
MONITORING AND ANALYSES OF SEISMIC EVENTS AT THE VELENJE COAL MINE

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abstract

Complaints about ground shaking and tremors were regularly addressed to the management of the Velenje Coal Mine. A micro-seismic monitoring system was set up on the surface in nearby urban areas and also directly in the vicinity of the mining activities. The results of these measurements were carefully analysed and presented to the public together with various safe-vibration-limit standards (in this case national standards). A system for automatically publishing measurements immediately after the event is recorded was also set up. This resulted in a dramatic reduction in the number 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.

keywords

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

1 INTRODUCTION

The Velenje coal basin has a very thick layer of lignite. Modern mining technology on large excavation plates ensures the viability of the operation, despite the 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 an invaluable insight into the processes that took place during the excavation.

2 GEOLOGY OF THE 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 to 160 m. The nearest coal is 60 m under the surface, in a seam that is 10 – 35-m thick. The largest amount of coal can be found at a depth of 290 m, where the thickest seam has been confirmed. The coal layer is 100-m thick at a depth of 400 m. The north area of the coal seam inclines at an angle of 10 – 15°, and gradually becomes thinner at a depth from 100 to 300 m, where in the south area it ends abruptly at a 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 of 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.

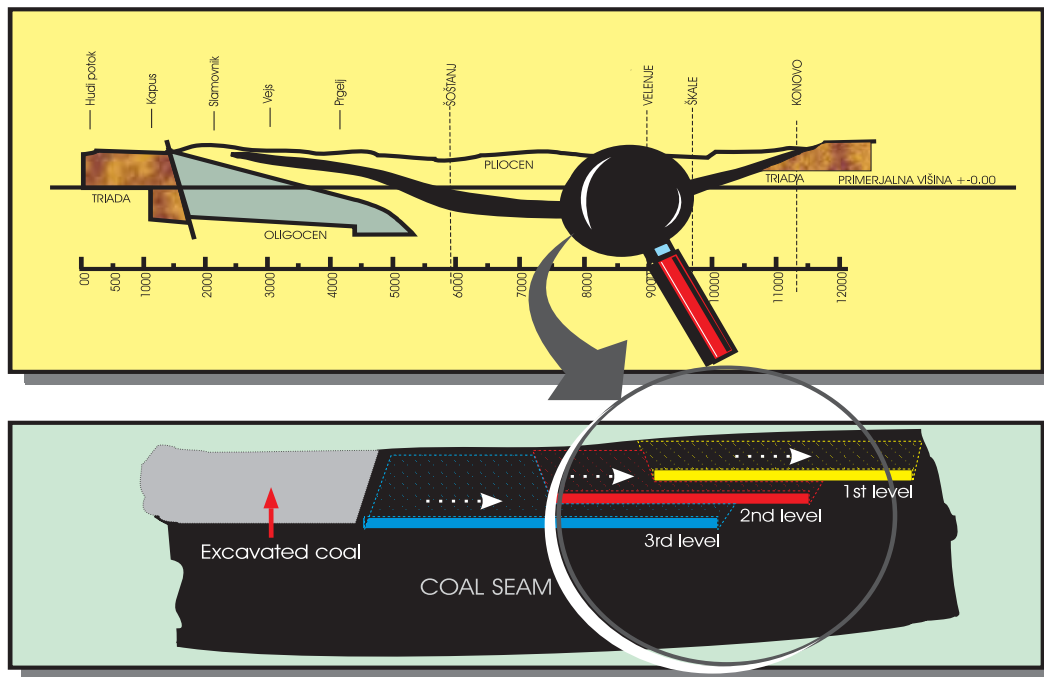


Figure 1. Longitudinal section of the coal seam and the sequence of extraction.

The river and lake alluvia consisting of sand and clay, whose thickness totals no more than 460 m, represent the hanging wall of the seam. Immediately above the coal seam there are clay layers, ranging from a few hundred meters to a minimum of six meters. They prevent water inflow into the haulages.

The footwall of the seam consists of clay and marl lying on triassic limestone and dolomites. In the 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 little cracked, and the fractures caused by the sinking of the seam are mostly of a local character.

The whole formation is soft with low values of the geomechanical properties. Brittle failure of the coal can be expected, based on experiences with laboratory compressive-strength tests. The geomechanical properties are collected in Table 1.

