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SPACE AND TIME DEVELOPMENT OF THE FOCAL ZONE IN THE NEIGHBOURHOOD OF UNDERGROUND WORKINGS

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ABSTRACT. Along the underground working the stress is displaced by any hit to the rock mass. There were defined zones of aggravation, influence, impact and destruction on the basis of continuous seismoacoustic monitoring of the saddle layers in the Ostrava–Karviná Coal Basin (OKR) in the neighbourhood of underground working. These zones develop in time from the beginning of mining operations in underground working through the stages of preparation, development, fully developed underground working till the final stage ending the mining activity in underground working.

Two types of seismic events were defined on the basis of a space and time model of the foci zone: local events (developed events) and global ones (triggered events).

The possibilities of prediction of seismic events in the influence and impact zones were discussed. Phenomena related to the extraction of the saddle layers were explained.

1. INTRODUCTION

In previous papers of many authors the influence of parameters such as excavated area, stratigraphy of the layers, intensity of mining [Konečný 1990], thickness of overlying strata [Kalenda 1992] and velocity of excavation [Kalenda 1994b] on the seismicity of the area were studied. These analyses were made with the presumption of stationarity of excavation process. The parameters of the process such as step of coalface, thickness of coal seam, width of coalface, diameter of underground working (gate), thickness and rigidity of the overlying strata are measured or estimated.

It has been shown that under similar conditions under similar stress state we can see a great difference in the seismicity of the area both in the connection with the excavation of one coalface but also in the connection with the extraction of the whole mining area [Konečný 1990; Holub at al. 1992b; Slavík at al. 1992; Kalenda 1995b]. The development stages were studied and described in details during the extractions of many coalfaces [Holub at al. 1992a; Slavík at al.1992; Kalenda 1995b].

Similarly as in the case of time development of seismic activity, the space zones defined on the basis of seismic event foci localizations in the neighbourhood of the mining works have their space development [Kalenda 1994b; 1995b].

On the basis of the model defined by the space and time development of zones in the neighbourhood of underground working the seismic activity can be divided into two parts: local and global seismic activities. Statistical prediction can be made

for the local and global seismic activities separately in different mining conditions [Kalenda 1995b].

2. Time Development of Focal Area in the Neighbourhood of Workings

Two model coalfaces in the Ostrava–Karviná Coal Basin (OKR) were analysed – coalface No. 13933 in the 3rd mining area of the CSA Colliery leading into the 39th coal seam with a fill of 3 m mining thickness, with 210 m wide coalface, and in coalface No. 7 of the Lazy Colliery leading into the 37th coal seam to the full thickness of 6 m for caving with a 240 m wide coalface [(Kalenda, Slavík 1992; Kalenda 1994a; 1994b; 1995b]. Although different seams of saddle strata were excavated there was found similar time development of seismic activity in the neighbourhood of both coalfaces. This feature of seismic activity was observed in other active coalfaces and retrospectively it was verified even on older coalfaces led in different coal seams [Kalenda 1994a; 1955a]. Based on seismic activity time development it can be said that in the case of monitored underground workings seismicity time development has the following stages (see Fig. 1):

