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INDUCED SEISMICITY BY OPEN PIT MINING IN NORTHWEST BOHEMIA

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ABSTRACT. Triggering of seismic events by unloading of the Earth's surface in case of deep pits is discussed by means of the Mohr diagram with the Coulomb failure criterion. All basic mechanisms of earthquakes with dip–slip, strike–slip and thrust faulting may possibly occur. Reduction of the vertical stress by mining can be quantified but the other factors may be only estimated. The potential for induced seismicity appears also by loading effect of big external spoil heaps during mining and interaction of loading and pore–pressure effects due to the filling of pits with water after the exploitation of mines.

KEY WORDS: induced seismicity, stress distribution, Northwest Bohemia

1. INTRODUCTION

Seismic events of different intensities triggered by human activities in the upper part of the Earth's crust are usually denoted as *induced seismicity or man–made seismicity.* In this case the pre–existing regional tectonic stress field accumulated during long–term geologic processes is released before the "natural" origin time of faulting due to the artificial increment of stress and/or decrease of breaking strength of rocks.

These phenomena are well–known with high dams where the incremental stress due to *reservoir impoundment* and the increased pore pressure can stimulate seismic activity under suitable geological conditions. Triggering of earthquakes is not excluded in reservoirs with maximum water depth over 100 m and capacity higher than $10^9\,m^3$ [Kisslinger 1976; Simpson 1976; Gupta, Rastogi 1979; Gupta 1992; Nikonov 1992]. In several cases some local tremors were influenced by *fluid injection or extraction of deep wells*, e.g., [Kisslinger 1976; Yerkes, Castley 1976; Cox 1991; McGarr 1991; Nicholson, Wesson 1992]. Seismic events connected with *underground mining*, the so–called rock bursts [Knoll 1992], were observed in different parts of the world [Hurtig, Stiller 1984] as well as in mines on the territory of the Czech Republic and Poland; the results of investigation into the last mentioned seismic events presented at Czechoslovak–Polish and Polish–Czechoslovak conferences on mining geophysics were published in *Acta Montana* and *Publ. Inst. Geophys. Pol. Acad. Sci.*. Seismicity induced by *open pit mining* was, besides a single paper by [Pomeroy et al. 1976] dealing with stone pit quarrying, studied mainly by Polish colleagues. Their attention was devoted to series of earthquakes triggered by mining of brown coal in deep open pit mines in former aseismic area near Belchatow [Gibowicz 1981; 1985; Gibowicz et al. 1981; 1982; Gibowicz, Kijko 1984; Kijko 1985]. Individual papers dealt with macroseismic and microseismic observations and geological aspects of the seismic energy release.

In connection with the projected big deep open pit mines in the Northwest Bohemian brown coal District (NBD), situated near the slopes of the Krušné hory Mts. and potential hazard of slope slide initiation by local earthquakes (e.g., seismo–gravitational rockfalls and rockslides), the problem of induced seismicity was studied taking into account the experience from Poland [Rybář et al. 1982; Drozd, Rybář 1983]. Conditions of earthquake triggering in NBD were, in comparison with the Belchatow district, characterized as follows:

(a) It is also a tectonically unstable zone, especially in the area of the Krušné hory fault belt, which was evidently active in the Quaternary and, in the part of the Komořany Lake including the Holocene.
(b) Abnormal horizontal stresses were found in the exploration gallery of Jezeří, as well as in the Jezerka gallery.
(c) Tectonically strongly deformed metamorphites in the footwall and the forefield of the basin, as opposed to limestones, cannot experience a dangerous sudden brittle failure; however, this cannot be excluded e.g. in the lower parts of granitic massif in the core of the Hora Svaté Kateřiny anticlinorium.
(d) There is no equivalent of salt layers.