3 MINING METHOD

The mining method used in the Velenje Coal Mine is known as the Velenje Mining Method and is unique in world mining technology. The basic principle of the

work on the faces was based on winning the lower and the upper excavation part of the face at a floor-level height of 10 – 15m.

The cracking of the roof influences considerably any 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 the longwalls amounts to 80 – 160 m and the length of the panels varies from 600m to 800m. The maximum face inclination in the direction of the advancing totals 15 degrees, and 7 degrees inclined along the face.

The technological coal-mining procedure is divided into:

- winning the lower excavation section of the coalface,
- 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.

The working cycle is completed when all the coal from the upper excavation part is extracted. The coal from

Table 1. Geomechanical properties of the different layers.

	Density (kN/m ³)	Moisture content (%)	Uniaxial compressive strength (Mpa)	Tensile strength (Mpa)	Elasticity modulus (Mpa)	Poisson modulus (I)	Cohesion (Mpa)	Friction Angle ϕ , (°)
Hanging wall - upper part	20.9	24.4	0.85	0.08	140	0.35	0.4	15.0
Hanging wall - lower part	19.2	32.6	2.50	0.23	430	0.20	0.7	17.0
Coal bed - upper part	12.6	39	8.40	0.92	480	0.25	0.7	30.0
Coal bed - lower part	13.6	35	5.4	0.59	480	0.30	0.7	30.0
High ash coal	17.7	25.6	1.6	0.17	375	0.35	-	-
Footwall	23.6	10.0	4.9	0.44	2917	0.30	1.4	21.6

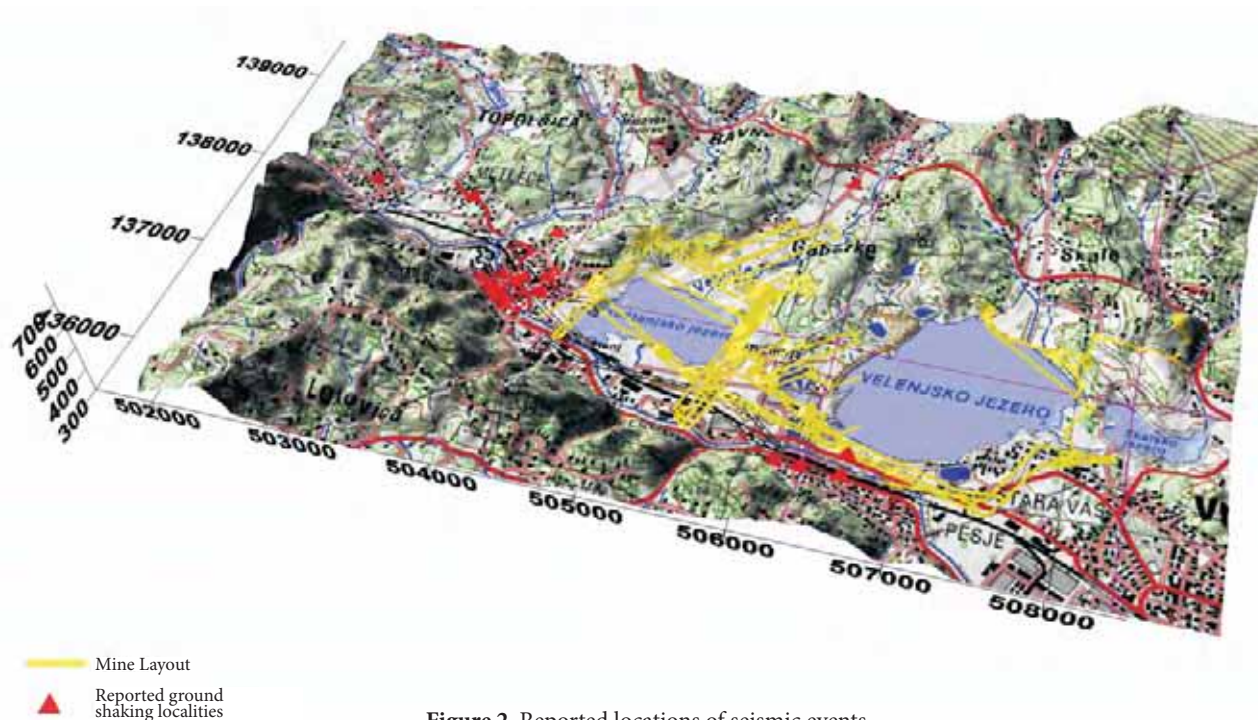
the upper excavation part is mined systematically after a certain number of cuttings in the lower part. The number of cuttings in the cycle depends on:

- the working height,
- the coal-face length,
- the slope and inclination of the face,
- the number of sectors in the upper excavation section along the face,
- the 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 event of favourable conditions.

