GEOPHYSICAL PROCESSES AND HUMAN ACTIVITIES

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Contents

Summary

Geophysical processes affect anthropogenic structures such as buildings and other engineering constructions, and they also endanger human life. On the other hand, human technical activities also influence some of the geophysical processes in the near-to-surface crust. This document is a treatise on mutual interaction between seismic and human activities. The seismic activities affected by human activity are primarily those induced by mining and water reservoirs. The instabilities which manifest themselves by sliding of geomaterials on slopes are caused both by natural processes (such as rainfall, weathering, earthquakes, volcanic activity, temperature variations, etc.) and by geotechnical operations (such as artificial embankments). Movements of natural, as well as artificially induced origin are very frequent geodynamic phenomena, and cause serious direct and indirect damage to buildings, roads, mining and water reservoir facilities, and linear constructions like power and pipe-lines.

The hazard to human security and buildings caused by technical seismicity is also discussed in this document. This includes seismicity induced by various forms of production, industrial and military blasting, vibration generated by transport, operation of machines, and pulsations of water flows. Finally, there is a section on earthquake hazard, which discusses risk of impact to surface buildings, water works and mining structures.

1. Introduction

With the progress of technical civilization, mainly in the twentieth century, extraction of mineral raw materials and consumption of energy have increased very rapidly. Extraction of fuel, metallic and uranium mineral raw materials involves mining operations, either in underground or open pit excavations. Energy production is founded mainly on the following resources:

- Black and brown coal
- Rock oil (and gas)
- Water flow
- Nuclear reactions

All these activities take place in the biosphere, on the surface and reaching to depths of a few kilometres into the Earth's crust, and they can affect various geophysical processes.

Generally, geophysical processes take place in astronomical dimensions (e.g. Sun–Earth relations), in global dimensions (e.g. plate tectonics) and in biosphere dimensions. term The phrase 'geophysical process in the biosphere' embraces the reaction of the upper part of the Earth's crust to variations of acting mechanical forces, physical parameters of rock massifs and physical processes in the atmosphere. Some geophysical processes in biosphere run very slowly (e.g. tide deformations, surface subsidence, etc.), and some of them have the character of sudden catastrophic events (e.g. earthquakes, landslips, floods, volcanic eruptions, atmospheric storms, etc.).

Geophysical processes, which can be influenced, induced or triggered by human activities are as follows:

- seismic events induced by mining,
- seismic events induced by construction and operation of water reservoirs and dams, and
- sudden landslips caused by geo-technical activity or variation in subterranean water flow.

On the other hand, technical structures can be disturbed by natural geodynamic processes taking place in the biosphere or its vicinity. Buildings and other man-made structures can be affected by earthquakes movements, storm rainfall, sudden landslips, rock fall, extreme temperatures and air movements.

In this article, we will discuss processes taking place only in the shallow part of the Earth's crust:

- Mining induced seismicity (MIS),
- Water reservoir induced seismicity (RIS),
- Landslide movements, and
- Seismic impact

Human activities significantly influence coastal processes but this is described in *Structure and Function of Marine Shoreline Ecosystems* and, therefore, it is not discussed here. Nuclear test explosions in the second half of the twentieth century had impacts on the environment, but hopefully any future testing will be very limited in scale. Discussion of catastrophic events in the atmosphere belongs to the field of meteorology and atmospheric physics (e.g. storm rainfalls, extreme changes of temperature, windstorm, progression of the ozone layer, etc.). Human-induced electromagnetic radiation may affect the magnetosphere and Earth's radiation into space, but these processes at least at present do not affect the human environment.

2. Mining Induced Seismicity

Deep mining activity induces significant interference in the state of the primary rock massif. The primary stress field is formed by:

- overburden weight (geostatic stress),
- tectonic stress (residual stress),
- thermal stress,
- cosmic factors (changes of centrifugal acceleration of Earth rotation, tidal forces, etc.), and
- change of Earth surface loading in connection with meteorological and hydrological processes.

Stress distribution in rock massif is non-uniform, as the rock massif is discontinuous, heterogeneous and anisotropic. For example, the local maxima of stresses is in the vicinity of cracks.