The basin fill of the NBD would be removed in the first stage down to depths of 200 m – 250 m, there are mostly internal spoil heaps and the amount of water is considerably smaller than in Belchatow. The authors' conclusion that the probability of induced seismicity is substantially lower than in Belchatow was supported by the fact that no tremors had been observed. At the same time the open pit mining in NBD exceeded the depth of 100 m which was sufficient in the case of Belchatow to "initiate" local earthquakes with macroseismic effects.

It has not been found yet which parameters determine uniquely man–made earthquakes by open cast mining. In the present article we attempt to model the changes of stress distribution due to unloading of land surface and to update factors valuable for the assessment of seismic energy release by open pit mining in the district of NBD. A practical sense of the study is directed to the problem of potential triggering of local earthquakes which may start dangerous sliding of the Krušné hory Mts. "critical" slopes situated in the forefields of several quarries [Rybář 1987; Tobyáš, Mittag 1992].

2. Models of Stress Changes by Open Pit Mining

We shall apply the Mohr circle with the Coulomb failure criterion for a simplified description of the influence of fast surface unloading on the massif faulting using the adjusted procedure for loading by a reservoir [Kisslinger 1976; Yerkes, Castley 1976; Hurtig, Stiller 1984]. The initial natural state of stress field is discussed in a plane with major and minor principal stress. We denote the major normal stress before mining σ_{01} and the minor stress σ_{03}. In the coordinate system with the normal stress σ on the abscissa and the shear stress τ on the ordinate, the Mohr circle has the radius $r_0 = \frac{\sigma_{01} - \sigma_{03}}{2}$ and its centre S_0 on the abscissa axis is at distance $\sigma_{S_0} = \frac{\sigma_{01} + \sigma_{03}}{2}$ (Fig. 1). Simple failure envelope is defined by the linear relation $\tau = \tau_0 + \sigma \cdot \tan\varphi$, where τ_0 is the shear strength of the rock massif in case of zero normal stress and φ is the angle of internal friction of rock. If the circle contacts this envelope, the condition for massive rupture is fulfilled. The contact point of circle in Fig. 1 is at distance σ_0 which is given by the following relation

$$\sigma_0 = \frac{p_0 \cdot \sin\varphi - \frac{\sigma_{01} - \sigma_{03}}{2}}{\sin\varphi} . \tag{1}$$

The value of p_0 corresponds to the distance between the centre of circle S_0 and the point of envelope intersection with abscissa. We suppose an approximate relation $\sigma_h = \frac{\sigma_v}{3}$ between the horizontal σ_h and vertical stress σ_v [Vacek 1980; Hurtig, Stiller 1984] which is valid exactly for the elastic halfspace. The horizontal component changes by $d\sigma_h$ when the vertical stress changes by $d\sigma_v$ and $d\sigma_h = \frac{d\sigma_v}{3}$. According to the orientation of the plane with maximum and minimum stress components, the initial position of the centre and radius of the Mohr circle will be changed and conditions for rock massif faulting are evaluated.

