in my house". These measures resulted in a drastic reduction of complaints.

Seismic monitoring helped us to gain back information about the processes in the mine and to get response of the coal formation to the mass mining. The response is immediate and therefore it is controllable. It was also found out, that some parts of the longwall face responded to mining with lower intensity of seismic events than other. This phenomena is especially noticeable at the start of the longwall excavation.

With time the database of measurements is increasing and also the knowledge base in that area, so it is very important to keep uninterrupted seismic monitoring of mining operations also in the future.

Povzetek

Na Premogovnik Velenje so se v preteklosti redno naslavljale pritožbe zaradi povečanega tresenja tal. Način reševanja problematike je bil večplasten in sistematičen. Postavljena je bila merilna oprema za spremljanje dogodkov na površini, v bližnjih naseljih, pa tudi na odkopih. Rezultati meritev so pokazali, da se dogodki dogajajo v materialu, ki ima v geomehanskem smislu precej šibke karakteristike in ga je težko vzročno povezati z nastajanjem dogodkov. V premogu, ki je najtrši, nastane le manjši del seizmičnih dogodkov. Meritve so obsegale tudi spremljavo intenzitete vibracij tal na površini, ne glede na to, od kod prihajajo. Za vse dogodke brez izjeme je bilo ugotovljeno, da s svojo intenziteto ne morejo povzročiti škode na gradbenih objektih, saj so prešibki in so v okviru najstrožjih tujih standardov. Domačih standardov, ki bi na nivoju današnjega stanja tehnike obravnavali problematiko vpliva vibracij tal na površinske objekte, nimamo, zato smo uporabili nemški standard DIN 4150, ki je najstrožji. Rezultate meritev v daljšem obdobju je ovrednotil tudi ekspert s področja vibracij tal, ki je potrdil pravilnost postopkov in rezultatov. Rezultati meritev so vedno na vpogled okoliški javnosti, ki jih ti dogodki motijo, skupaj z razlago, ki pojasnjuje postopke in rezultate meritev na za javnost sprejemljivem nivoju. Pojasnjena je bila tudi osnovna dilema, ki povzroča skrb zaradi tresenja tal, namreč da je človeška občutljivost za vibracije več desekrat nižja od tiste, ki v najneugodnejših razmerah lahko povzroči majhne razpoke na objektih.

Navedeno je imelo za posledico drastično zmanjšanje števila pritožb glede tresenja tal, saj je vsak dogodek izmerjen in tudi zapisan. Ni se še namreč zgodilo, da bi se kdo pritožil zaradi tresenja tal, ki ne bi bilo tudi izmerjeno.

Nekateri od teh dogodkov so zapisani tudi na več postajah državne mreže potresnih opazovalnic, kar je omogočilo tudi bolj poglobljeno analizo mehanizma izvora dogodka. Ugotovljen je bil dilatacijski mehanizem nastanka seizmičnih dogodkov. Seizmičnost je spremljana tudi z jamskim sistemom. Primerjava podatkov s površine in tistih iz jame je pokazala le delno skladanje dogodkov, kajti veliko več dogodkov se zgodi na površini, v jami pa sploh niso ugotovljeni oziroma so pod pragom zaznavanja inštrumentov. Po drugi strani pa lahko z jamskim sistemom ugotovimo direkten odziv na pridobivalna dela, kar nam daje možnost spremljanja odziva hribine na rudarska dela. To je sedaj postalo pomemben del obratovalnega nadzora, saj nam meritve dajejo vpogled v intenzivnost odziva hribine in na dogajanje na površini.

References

[1] Brown, E. T. (1984): Rockbursts. Prediction and Control, *Tunnels and Tunneling*, pp. 17–19.

[2] DIN 4150 Teil 1 bis Teil 3-Erschutterungen im Bauwesen, DIN Deutsches Institut fur Normung, Berlin (Germany), 1993.

[3] Hatherly, P., Luo, X., Dixon, R. & McKavanagh, B. (1997): Seismic monitoring of ground caving processes associated with longwall mining of coal. *Rockbursts and seismicity in mines*, Rotterdam, pp. 121–124.

[4] Toper, A. Z., Grodner, M., Stewart, R., D. & Lightfoot, N. (1997): Preconditioning a rockburst control technique. *Rockbursts and seismicity in mines*, pp. 267–272.

[5] Westway, R. (1992): Seismic Moment Summation for historical Earthquakes in Italy. Tectonic implications, J. Geophys. Res. 97, Washington, pp. 15437–15464.

[6] Brune, J. (1970): Tectonic stress and the Spectra of Seismic Shear Waves from Earthquakes. J. Geophys. Res. 75, Washington, pp. 4997–5009.

[7] Stanković, R. S., Stojić, M. R., Bogdanović, S. M. (1988): Fourier transformations of seismic signals. *Naučna knjiga Beograd*, 142 p.

[8] Cox, A. & Hart, R. (1986): *Plate Tectonics – How it works?* Blackwell, Oxford, 392 pp.

[9] Aki, K. (1966): Generation and propagation of G waves from the Niigata earthquake of June 16, 1964, Part 2 Estimation of earthquake moment, released energy, and stress-strain drop from the G wave spectrum. Bull. Earthq. Res. Inst. 44, pp. 73–88.

[10] Mayer, J. et al. (2002): Spremljanje rudarsko induciranih seizmičnih pojavov v Premogovniku Velenje. *RMZ* 49/1, pp. 51–60.

[11] Žorž, Z. et al., (1984) : Geomehanski model intaktne premoške kadunje Rudnika lignita Velenje, *GZL*, Ljubljana pp. 15–18.

[12] Živec, T. (2005): Analiza potresne dejavnosti na območju premogovnika Velenje, diplomsko delo, Ljubljana, 69 p.