4 TREMORS AND MINING

Tremors regularly accompany longwall mining. They are felt by local inhabitants of the nearby town of Šoštanj and the village of Pesje, which is only a few hundred metres away, measured in a horizontal distance from the longwall faces (Figure 2, next page). 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 a strong media campaign against the mine authorities, which from time to time has been very heated. New, minor superficial cracks were regularly reported to the mine and damage compensation was

**Figure 2.** Reported locations of seismic events.

claimed. After careful examination of the reported damage it was found that the cracks could not be ascribed to tremors, rather they were ascribed to other causes, like uneven settlements of foundations, changes in humidity and constructional reasons.

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

5 RESULTS OF THE MICRO-SEISMIC MONITORING

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

When the results were presented to the public there was a lot of scepticism and disbelief among the local inhabitants. Measurements were collected for a period of more than one year and sent to independent and internationally acknowledged experts on blasting techniques and vibration. The experts' opinion was that the damage due to vibration in terms of a reduction in utility values is unlikely to have occurred. The vibrations at the recorded levels were not able to damage buildings in a causal manner according to the DIN 4150 standard. However, already existing damage could change, and if damage was found, it must be assumed that other causes are responsible for this damage.

We openly presented the conclusions from the experts and presented the measurements to the public. In the meantime we also set up a system for automatic measurements and published the results on the compa-

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

6 CHARACTERISATION OF EVENTS

The seismic monitoring system on the surface and in the mine gave us an invaluable insight into the processes that took place. Figure 3 displays the seismic activity for December 2004 in terms of days and the hour in the day. Stronger events occur at the beginning of the week and are connected with the cracking of the console in the hanging wall that is built for the weekend. With the constant and progressive progress of the longwall the level of activity decreases and the number of events increases. The accumulated energy is released in smaller amounts. We can see the decrease in the activity in the time of shifts in Figure 3b (6, 14 and 22 hours). The relative amplitude shown in Figure 3 was used to calculate the energy of seismic events by considering the distance and depth difference from the seismic event to the seismic station.

Caving is the most critical process during coal extraction. There have been previous studies of the caving processes associated with the longwall mining, for example Hatherly et al, (1997). An accurate location of the mine tremors is possible only with the use of an in-mine seismic system. We have also deployed a mine-wide seismic system consisting of accelerometers and signal transmission to the surface. An example of an accelerogram is displayed in Figure 4.

The values are measured in volts and a factor of sensitivity $1/G=9,684 \text{ m}/(\text{Vs}^2)$ should be used to convert the values to ground-vibration accelerations. The locations of the events are usually above the level of the excavation. The process of caving is taking place in that area. High stresses fracture the coal. The process can be improved by de-stress blasting or preconditioning (Tooper et al., 1997).