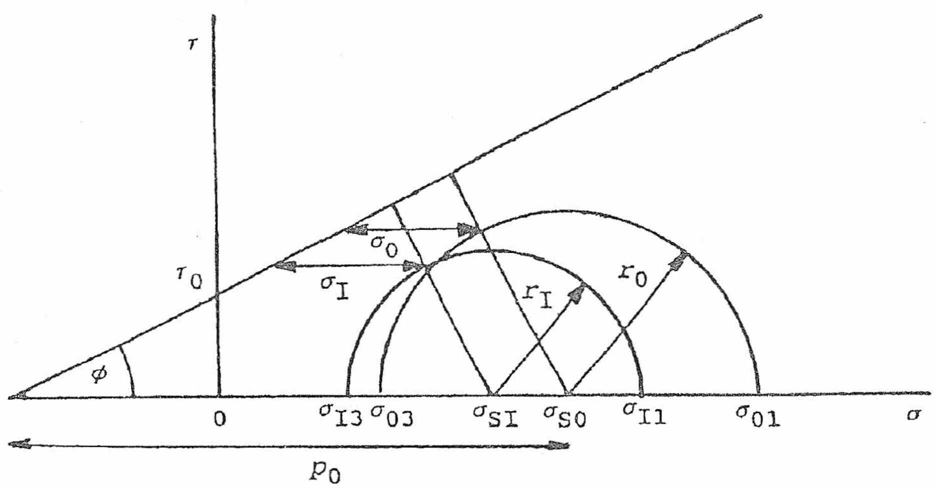

FIG. 1. Scheme of the Mohr diagram for the initial stage and case I of stress distribution.

Let us mention three simplified variants of surface unloading by open pit mining which correspond to basic mechanism of earthquakes with dip–slip (I), strike–slip (II) and thrust faulting (III). Their parameters will be further denoted in particular cases by relevant indexes I – III.

I. Maximum stress σ_{01} is in the vertical plane, minimum stress σ_{03} is in the horizontal plane

When unloading surface layers the initial maximum vertical component of stress σ_{01} is decreased by $d\sigma_v$ and the initial minimum horizontal stress σ_{03} by $\frac{d\sigma_v}{3}$. The centre of new circle has abscissa $\sigma_{S_I} = \sigma_{S_0} - \frac{2.d\sigma_v}{3}$ and its radius will be $r_I = r_0 - \frac{d\sigma_v}{3}$ (Fig. 1). New circle has therefore a smaller radius than the initial one and its centre is shifted to the origin of coordinate system. The distance σ_I of the circle contact point from the envelope is in this case

$$\sigma_I = \frac{\left(p_0 - \dfrac{2.d\sigma_v}{3}\right) \cdot \sin\varphi - \dfrac{\sigma_{01} - \sigma_{03}}{2} + \dfrac{d\sigma_v}{3}}{\sin\varphi} . \tag{2}$$

The influence of unloading in relation to the initial conditions will be characterized by the difference $d\sigma_I$ between distances of contact points of corresponding circles

$$d\sigma_I = \sigma_I - \sigma_0 = \frac{-d\sigma_v \cdot \left(2 - \dfrac{1}{\sin\varphi}\right)}{3} . \tag{3}$$

If the angle $\varphi = 30°$ the value $d\sigma_I = 0$ and the conditions for rock failure in the course of surface mining do not change. For $\varphi < 30°$ the $d\sigma_I > 0$ and the contact point moves to a greater distance; hence, the failure criterion cannot be reached. Only in case that $\varphi > 30°$ the dip–slip faulting can be attained.

II. Maximum and minimum stresses are in the horizontal plane

When the vertical stress is decreased by surface rock unloading both above mentioned stresses in the horizontal plane are decreased by the same value $\frac{d\sigma_v}{3}$. Radius of circle r_{II} remains the same, i.e. $r_{II} = r_0$ and its centre is shifted to the origin of coordinate system by $\frac{d\sigma_v}{3}$. Therefore, the distance of contact point from the failure envelope is

$$d\sigma_{II} = \sigma_{II} - \sigma_0 = -\frac{d\sigma_v}{3} . \tag{4}$$

It means that in this case the contact point of the circle moves closer to the envelope by surface rock mining and horizontal slip (strike–slip) faulting may be obtained at the limit.

III. Maximum stress σ_{01} is in the horizontal plane and minimum stress σ_{03} is in the vertical plane

We derive necessary parameters in a similar way as in the first case and obtain

$$r_{III} = r_0 + \frac{d\sigma_v}{3}, \quad \sigma_{III} = \sigma_0 - 2 \cdot \frac{d\sigma_v}{3} . \tag{5}$$

It means that the new circle radius is increased and the circle centre is shifted to the coordinate origin. Value of

$$d\sigma_{III} = \sigma_{III} - \sigma_0 = \frac{-d\sigma_v \cdot \left(2 + \dfrac{1}{\sin\varphi}\right)}{3} \tag{6}$$

is negative independently of the value of angle φ. The contact point moves closer to the failure criterion as in case II. By this stress distribution the unloading of surface may finally lead to thrust faulting.

