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CHARACTERISTIC FEATURES OF INDUCED SEISMIC PROCESSES IN MINING REGIONS EXEMPLIFIED BY THE POTASSIUM SALT DEPOSITS IN BELARUS AND BULGARIA

I Paskaleva[1], A G Aronov[1], R R Seroglazov[1], T I Aronova[2]

[1]Central Laboratory of Seismic Mechanics and Earthquake Engineering, Bulgarian Academy of Sciences, Acad. G. Bonchev str., block 3, 1113, Sofia, Bulgaria,
e-mail: paskalev_2002@yahoo.com

[2]Centre of Geophysical Monitoring (CGM) of National Academy of Sciences of Belarus, Kuprevich str. 7, 220141, Minsk, Belarus, e-mail: centr@cgm.org.by

This work focuses on the assessment of seismic risk issues associated with the potassium salt deposit of Provadia and Soligorsk, with the monitoring provided by Belarusian and Bulgarian specialists in the framework of a bilateral project.

The long-term studies 1983–2005 of the only terrestrial Bulgarian salt deposit (Provadia, $\varphi = 43.06°$N, $\lambda = 27.45°$E) and Belarusian (Starobin $\varphi = 52.84°$N, $\lambda = 27.47°$E) in connection with the observed higher seismic activity and probable manifestations of technogenic seismicity in the region is presented.

The characteristic features of the seismic processes as the identity of the curves of recurrence of seismic events of the energy range of $4 - 8$ are discussed. A quasi-periodic character of the seismicity activation in time against the general trend of seismicity activation is established. It is shown that the zones of the epicenters of the seismic events are larger that mining areas.

Some differences in the pattern of seismic processes, such as: 1. the seismic activity in the range of small energies ($K = 4 - 8$) is higher in the Soligorsk region; 2. events of the higher energy class, $K > 9$ are characteristic of the Provadia region.

Keywords: geophysics; induced seismicity; seismic hazard

Introduction

In many regions the large urbanized areas are overlapped with the regions of manifestations of different natural disasters. This is one of the reasons that has provoked bilateral international project exploring the problems of the “natural” and “technogenic” hazards and their possible mitigation (Aronov et al. 2005). There is a trend for the quantitative assessment of the natural phenomena and their consequences analyzing different scenarios. A great problem is the formulation of the optimal measures for the possible loss reduction and particularly their effective implementation. Next items described technologically provoked problems in the salt mines Mirovo near Provadia, Bulgaria and Starobin, Belarus.

General information

Provadia. The Provadia salt deposit is the only terrestrial salt deposit in Bulgaria. It is placed in industrial area, 50 km inland westwards of the Black Sea and the town of Varna.

The mining process and the exploitation have been started some 47 years ago by leaching caverns into the salt deposit. The salt is extracted by solution from three levels in depth – 700, 1000 and 1200 m, using telescopic borehole system circulating water at a well head pressure of 50 bars. There are 43 underground chambers with diameter varying between 100–140 m and height in the range 50–200 m. The roof of the chambers is controlled by floating oil layer.

During the last 15–20 years the population in the region has become increasingly alarmed by two problems – increased seismic activity and large surface subsidence, which influence the salt body, the whole underground chamber pillar system and the salt extraction installation and all the equipment in the target area, as well as the neighbourhood villages.

Starobin. Mining works at the Starobin deposit of potassium salts started in the early sixties of the past century. At present four potassium mining works are operating and the fifth one is under construction. The II and III potassium horizons located at depths from 400 to 1000 m. At the first stages clearing works were performed with the chamber method. At present various kinds of mining by the wall method are used. The total thickness of impermeable layers ranges from 210 to 250 m.

Like in the case of the Provadia mining region, negative ecological consequences are considerable deformations of the ground over worked out underground mines, vast areas occupied by wastes of potassium production, as well as phenomena of induced seismicity. An intensity of individual shocks is as high as 4–5 on the MSK-64 scale. The impact of deposit mining work is responsible for troughs resulted from pushing together movements and for deformations of buildings and constructions on the earths surface.