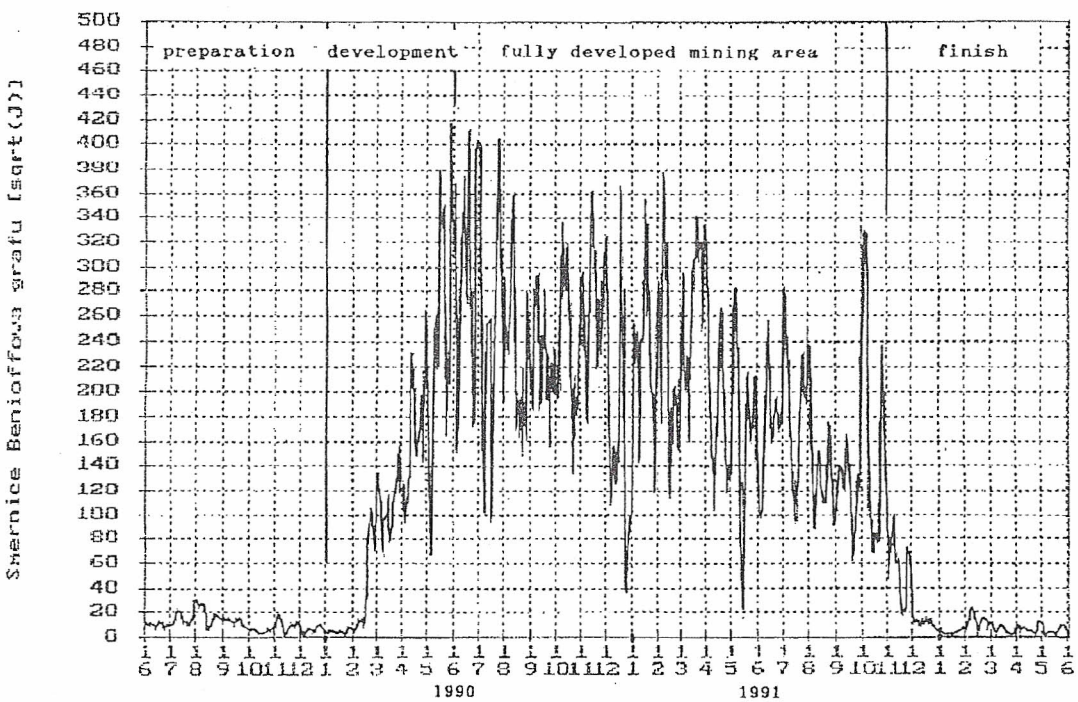

FIG. 1. Time development of the Benioff graph gradient (excavation of coal face No. 13933 in ČSA Mine during years 1990 – 1991)

– preparation stage
– development stage of the underground working (development stage)
– stage of the fully developed underground working

– stage of finish of the underground working (after completed extraction).

2.1. Preparation Stage

The first stage is referred to as the preparation stage of the underground working. In this stage there is an occurrence of moderate increase of seismic activity, caused by the alteration of stress conditions resulting from the previous extraction. The seismic activity can be brought back to life by various activities including e.g. drilling, relieving holes or widening of the initial break–through (in coalfaces). The increase seismic activity in new mining areas is very small but on the other hand even preparatory activities under conditions of high burdening and immense level of accumulated energy can cause rockbursts. In the case of preparation of drivings increase in seismic activity is mostly insignificant.

2.2. Development Stage of the Underground Working

The second stage is referred to the development of a coalface or driving when there is an occurrence of linear increment of the gradient line in the Benioff summary graph. This stage will last in dependence on stress condition of the massif, loading conditions of the overlying strata, size of the coalface and on thickness of the extracted seam from a few weeks to a few months (see Fig. 1).

In the course of this stage the higher and higher overlying strata are getting under the influence of a coalface which sets off against the increment of line slope in the Benioff summary graph which need not be completely linear but may become non–linear particularly in the case of thick blocks of overlying sandstones. As found on detailed spatial localization of events by means of seismoacoustic monitoring of the coalfaces (hereinafter SA monitoring) [Kalenda, Slavík 1992; Kalenda 1994a;b], the influence of coalface propagates to overlying strata step by step from the nearest strata to the distant ones. The energy of events increases depending on shifts of foci until reaching its limit which is given by the thickness of a layer or a few layers and according to the relation [Kalenda 1992]

$$\log E_{\text{lim}}\ [\text{J}] = 4.29 \cdot \log h\ [\text{m}] - 0.56\,, \tag{1}$$

where h is the thickness of the overlying layer formed primarily by sandstones and conglomerates in conditions of the OKR. Minute events are observed within full thickness of the layer above and ahead of the coalface, but in case of breaking down the layers into free space in a collapse, some events were initially observed on the upper side of the layer where the greatest tensile strength occurs. In the case of additional stress along coalface No.13933 the foci of events were located up to the height of 120 m above the extracted area. In the case of absence of additional stress (coalface No. 138704), the values coming from the event foci coordinates reached 50 – 70 m above the coalface.

In the case of drivings the stage of their development is relatively short because the reach of driving's influence is relatively small, approximately within 5 – 10 m. Only in cases of high initial loading and a high amount of previously accumulated energy the drivings may bring about seismic events even from more distant localities (approx. 100 m).