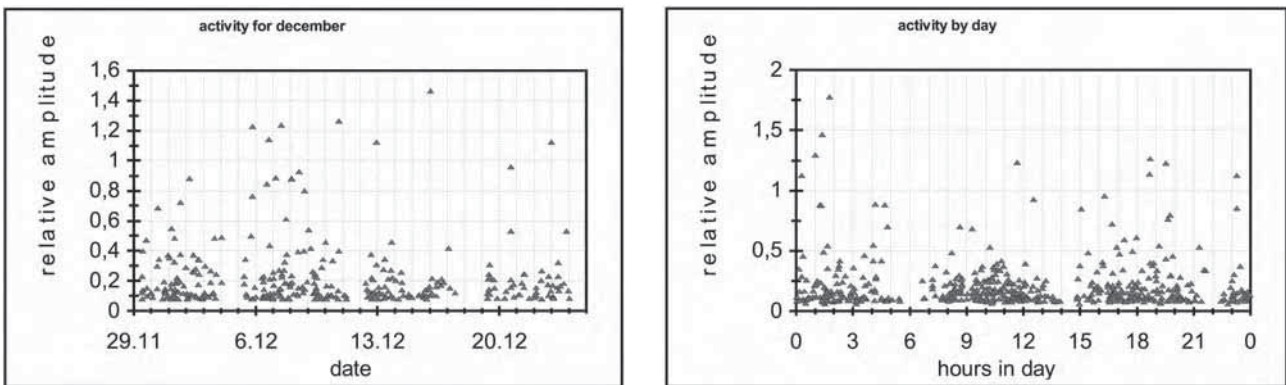


Figure 3. Activity for December 2004 (a) and its display in terms of hours in the day (b).

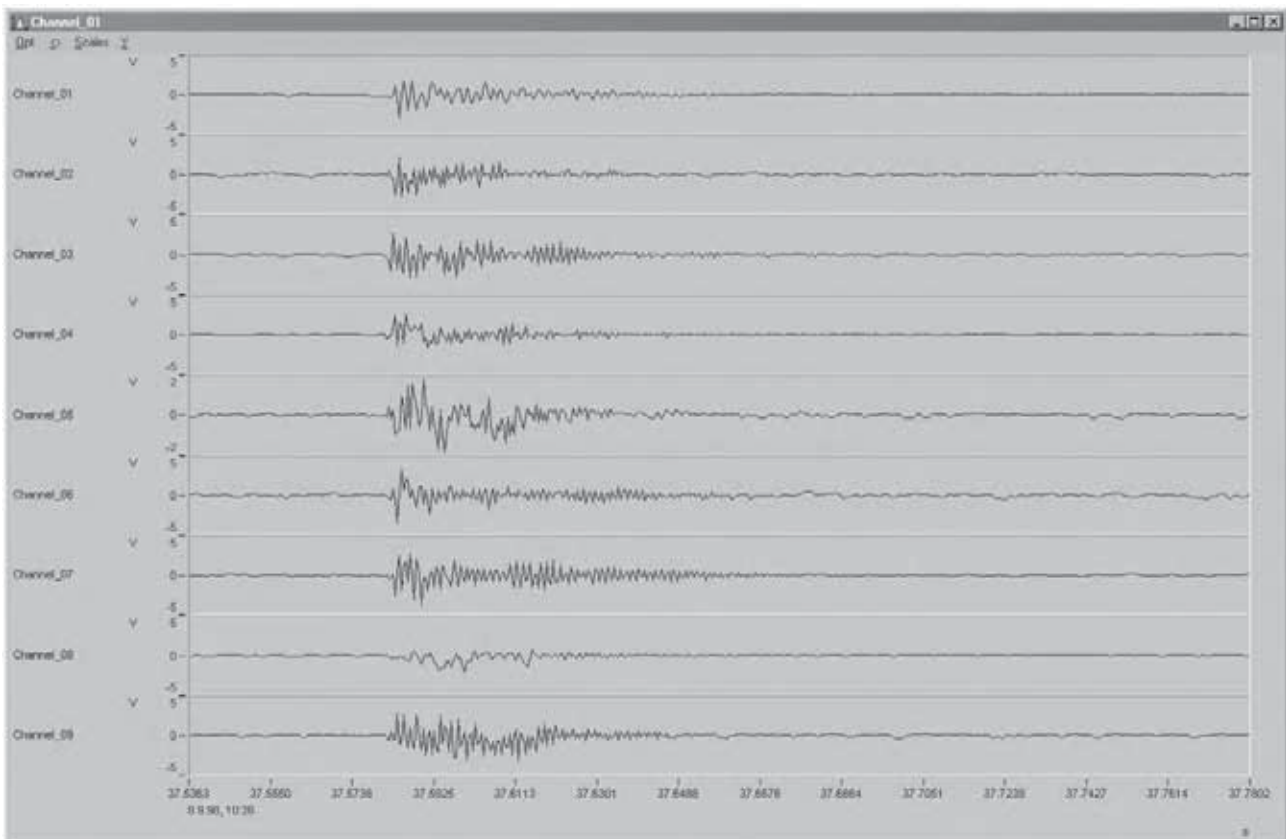


Figure 4. An example of the accelerogram recorded by the in-mine system. time is in seconds, amplitude is in volts.