Geological settings

Provadia. Generally the lithosphere of the Balkans shows a rather complex tectonic structure indicating a complicated stressed pattern and differential movement of micro plates. The thickness of the crust (depth of Mohorovicic discontinuity) varies between 30 and 36 km, with a maximum in the western and southern parts of the Moesian mega block (to which the salt deposit belongs), a minimum in the depression and the shelf section of the Black Sea. The salt deposit is the only terrestrial salt deposit in Bulgaria, several km across at its surface exposure, extending and broadening to depths perhaps 3500 m. It passes trough the whole sediment complex including Perm to upper Eocene and is covered by Quaternary depositions. Starting from 12–20 m under the surfaces, the salt, with a shape of a frustum of a cone, reaches depths of 3500–4000 m, where a salt layer is formed. The deposit is imbedded in Cretaceous limestones and dolomites, and Quaternary sediments cover Paleocene marlstones and it. The salt body is in contact with the surrounding rocks by the so-called residual breccia. The rock salt massif, built up predominantly by halite, is rather inhomogeneous. For example, the compressive strength varies from 8.5 MPa to 30 MPa with average values $R_c = 14 - 16$ MPa (lab. tests) and R_c mass = 5.5–5.8 MPa (massif).

The neotectonic and recent features of the Provadia region's formation are conditioned by its location. The recent vertical movements (state geodetic network data) of this region are influenced more by Balkanidi development features than the Moesian platform ones. There is a positive correlation between the neotectonic and recent vertical movements, showing the continuation of the general trends of the tectonic regime, occurred during the neotectonic stage of the discussed region development, in the recent epoch (Paskaleva et al. 1992, 1994).

During the period 1981–1991 extensive geodetic measurements have been carried out to monitor the vertical movements. They show that, there are movements along some faults in the salt deposit region. The central part of the deposit goes down and the velocity decreases going far from the center. This means, that the movements along the faults limiting the deposit continue. The geodetic observations have been processed on large and close net. A constant subsidence with average velocity 3–4.5 cm per year and horizontal block movements have been observed in this region for the recent few years. The largest subsidence is observed in the central part where the top of the salt body is located.

Starobin. The Starobin deposit of potassium salts is situated in the north-western centroclinal part of the Pripyat Trough, which is a sublatitudinally strikig palaeorift.

Saliferous strata are interbedded members of potassium salt and carbonate-clayey rock, as well as of sandstone and siltstone layers. The deposit territory is of clearly defined block structure. The subregional Liakhovichi and Lusk faults with amplitudes of 150–350 m bound it on the north, and by a set of faults forming the Southern tectonic zone on the south. The Central, North-Western, Northern (Guliayevo) faults are running immediately within the deposit and divide the territory into the eastern, central, western and north-eastern block. Four potassium horizons are found within the saliferous strata; the II and III ones are mined. The II potassium horizon occurs in the depth range from 250 to 700 m, the III potassium horizons — from 350 to 1000 m.

In the region of the Starobin deposit the crystalline basement occurs at depth of 1700–2100 m. Upper-Proterozoic formations overlie it conformably and are represented by Riphean and Vendian complexes. The Paleozoic erathem involves the middle and upper divisions of the Devonian.

Saliferous strata with abundant potassium horizons are of Lebedian-Streshin age (D_3^2 lb-str).

A thickness of sub salt clayey-marlaceous deposits varies between 230 and 560 m.

The Mesozoic erathem comprises deposits of the Jurassic and Upper Cretaceous. Mainly sandstones represent the Palaeogene. The Neogene is restricted in area. Quaternary deposits are 20 to 150 m thick.

Some active faults were identified from a series of aerospace survey and geologic and geophysical data obtained in the region of the Starobin deposit. Systems of lineaments distinguished show correlation with the preplatform and platform faults, as well as with dislocations of disjunctive nature. The Stockhodsk-Mogilev super regional fault belongs to the preplatform age structures, and the Liakhovichi, Chervonaya Sloboda, Rechitsa, Glusk and Mikashevichi faults are structures originated at the platform stage of evolution.

When potassium ores were mined in the Starobin deposit region a number of geological features was revealed, such as:

— rock fissuring,

— zones of rupture dislocations,

— zones where salvinite was replaced by potassium salt in productive beds,

— subsidence troughs and their associated gas-dynamics phenomena,

— squeezing-out brine inflows into mine works (Vysotsky et al. 2003).

As regards seismic processes, their effect on mining works was not appreciable until the present.