The end of this stage is given by maximum expansion of influence of a coalface (driving) in horizontal direction and towards the overlying strata when bilaterally fixed girders in the virgin coal area and in the collapse are no longer destructed (cut), and only the girders fixed into the virgin coal area of the coalface begin to cut. Prediction of seismic events in this stage is the most difficult, since it is impossible to determine in advance when this stage will cease. Moreover the probability of a falsely predicted anomalous event is the greatest by the end of this stage because it is not unambiguously determinable whether any other overlying strata get under the influence of coalface or not.

2.3. The Stage of Developed Underground Working and Its Finish

The third stage is the one of a fully developed underground working in which the line slope of the Benioff graph tends to be slightly decreasing and the situation in the coalface is stationary. Local changes of seismic activities given by local influences can be best seen in this stage.

In the stage of developed coalface the sandstone layers are cut mostly only in the virgin coal area of the coalface, because they are just unilaterally fixed. Therefore, this results in decreasing influence of the coalface towards the overlying strata as a result of lesser load capacity of unilaterally fixed plates against bilaterally fixed ones in the stage of coalface development.

In case of high level of additional stress in the neighbourhood of coalface No. 13933 there were foci of events localized up to the heights of about 50 – 70 m above the extracted coal seam, in case of no additional stress (coalface No. 138704) the foci of events reached the height of 20 – 30 m above the coalface.

The end of the stage of developed underground working is given by the termination or long–term interruption of mining activity in the underground working in the sense of extraction of material, when the line slope of the Benioff graph starts to fall exponentially till reaching some steady rest values.

If the coal mining or driving activities in the given colliery re–starts, then the stage of development of the underground working will be restored with the exception, that maximum line slope of the Benioff summary graph will not reach its initial high values of the first development, but only the maximum values given by the previous stage of developed coalface, since bilateral breaking of the overlying slabs has already taken place there.

3. Spatial Development of Focal Area in the Neighbourhood of Underground Workings

Based on detailed SA space monitoring (see above) and on localization of foci of events the following space zones being formed in the course of coal mining and driving activities were defined (see Fig. 2):

- zone of aggravation
- zone of influence
- impact zone

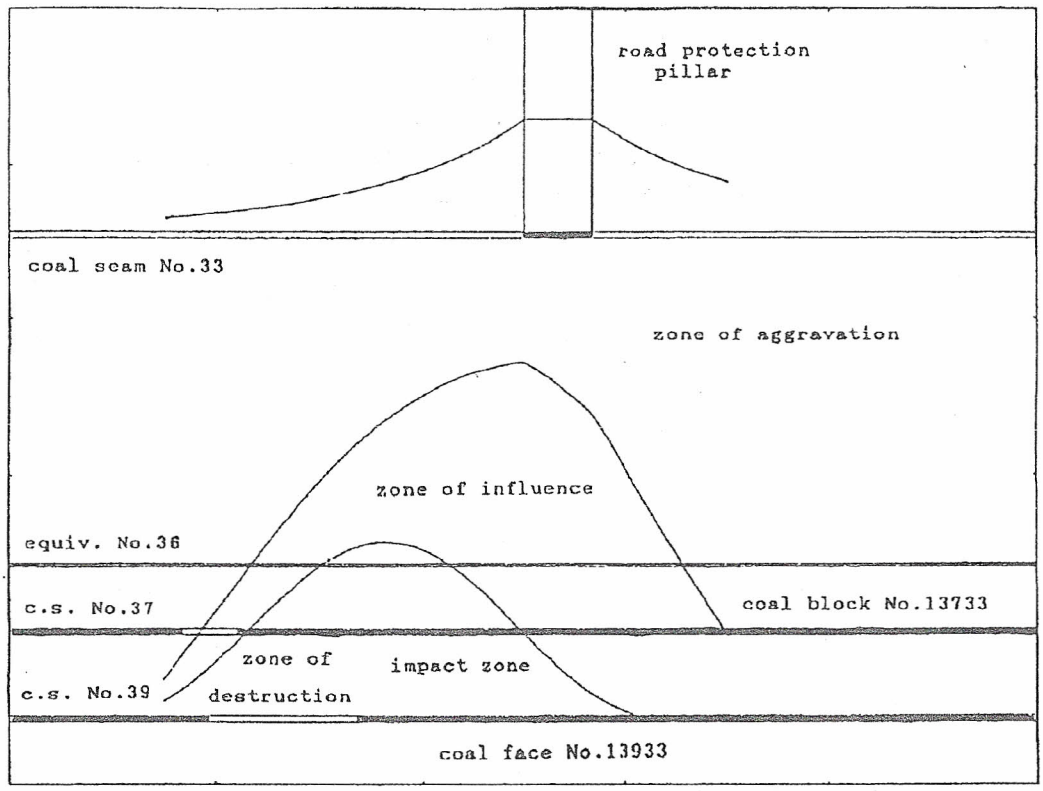

FIG. 2. Influenced zones in the surrounding of coal face No. 13933 in the ČSA Mine