Besides the above discussed three cases of surface unloading we have to take into account the stress–reducing effect of water–filled pores. Because the water pressure acts equally in all directions, both maximum and minimum stress is decreased by the same value. We denote it as $d\sigma_w$. The situation is similar as in case II, if we put $d\sigma_w$ instead of $\frac{d\sigma_v}{3}$. The total shifts of circle contact points including the water–pressure effect in particular cases I – III will be therefore

$$d\sigma_{Iw} = d\sigma_I - d\sigma_w\,, \tag{7a}$$

$$d\sigma_{IIw} = d\sigma_{II} - d\sigma_w\,, \tag{7b}$$

$$d\sigma_{IIIw} = d\sigma_{III} - d\sigma_w\,. \tag{7c}$$

The condition for reaching the limit of failure is getting closer and the character of motion on the fault surface remains the same as in the corresponding previous case of unloading.

3. LOCAL FACTORS OF INDUCED SEISMICITY

We shall try to support the geological interpretations [Rybář et al. 1982; Drozd, Rybář 1983] in the NBD region by additional data for the given model of triggering local seismic events. Projected depths of pits can be used for the calculation of vertical stress decrease. The sketch–map of the region in Fig. 2 shows the distribution of several "critical" slopes of the Krušné hory Mts. in the forefields of mines where maximum depths of pits over 200 m are indicated [Rybář 1987]. In the other sectors the projected depths are mostly over 100 m.

In an open pit mine with a depth of h (m) and the average density of the stripped rocks s (kg/m^3) the vertical stress is decreased by $d\sigma_v = h \cdot s$, where $d\sigma_v$ is in bar. Supposing that $s = 1700\,\mathrm{kg/m^3}$ and $h = 100$ m the value of $d\sigma_v$ is equal to 17 bar, i.e. 1.7 MPa. If we take the maximum depth range in particular sectors between 200 m and 600 m the calculated vertical stress decrease $d\sigma_v$ is between 3.4 MPa and 10.2 MPa.

Different parts of the vertical stress decrease are applied in the previous formulae for stress difference between the contact point of the Mohr circle and the failure envelope. According to (4) a constant of one third of $d\sigma_v$ is effective for the case of the strike slip. For the other cases the angle φ should be taken into account. This angle must represent the rock massif underlying the pit as a whole including