The regional seismic situation and monitoring

Provadia. The Provadia region is considered to belong to a zone with moderate seismicity between 1900 and 1970 (Ranguelov et al. 1994). The seismicity of this region is determined mainly by the Devnia fault in the north of Provadia. The region is characterized by compression stresses in NE-SW direction that is in agreement with the general situation in northern Bulgaria (Knoll et al. 1995, Karaguleva et al. 1974). According to the potential seismic source map the maximum expected magnitude at this site is $M = 5.6 - 6.0$ and depth 5–10 km. Within the time, since 1900 there were only few events felt near the Mirovo salt deposit (in 1901, with $M = 3.8$ and epicentral intensity $I_0 =$ V MSK-64; 1901, $M = 3.6$, $I_0 =$ V; 1902, $M = 3.6$, $I_0 =$ V; 1903, $M = 2.6$, $I_0 =$ III). Up to 1964 there are not other data concerning the seismicity of the Mirovo district. Generally the seismic regime of the whole Bulgarian territory is characterized by a recurrence rate with relatively low slope, which is 0.36 for the period 1900–1930 and 0.34 for the period 1931–1970.

The nearest seismological station, PRV (Providian), was established somewhere in 1980. In 1981 a strong ground motion network with five instruments SMA-1 was built. The digital Reftek station was installed and calibrated by the GTU Engineer Bureau Knoll specialists.

About 81 events within epicentral distance up to 27 km occurred in the last 20 years. More than 200 strong ground motion components registered by the SMA-1 instruments were processed. All the records are "saturated" with high frequency vibrations. According to the response spectra for the accelerations and 5 % damping the maximum periods are in the range 0.085–0.2 sec for the vertical and 0.1–0.57 sec for the horizontal components. Another feature of these events is their short duration (0.12–2.97 sec); most of these earthquakes act as impact excitations. The peak ground accelerations are quite high, in some records they overcome 0.5 g. The dynamic effect of single events obtained from the response spectra with 5 % damping varies from 1.2 to 6.0 for the horizontal components and reaches up to 7.0 for the vertical components. The ratio between the peak accelerations, vertical and horizontal, is 0.17–2.26, which shows the predominant influence of the vertical component and confirms the local origin of the earthquakes. The duration of the intense part of the accelerograms is about 3 sec. Such short duration means that these events act as single short-time impulse load on the chamber-pillar system. The fact that the peak vertical accelerations are often higher than the horizontal (50 % of the registrations) has to be considered when performing a dynamic analysis of the stress-strain state of the system too, since there is a possibility for pillar failure due to vertical cracks occurrence. The available records can be efficiently used for the vulnerability analysis of the structures in the region of Provadja, for pillar capacity reestimations.

Starobin. According to a division of the east European platform west into seismotectonic regions, the territory of the Starobin deposit of potassium salts is related to the Pripyat potentially seismic super zone with a magnitude $M = 4.0$ and a focus depth $H = 5$ km (Garetsky et al. 1997).

As to induced earthquakes, the first of them was recorded in 1978 ($K = 9$ $I_0 = \mathrm{V}$) by the seismic station "Minsk" located at a distance of 170 km from it. Continuous instrumental seismic observations in the deposit region were carried out in 1983 by equipment with short period seismographs. Operating frequency bands were 1–10 Hz with analogous recording. Besides within 1983–2000 observations were carried out by self-contained seismic instruments with operating frequency bands of 0.5–60 Hz and duration of independent work of 20 hours, and the information was recorded on magnetic tape. About 1000 seismic events were recorded in the region within this period (Aronov et al. 2003).

A seismologic telemetric complex was installed in 2004, and the information was transmitted into the computer. At the first stage the complex was composed of four observation stations. A total of six observation stations were envisaged. Each station was instrumented with three-component short-period seismic detectors with capacitance-type transducer and magnetic-electrical feedback. The operating frequency band was 1–70 Hz. The information was continuously transmitted to a computer in the real time network and then to a computer when it was accumulated, processed and stored. Observation stations were located both in mines, and on the ground surface. A dynamic range was at least 120 dB. A reception range was at least 30 km.