Due to creation of free mining spaces the three-axis stress state partially drops to biaxial stress, and the stresses increase around the mine openings. Interaction of these changes induced by human activities and primary stress-strain state, tectonic conditions and physical properties of rock, can precipitate sudden, brittle and irreversible deformations. Seismic energy is released during this process. These phenomena are called mining induced seismic events (MISE), or mining tremors. From the physical point of view they are the analogue to tectonic earthquakes. These seismic events, which affect work activity, are called rockbursts. The strongest mining tremors reach magnitude as much as M = 4.5.

Extensive studies of mining seismicity have been carried out in the following countries:

- **South Africa:** Gold bearing reefs of Witwatersrand. Depth of mining excavations is more than 3.5km; Western deep gold mine; Welkom gold mines; Klerksdorp mining area.
- **Poland:** Upper Silesian Coal Basin; Lubin Cooper district in Lower Silesia.
- **Canada:** Sudbury mining district (Ontario); Northwestern Quebec district (depth is about 2 km); Noranda mining camp.
- **USA:** Wasatch Plateau and Book Cliff coal mining districts; Gentry mountain area (maximum local magnitude M = 3.8); Coeur d'Alene mining district (Idaho); Lucky Friday mine.
- **Czech Republic:** Ostrava – Karviná coal mine (Upper Silesia); Kladno coal basin; Příbram ore mines; Příbram uranium mines (maximum depth as much as 2km).
- **India:** Kolar Gold Fields (Karnaka state) – depth exceeding 3.2 km.
- **Russia:** Doneck basin; Kuzneck basin; Khibiny massif apatite deposit (Kola Peninsula) – the strongest tremors have magnitude M = 4.3, in Kirovsk mine; Northern Ural bauxite mines (maximum M = 3.5); Tashtagol iron-ore deposits (Gornaja Shoria) – M = 3.5.
- **China:** Taiji coal mine (Beipiao county) - M = 4.3; Xilin, Haizhou, Wulong , Aiyou coal mines; Binngou coal mine (Jianchang County) – M = 3.9.
- **Australia***:* Bowen basin – coal mines; Capcoal's Southern Colliery, German Creek; Gordonstone mine (Central Queensland); Newstan, West Wallsend, Moonee and Clarence coal mines.
- **Chile***:* El Teniente Mine – copper mine (central Chile).
- **France:** Provence Colliery – coal mines.
- **Japan:** Miike coal mine (undersea mine, Kyushu province).

In all the above mentioned mine districts, seismic monitoring systems have been installed. These local seismic networks provide instrumental data concerning the seismic parameters of mining tremors. On this basis the following tasks are accomplished:

- location of tremor's focus,
- determination of released seismic energy,
- identification of mechanism of seismic sources,
- determination of seismicity of tremor regions,
- analysis of time series of mining tremors and their forecasting.

2.1. Location of Mining Tremors

Mining tremors occurred regardless of the depth of mines (from only 200m to the deepest mines, greater than 3500m) and mined substance—coal, industrial minerals, ore, uranium etc. From this fact it follows that the origin of mining tremor is mutual interaction between natural conditions (stress–strain distribution, rock structures etc.) and mining activities. The probability of tremor occurrence increased with the depth of mining. The tremor foci are mostly clustered in the neighbourhood of excavations and tectonic faults. This fact is very important for local mining measurements. For this purpose, seism-acoustic methods—strain measuring, analysis of detailed geological conditions, geo-electrical methods, etc.—are applied. Migration of foci depends on the mining geometry and mining progress. Seismically determined coordinates of foci are fundamental information for mining tremor activity. On this basis further investigations are carried, e.g. monitoring of local stress–strain state and rock strength, determination of magnitude (seismic energy), attenuation of seismic wave amplitudes, spectra of vibrations, source mechanism, source time function, directivity of seismic wave radiation, etc.

2.2. Seismic Energy

Mining seismic networks permit monitoring of seismic tremor across a wide range of energy, from 10 Joule to 10^{10} Joule; this corresponds in the magnitude scale to values from 0.5 to 4.5. Seismic energy is released non-uniformly in time. The course of seismic energy release is demonstrated by cumulative Benioff's graphs. On the basis of these graphs it is possible to evaluate current danger of rockburst occurrence. An example of Benioff's graph is show in Figure 1.