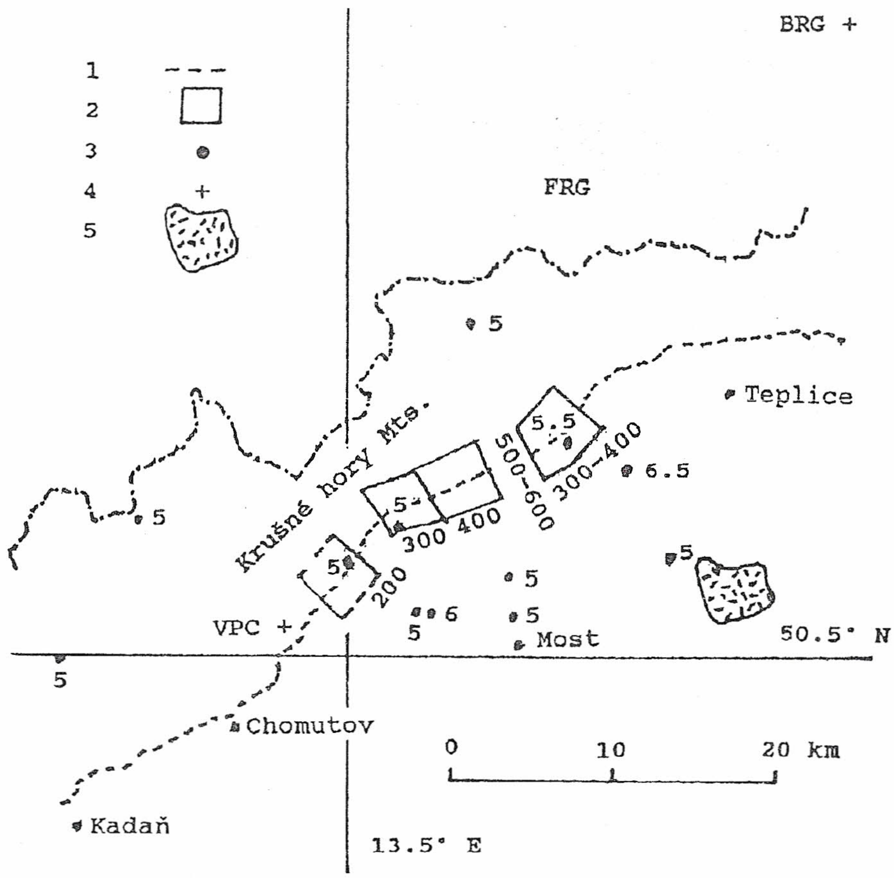

FIG. 2. A sketch-map of a part of the NBD and the Krušné hory Mts. 1 – boundary of basin with mountains, 2 – sectors with the projected depths of pits in metres, 3 – macroseismic intensities at given localities, 4 – the nearest seismic stations at Berggiesshübel (BRG) and Vysoká Pec (VPC), 5 – external Radovesice dump.

the area with the minimum strength. For comparison we suppose φ to be in the interval $20° - 40°$. Therefore, in (3) for the dip–slip a smaller part between 0 and 0.15 of $d\sigma_v$ and for the thrust faulting in (6) a higher value between 1.64 and 1.18 of $d\sigma_v$ is applied. It means that the probability of induced seismicity for the constant vertical stress decrease varies with the potential mechanism of earthquake. Regional tectonic stress state before mining should be especially for the dip–slip faulting near to the breaking strength of rock under the mining area. Data about fault plane solution of local earthquakes which yield information on stress distribution in the focal area are not at disposal either for the past events with macroseismic effects or for the present microearthquakes recorded mainly by 2 – 3 nearby seismic stations. We know only approximate positions of epicentres of both groups of seismic events.

Direction of maximum horizontal stress on the surface and in shallow boreholes

[Grünthal et al. 1985; Grünthal, Stromeyer 1986; Peška 1992] in the region occurs between NNW – SSE and NW – SE. It means that it is oriented approximately perpendicular to the Krušné hory fault zone. This direction is assumed to be the same as in the hypocentral area as obtained for the earthquake swarm in west Bohemia in 1985 – 1986 [Grünthal et al. 1990].

The maximum macroseismic intensity of 6.5° of the MSK–64 scale near Duchcov in 1784 and 6° near Komořany in 1896 (during earthquake swarm) were observed in the investigated region [Procházková et al. 1987]. The other localities with intensities 5° at minimum are given in Fig. 2, too. The strongest local earthquake intensity corresponds to magnitude class of 4.8 ± 0.3. The empirical length of the rupture zone for such earthquake is about 1 km. The theoretical probability to create fault on the Earth's surface in such case is below 3 % [Kasachara 1985]. Higher mobility is recently observed in the epicentral area of the earthquake swarm where extreme changes of the horizontal gradient of vertical deformation were received. The maximum annual rate of surface uplift of 2 mm was observed there [Vyskočil 1981]. Relative horizontal strain in E–W direction of $0.2 \cdot 10^{-6}$ per year on the neighbouring territory of FRG was determined from geodetical measurements [Thurm et al. 1977]. Logarithm of cumulative frequency of all macroseismic data starting with intensity of 3° fits well linear relation with magnitude and the mean return period for the maximum magnitude class about 500 hundred years was obtained [Tobyáš, Mittag 1992]. Mean return period for the lower magnitude class 4.2 ± 0.3 was about 100 years. Relative release of tectonic strain in time, represented by the cumulative square root of seismic energy, demonstrates the potential release of energy $8 \cdot 10^{12}$ J at the end of this century which corresponds to single earthquake with a magnitude equal to 5.2.