A three-level database was the result of long-term seismic monitoring based on an automated telemetric complex:

- *Level* 1 contains general geological and geophysical information on the territory under monitoring, specific data on the seismograph network, tectonic blocks, velocity models, seismic wave travel time curves, etc.
- *Level* 2 contains digital seismograms of recorded seismic events, digital event
- Seismograms, arrival times and amplitudes of seismic phases, major wave groups with maximum amplitudes, etc.
- *Level* 3 contains the main results of interpretation, i.e. space and time, energy parameters of foci of seismic events as well as some other parameters.

The data are considered to be most important for studying geodynamics of the Soligorsk industrial region.

Results

The map of epicenters of the Soligorsk seismic events recorded in the period from 1983 to 2004 is presented in Fig. 1. Over the period mentioned more than 1000 seismic events have been registered in the area monitored, 4 of which produced a tangible effect: 10 May 1978; 2 December 1983; 17 October 1985; 15 March 1998. The energetic class which is connected to the magnitude correlating $K = 1.8 \cdot M + 4$ for those events are located within the diapason of 8.0–9.5. The intensity of soil shaking rose up to 4–5 scores. All the earthquakes were accompanied by macrofeelings: rumble, window glass rattling, swaying of hanging objects, furniture and floor creaking on the ground floors of wooden constructions. The scattered plaster cracks were observed. During the earthquakes 1978 and 1998 roof collapse took place.

This map also shows rupture dislocations active at the present-day stage. The strongest seismic events recorded recently in the Soligorsk region are confined to zones of tectonic disturbances active at the latest stage. These are a set of the North-Pripyat super regional faults, the Chervonaya Sloboda and Stokhodsk-Mogilev fault systems. This is also evidenced by the prevailing fracturing orientation measured immediately in mines and by the regional stress system of the East European Platform west.

At present continuous seismic observations at the Soligorsk geodynamic testing ground are carried out with an automated telemetric seismic complex intended for prompt monitoring of space and time distribution of seismicity and assessment of the geodynamic environment by outlining seismically active areas (tectonic blocks).

The Provadia deposit area is situated in the eastern part of Bulgaria. Seismic observations have been carried out there since 1994 by a local network of five stations.

The map of epicenters of seismic events in the Provadia region is presented in Fig. 2. This map also shows the location of local seismic stations that are operating there. The distribution of epicenters suggests that they are tending to linear arrangement in a direction from southwest to northeast along the profile joining the

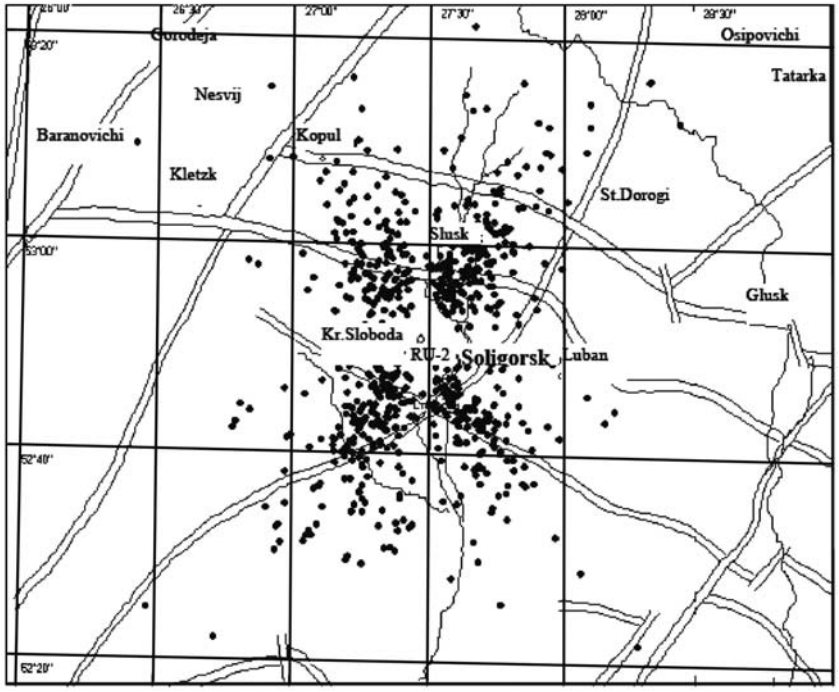

Fig. 1. Map of epicenters of seismic events in the Soligorsk region

settlements of Dulgopol and Tolbukhin. Most of epicenters are confined to a zone measuring 20 km across and situated between the settlements of Markovo, Dulgopol and Momino. The strongest earthquake of this region with a magnitude of 4.4 also took place there in December 18, 2003.