– zone of destruction of massif

3.1. Zone of Aggravation

Any impacts to the massif cause the formation of the first zone in its neighbourhood – zone of aggravation. This zone is not seismically defined, but it is possible to monitor it on the basis of other measuring methods (by strain gauges or by levelling). Re–grouping of stress and its local growth takes place in this zone, however, this stress does not reach the breaking strength, nor the weakest components of the massif and that is why no seismic events arise there. On the other hand, accumulation of flexible energy takes place in the overlying strata which can be seismically active later.

Zone of aggravation may theoretically reach an infinite distance but, in reality, it is measurable in the case of the OKR e.g. by levelling up to the distance of 1 kilometre. Its limitation is mostly given in horizontal direction by tectonic limitations of extracted areas and in vertical direction it mostly reaches the surface.

Zone of aggravation already arises in the course of preparation of the mining works and in the period of development of underground working its range rapidly grows, and so that at the time of ending of the coalface development it is measurable for the majority of coalfaces up to the distances above 400 m. Then its propagation velocity decreases till the end of the underground working.

3.2. Zone of Influence

The second zone – zone of influence – always arises in the neighbourhood of drivings and coalfaces when the surcharges taking place in the massive are so huge that they overcome its breaking strength, which results in arising "triggered" seismic events. However, their energies were largely accumulated from other sources rather than from driving or extraction by which they are "triggered", e.g. due to previous extraction of the overlying coal seams and leaving small pillars or due to the extraction of neighbouring coalfaces and re–grouping of stress in the wide area. These events have a global character and they are completely dependent on previous extraction and re–grouping of the stress. The released energy may be considerable depending upon the period of previous extraction and accumulation ability of the strata.

The zone of influence reaches as far as about 400 m from an active coalface and as high as 150 m above the coalface (coalface No. 13933) in the case of thick sandstone complexes. The zone of influence usually reaches dimensions up to 200 m from the coalface and almost 80 m above the coalface. At drivings in places with high additional stress the zone of influence may reach as far as 150 m and as high as 80 m (rockburst, Jan.7, 1992, Coal Area 4, Doubrava Colliery – Kalenda 1995c). Largely the zone of influence is directly linked to another seismically defined zone – impact zone, but this one need not follow the former zone completely, especially when local region is aggravated by additional stress in such a manner that seismic events in this region are triggered at large scale. On the other hand the zone of influence of underground working is completely separated in space as it was for example at coalface No.133933 in the period of its drawing near a small pillar in the overlying coal seams [Kalenda, Slavík 1992], or in the case of the "triggered" events on mining line between the 8th and 9th coal areas of the Darkov Colliery [Kalenda 1995a] (see Fig. 3). The zone of influence arises alongside drill holes, drivings and coalfaces after the initiation of their development stage and its maximum dimension is formed mostly by the end of the development stage. Only in case when the mining work proceeds to anomalously aggravated area in space, then the aggravated area may become larger at that moment and interfere with the area mined.

3.3. Impact Zone

The impact zone of a coalface arises largely by the extraction of coal in the course of development stage of the coalface. Breaking strength is exceeded in full volume of the rock in this zone, above all, due to the extraction of the coalface itself. Other effects have less influence and just expand or, the other way round, contract the size of this zone. The events in this zone have largely a local character and may be statistically predicted on the basis of seismicity development.