No macroseismic events have been observed since 1910 in the investigated territory. The recent seismic activity has been systematically monitored by the nearest seismic station of the international network at Berggiesshübel since 1972 and by one additional temporary seismic station situated in the district at Vysoká Pec since 1982 (Fig. 2). Only microseismic events with magnitudes in the range between 0 and 1.2 ± 0.3 were detected. Of course, we are not able to differentiate records of microtremors which occur due to the standard natural release of tectonic stress from those "induced" by stripping in open pits. The observed cumulative annual frequencies for the time interval 1972 – 1988 were of the same order as the annual frequencies extrapolated from macroseismic data [Mittag, Tobyáš 1992]. Localized microtremors were distributed over the whole territory with no conspicuous concentration in some area [Tobyáš et al. 1987].

4. CONCLUSIONS

In addition to unloading by open pit mining the opposite case of surface loading must be taken into account for big external heaps. Such an example indicated in Fig. 2 is the so–called Radovesice dump near Bílina [Hurník 1982]. According to the project nearly 1.5 – 2 milliards of tons of rock and soil are to be dumped on the area of about 10 km^2. At the same time the highest column of dumped earths should be more than 200 m high. In relation to the expected density of the stripped material it corresponds to the column of water about 340 m high.

The model of rock failure which was discussed here for unloading of the Earth's surface can be applied with small changes for the surface loading, too. Relations (3), (4) and (6) for the shift of the contact point of the Mohr circle with the failure envelope are valid with the opposite sign for uploading and for the same orientation of maximum and minimum stresses in the initial stage. Then we receive the possibility of rock failure in the first case only for $\varphi < 30^\circ$ and in the second and third case major and minor stress orientations the failure conditions cannot be reached at all. Therefore, the potential faulting is in relation to unloading limited to the dip–slip. The influence of water pressure becomes obviously negative in the same way as given by (7a – 7c) and helps to reach the failure criterion in all cases of the stress distribution.

The free spaces of open pits are partly filled by internal heaps during quarrying. After the end of mining the rest of the area is projected to be inundated with water. We arrive at the situation as for big and deep reservoirs mentioned in the introduction with two basic differences: the inundation of pits will continue several tens of years after closing the mining operations and the water column height will not be possible to reduce quickly if seismic events occur.

The total water amount will be, e.g. in smaller Ležáky–Kopisty mine about 120 million cubic metres and in the CSA mine more than 700 million cubic metres with the height of water column exceeding 100 m. Vertical stress will be lower than before mining due to smaller density of water in comparison to the stripped material. The situation of Mohr diagram is similar as in the preceding case of external heap but with outstanding pore pressure in bedrock. Then the rock failure may be reached in principle for arbitrary initial principal stress orientation. [Chen, Nur 1992], presented a model of pore fluid pressure in anisotropic rocks for these purposes.

It follows from the above discussion that the great interferences of man with nature by open pit mining bring potential seismic energy release not only due to quarrying but also later when the surface is reverted in good order and conditions. We are not able to reject the possibility of triggering a stronger earthquake in the future although the "critical" depth of 100 m in open pit mines was exceeded with no occurrence of macroseismic events. For the effect of the vertical stress decrease the initial stress distribution is substantial as well as that the mine pit is situated over a massif with some weakened zone. Our knowledge necessary for the application of a simple model of induced seismicity is inadequate. Factors necessary for proper assessment of induced seismic risk are not well known yet and parameters concerning local conditions should be further monitored and quantified.

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