The other smaller zone where epicenters are abundant is situated 30 km southwestward of the settlement of Tolbukhin. The area of epicenters extends to approximately 70 km sublatitudinally and 65 km submeridionally. In the first epicentral zone events with a magnitude of $1.5 - 2.4$ are slightly prevalent, and in the second zone events with a magnitude of $2.5 - 3.4$ are dominant.

In both deposits epicentral areas of seismic events overstep the limits of mine workings. This is typical of induced seismicity zones.

The seismic energy of the Soligorsk events was calculated from wave patterns. The energy in Provadia was calculated from the local magnitude using $\text{Log}\, E(J) = 1.8 \cdot M + 4$.

Figure 3 presents a curve of recurrence calculated by the method of intervals for both regions. The average annual value of a number of seismic events is plotted as ordinates. This curve shows that in the region of Soligorsk the seismic activity is higher for a range of energy classes 4–9. The curve shape in this range is almost uniform. It should be noted that this range of energies corresponds to rock-tectonic shocks according to Malovichko classification (Malovichko et al. 2000). A quasi-similarity of curves suggests the similar origin of seismic events.

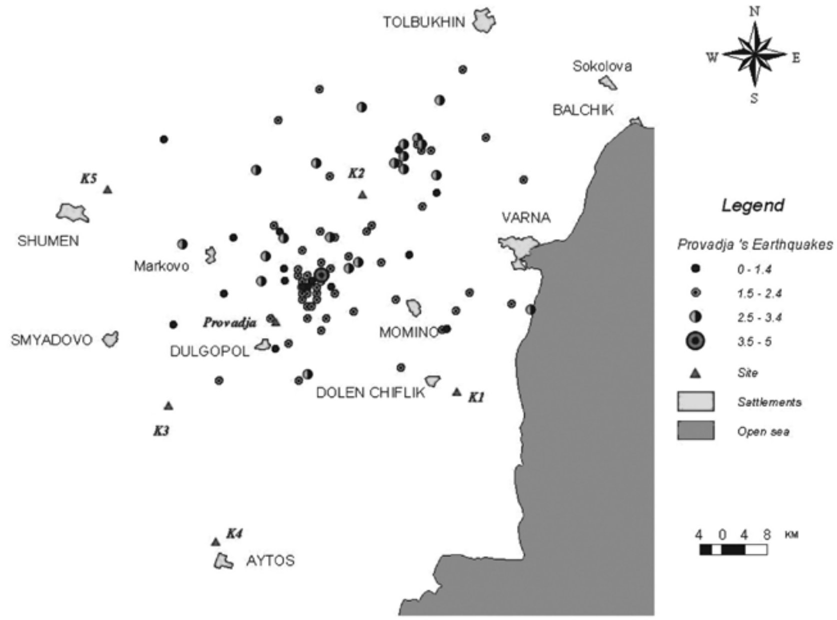

Fig. 2. Map of epicenters of seismic events in the Provadia region

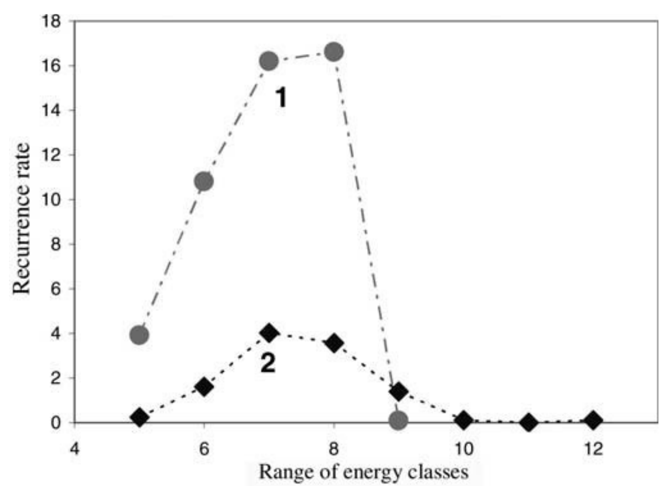

Fig. 3. The curve of recurrence for the Soligorsk (1) and Provadia (2) regions

However, in the Provadia region seismic events with energy class of 9 and higher, i.e. in the energy range related to "technogenic" earthquakes (4) are more abundant. One earthquake which took place between the settlements of Markovo and Momino in December 18, 2003 had a magnitude of 4.4 ($K \approx 12$). The time distribution of seismicity in Provadia in Fig. 4 a, b and Soligorsk is shown in Fig. 4 c.