7 ANALYSIS OF THE FOCAL MECHANISM

Even if the shaking tremors were now better described, some uncertainty still remains. Especially the question of whether all the big events originate from the mine works

or whether their origin is natural. For these reasons the analysis was widened and also the national seismological station was used for analyzing the tremors (Figure 5). The answer is that some stronger tremors were registered by the Slovenian seismological stations and some were not. Another reason is that only for the national seismological stations are the sensors' orientation data

provided accurately enough for a first-motion analysis. For these reasons, the selection of events registered at the mine and the Slovenian seismological observations network was needed. In fact there were just a few events that we were able to prove had their origin in the area of the mining works. For a better understanding of the governing mechanism we decided on an analysis of the fault-plane solution. The fault-plane solution (or the focal-mechanism solution) is a method for identifying the type of earthquake (Cox and Hart, 1986). The fault-plane solution is constructed from the detected signals of different stations and gives an insight into the type or the source of the earthquake (normal fault, thrust fault or strike slip). To achieve a fault-plane solution, it is necessary to know the azimuth as well as the angle of incidence and the type of the first wave (compression or dilatation) that reaches the detecting station. The data is projected onto a circle in such a 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 wave.

Our aim was to identify whether the events observed in the mine and in the national observation nets mainly have their origin in normal fault movements or the components of thrust fault movements. If they

were to have their origin in thrust fault movements their origin would be unlikely to be due to the mining works. The events were first compared on the basis of their frequency and the calculated seismic moments. Seismic moment is a quantity used to measure the size of an earthquake (Aki, 1966). The seismic moment of an earthquake is typically estimated using whatever information is available to constrain its factors. For earthquakes the moment is usually estimated from ground-motion recordings of earthquakes (Westway, 1992). In 1970 Brune set up this relation for a dislocation along the fault:

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

where:

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



Figure 5. Seismological stations used for the analysis of focal mechanisms. The yellow stations had a sufficient number of good signals for making the analysis.

Using a Fourier transformation of Equation (1) means that Equation (2) can be found (Stanković, 1988):

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

Equation (2) describes the amplitude spectra of the dislocation on the free distance from the fault plane. In Equation (2) the factor $(R_{\Theta,\phi})$ defines the seismic waves that 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 spectra of the dislocation movement along the fault using Equation (2) and putting the calculated values on the y axis composed of $\log(u(\omega))$ and the ordinate of $\log(\omega)$ we obtain the diagram in Figure 6.

Looking at Equation (2) and taking into consideration the well-known expressions for the seismic moment $M_0 = (18/7)\sigma r^3$ and $\sigma^2 = (14\pi/9)(\beta/r)^2$ (Brune, 1970) and setting ω to 0 we obtain the following equation:

$$u(\omega) = R_{\Theta,\phi} M_0 \eta (4\pi\rho\beta^3)^{-1} \quad (3)$$

From Equation (3) we can see that the seismic moment depends on the spectrum of the dislocation at low frequencies. This implies that using the low spectrum frequencies we are able to compare the events registered

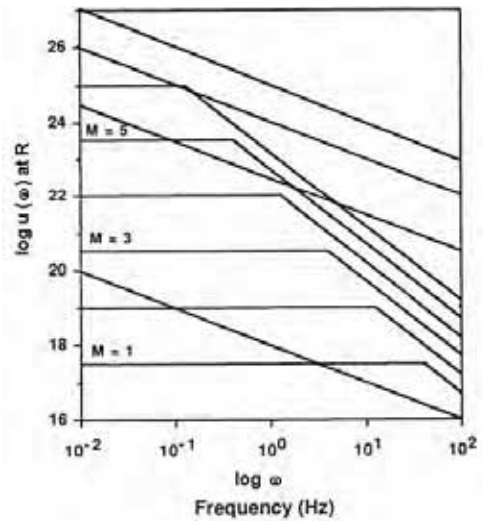


Figure 6. Displacement spectra (Brune, 1970).

on the mining seismological nets with those on the Slovenian seismological net.

On the basis of the theory described above, only a 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, in the end, only four events had data good enough for a first-motions analysis (Figure 7).