In the case of thick sandstone layers the impact zone of a coalface reaches as far as about 200 m away from the active coalface and as high as 70 m above the coalface. The impact zone of a coalface usually reaches as far as about 100 m away from the coalface and as high as about 30 – 40 m above the extracted seam (coalfaces No. 138704 of the Lazy Colliery, No. 140804 + 5 of the Darkov Colliery). In the case of drivings the impact zone reaches as far as 5 – 10 m away from the driving,

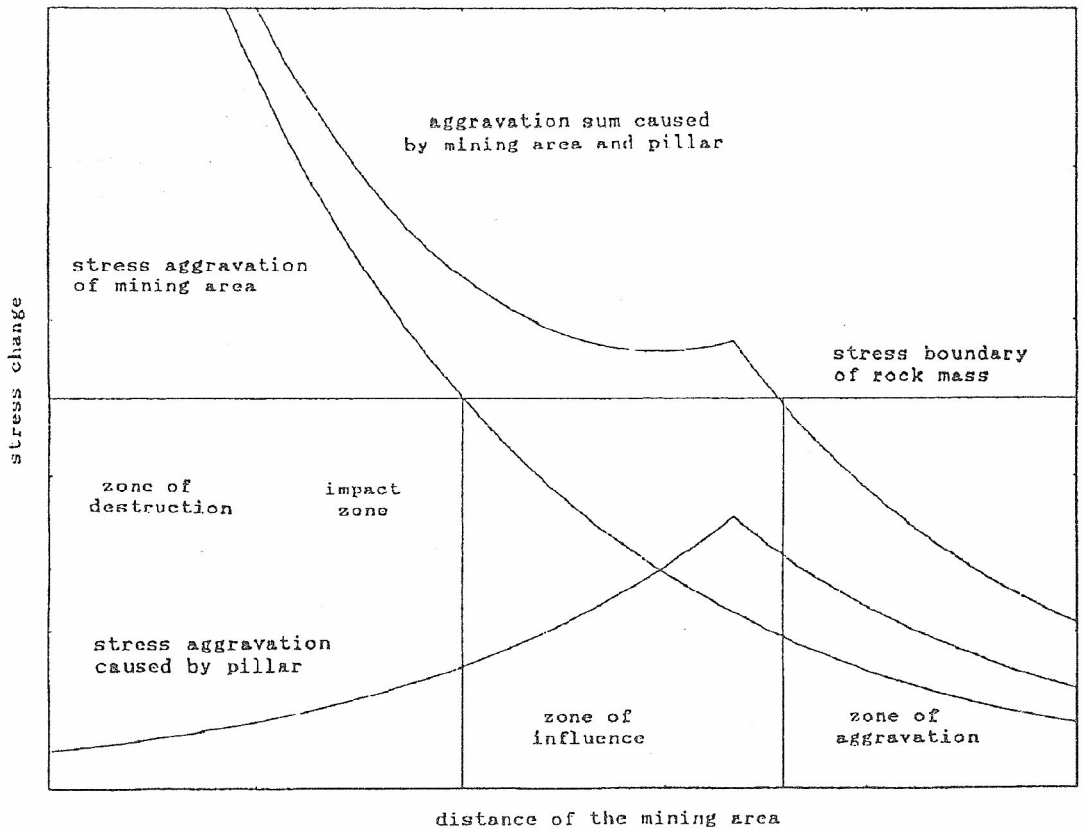

FIG. 3 Diagram of the stress changes in the surrounding of mining area

which was verified by seismic tomography (Staš – internal material of the VVUÚ Ostrava), but it may be even smaller or none.

The impact zone arises no sooner than in the course of development stage and its evolution, as for its height, is largely finished at the beginning of the stage of developed working. The impact zone shifts horizontally in the stage of developed underground working according to the advance of the given underground working. The impact zone of a coalface corresponds to geomechanical evaluation of the distance L of the influence range.

3.4. Zone of Destruction of Massif

A complete destruction of strata takes place in the neighbourhood of extracted underground working after releasing the seismic energy in the impact zone. Therefore the rock loses its ability to accumulate energy, which results in the formation of a seismic zone of destruction.

This zone is spread largely in caving – behind the face and its height reaches about 20 – 50 m depending on the height of the impact zone. Its height usually does not exceed 20 m above the coalface and its size is largely limited horizontally by the outline of the caving whereas its height is lower at edges. Its dimension at drivings largely does not exceed 2 – 3 m towards the coal seam and 1 – 2 m towards the hangingwall, which causes, among other factors, also greater consequences of

seismic events on the corridors than on the coalface area.

The zone of destruction arises no sooner than with the developed underground working and it is spatially related to the underground working alongside which its formation is about to arise.