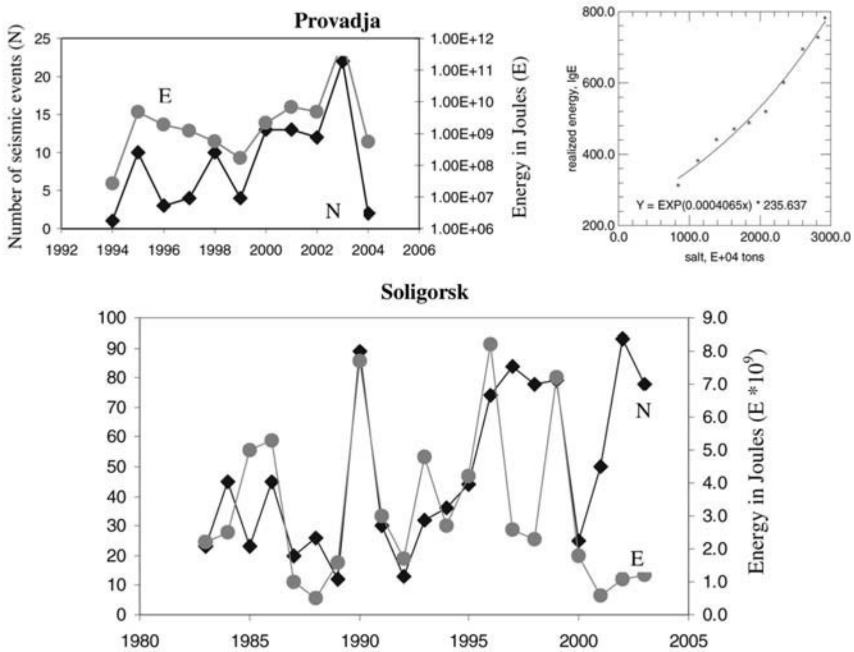

Fig. 4. a) Annual number of seismic events (N) and annual values of seismic energy (E) for the Provadia. b) Released energy versus extracted salt quantities, considered period – up to 1995. c) Annual number of seismic events (N) and annual values of seismic energy (E) for the Soligorsk region

This figure represents the total annual number of seismic events and the total (cumulative) released seismic energy.

A quasi-periodic character of a number of seismic events with the general tendency to increase is characteristic of the Provadia and Soligorsk regions. The total annual energy value agrees in general with the number of events. This regularity has been slightly disturbed since 1996 in the Soligorsk region. When a number of events increase there the total annual energy is tending to decrease. For the curves drawn from the Provadia data two extreme points are not informative, since during 1994 and 2004 the observations were not carried out regularly there.

In the Soligorsk region the events of the small energy class are dominant suggesting a technogenic effect. Besides, there are suppositions that the seismicity in the Soligorsk is influenced (though to a lesser extent) by the other factors, e.g. lunar-solar tides (Seroglazov 2003). In the Provadia region tectonic processes seem to play the more important part, which is confirmed by the stronger seismic events that occur there. This is due to the fact that the Provadia region is situated in a seismically active zone.

Conclusions

Seismic processes in the regions of potassium salt deposits of Provadia and Soligorsk show the following characteristic features: a) the identity of the curves of recurrence of seismic events in the energy range of 4–8; b) a quasi-periodic character of the seismicity activation in time is observed; c) increasing of the seismic activity as a general trend is established; d) it is turn out that the zones of epicenters of seismic events are larger that mining areas.

There are some differences in the pattern of seismic processes, such as: a) seismic activity in the range of small energies ($K = 4 - 8$) is higher in the Soligorsk region than elsewhere; b) events of the highest energy class $K > 9$ are characteristic of the Provadia region.

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