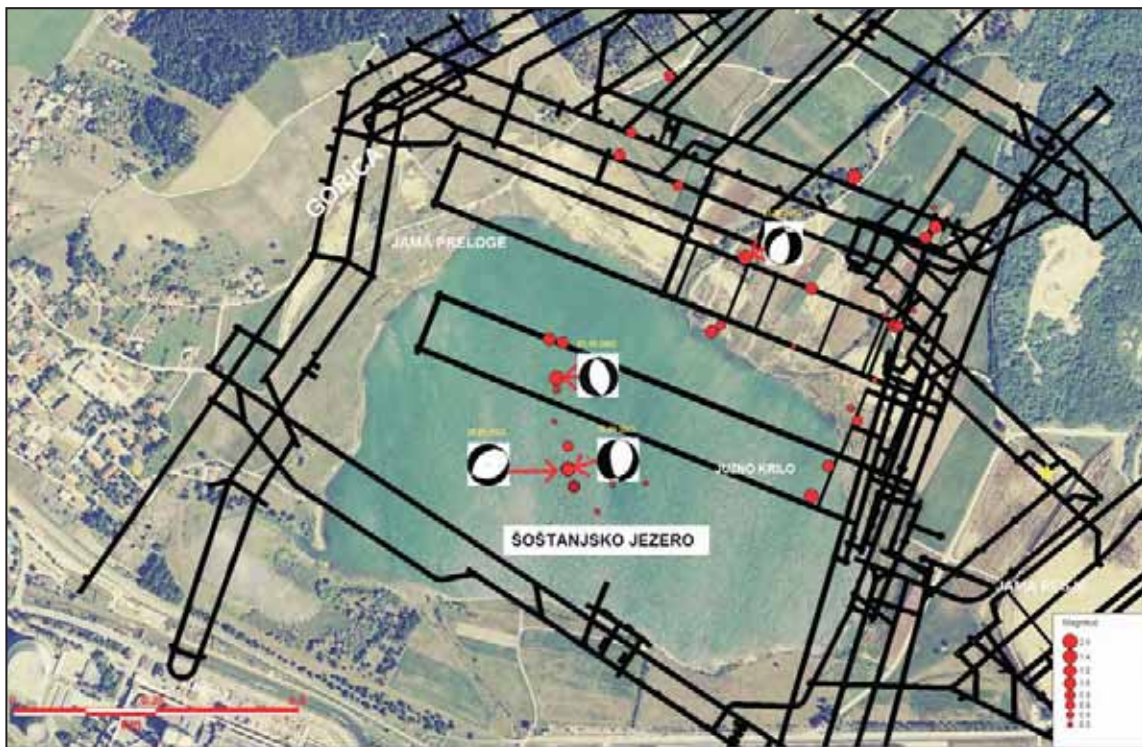


Figure 7. The results of the focal-mechanism solution analysis.

It seems that with the four analyzed events the normal movements are present in the governing mechanisms of the tremors. This can be associated with the dilations occurring due to the excavations of the coal seam. Because of the data uncertainty we cannot definitely associate all the major events with the mining works, but on the basis of the first analysis, as some indications are strong enough, further work in this direction will be carried out.

8 CONCLUSIONS

A mine-wide seismic monitoring system has become an essential part of mining-surveillance monitoring systems, especially for mines operating near urban areas. It provides data about the time and the intensity of recorded seismic events at the locations where most of the complaints are coming from.

The surface station in the nearest village, Pesje, and the town of Šoštanj convinced us that the mine tremors do not cause damage to the buildings, as they are much smaller than the allowed values, according to the DIN 4150 standard. The opinion of independent experts confirmed this 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 understanding the governing mechanism of the tremors. It seems that some major events also had their origin in the mining works rather than in natural geological events.

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

Seismic monitoring helped us to obtain information about the processes in the mine and to get the response of the coal formation to the mass mining. The response is immediate and, therefore, it is controllable. We also found that some parts of the longwall face responded to mining with a lower intensity of seismic events than others. This phenomenon is especially noticeable at the start of the longwall excavation.

With time the database of measurements is increasing, as is the knowledge base in that area. So it is very important to maintain uninterrupted seismic monitoring of mining operations in the future.

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