4. Discussion

The outlined time–space model coming from monitored seismologic and seismoacoustic events enables to explain some apparent paradoxes in the behaviour of seismic activity in the course of mining.

The most important feature of this model is the fact that it separates apparently homogeneous seismic events from those induced by natural activity of the coalface in the impact zone – (local events) and the other ones which are "triggered" in the zone of influence – (global events) whose energy accumulation passed through due to whole previous mining. This feature of the model explains a phenomenon of the so called "third coalface" which says that the third coalface under extraction in a given mining area is the most dangerous one.

If we investigated the increase maximum global energy in time since the beginning of the extraction in the given coal area, we would find out that its dependence on time can be described by the equation

$$\log E\ [\mathrm{J}] = b \cdot \log(t - t_0) + a\,, \tag{2}$$

where $t - t_0$ is the time when the extraction of the given coal area started. It can be shown on practical data that at the extraction of saddle seams in most cases the value of coefficient b is of such an amount that the theoretical and even the observed maximum energy after 3 – 5 years from the beginning of extraction reaches the value of $10^6 - 10^8$ J, i.e. when the rockbursts are already coming into being [Kalenda 1994b; 1955b].

According to this model, the "triggered" events have global character given by the extraction of the whole coal area and their coming, based on the observations of the events arising in the zone of influence, need not be anyhow signalled in advance. In case that global events are induced in other layers than in local ones, this may result in alterations of coefficient b in the energy – frequency (hereinafter E – F) distribution [Kalenda 1995a]. However if the global events are "triggered" from the same layer complexes, then their occurrence is quite incidental and it is possible to determine only the probability of their occurrence given by the relation

$$P = 1 - \exp(-N_i)\,, \tag{3}$$

where N_i is the calculated numbers of events in class E_i according to the cumulative E – F distribution inset by its statistically significant classes of registered events and calculated from time of beginning of extraction in a given coal area [Bäth 1979].

The second significant feature of the model is the fact that in the course of extraction of each coalface the most dangerous stage is the one of its development when the wide zone of influence comes into being and global maximum events may

be "triggered". Simultaneously, a new sinking mechanism of layers will result in a higher level of seismic activity than observed in the course of next extraction in the stage of developed coalface. Therefore, it is necessary to situate the initial breaks–through at coalfaces in such a manner as to prevent from addition of the adverse factors. Thus it is possible to explain e.g. the crash of coalface No. 13733 in coal area No.3 of the CSA Colliery when – due to the extraction of the neighbouring four coalfaces – the maximum event energy of approx. 10^{10} J accumulated in the stage of developing coalface and simultaneously the zones of influence and impact reached under the edge of unmined area with high level of additional stress.

With the same mechanism it is possible to explain the initiation of rockbursts caused by drivings or relief drilling when global events are "triggered" in the zone of influence particularly in the areas with high additional stress and substantial accumulated energy given by previous extraction.

The third feature of this model is the fact that it is possible to predict local events in the impact zone based on previous evolution of seismic activity in the same zone for a period whose length is proportional to the magnitude of the impact zone and to the rate of coalface advance when total accumulation and release of energy takes place within greater volume of strata in the impact zone with formation of the zone of destruction primarily in the stage of developed coalface.

Local seismic activity is determined by local properties of strata in the impact zone, by the advance rate of coalface, variations in stress as well as by its re–grouping. It is possible to determine local rate of risk in the coalface by means of predictive filtration [Rudajev, Pěč, Buben 1976; Lasocki 1993].

However, this does not enable to predict global events.

5. CONCLUSION

The outlined time–space model which – on the basis of seismic activity in the neighbourhood of underground working – defines the formation and time evolution of spatial zones in the neighbourhood of the working, gives answers to questions related to the method of leading the underground working and its possible exposure to danger of an anomalous seismic event.

At the same time, the model provides the possibility to divide seismic events into local ones bound directly to the activity of the coalface and to its immediate rock neighbourhood and into the global ones related to the general state of mining in the extracted coal area. It is indicated that local and global seismic activities do not directly cohere with each other and then it is impossible to predict global events on the basis of local seismic activity. On the other hand, the prediction of local events based on previous seismic activity is possible with a high degree of probability and, at the same time, it is possible to estimate maximum energy value of the seismic event being determined by total extraction in the given coal area and "triggered" by the extraction of coalface or by driving.

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