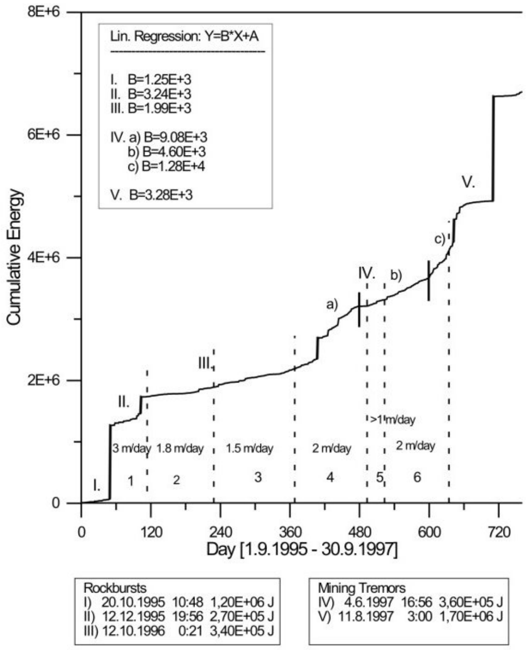

Figure. 1. Seismic energy release (Benioff's graph), from Ostrava Karviná basin (Czech Republic).
Linear regression: Y = B.X + A, where X is time in days, Y is value proportional energy, A and B parameters of regression. B is slope of straight line [E/day]. Values m/day, stated in separate intervals, denote progress of mining.

2.3. Mechanism of Mining Tremor Foci

By analysis of seismic data (distribution of P wave onsets, Fourier spectra of P and S waves, inversion of seismic moment tensor) and by laboratory experiments, it was found that the mechanism of tremor sources is complex, consisting of shear, tensile and compression movements.

2.4. Seismicity of Tremors

The following parameters of seismicity are the principal foci of study:

- Time release of energy,
- Energy-frequency distribution and its time variations,
- Spatial distributions, and
- Time distributions.

From investigation of seismicity of mining induced tremors it follows that tremor activity is a non-stationary process and energy release depends on the mining technology and on local geological conditions. The energy-frequency distribution can be described by a negative exponential relation (analogical to natural earthquake distribution). The parameters a and b of this distribution ($\log N = a - b \log E$, where N denotes the number of events which have energy E, a and b are parameters of distribution) are not constant in time. The changes of parameter b have a predictive character and therefore they were used as a precursor of occurrence of strong rockbursts.

2.5. Analysis of Time Series of Mining Tremors and Their Forecasting

Triggering of mining tremors depends, on one hand, on the natural geological conditions (e.g. structure and tectonics of rock massif, rock composition, stratigraphy etc.) and physical factors of rocks (e.g. physical parameters of rocks, stress field in rock massif), and on the other hand on mining activity (mining progress, creation of new free underground spaces, amount of mined material, mining technology, use of explosives, etc.). Because of the complexity of the process of tremor occurrence and insufficient information, especially time-space data on accumulation of deformation energy in the rock massif, the prediction of tremor occurrence cannot be solved deterministically. Therefore multi-channel statistical methods of time series extrapolation are employed. The prediction procedure is schematically illustrated as a flow diagram in Figure 2.

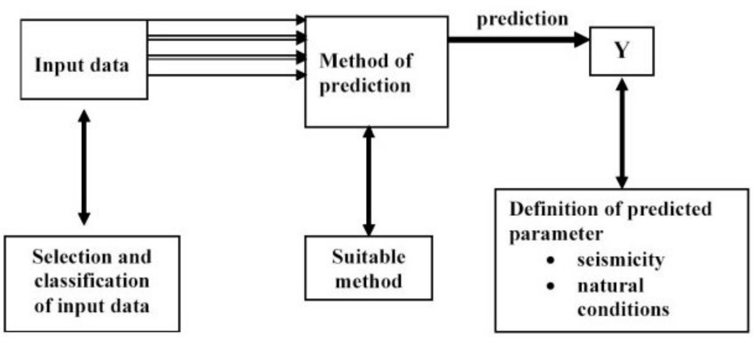

Figure. 2. Flow diagram of prediction of seismic events.

The *input time series* are created mainly by data from records of local seismic networks (series of foci times, energy, number of tremors recorded during certain time intervals, etc.). Seismo-acoustic, deformational and other measured data and also parameters of mining (progress of mining, technological data, etc.) can create further input time series. Success of prediction depends on the knowledge of seismic process of investigated region, on the knowledge of natural geomechanical conditions and anthropogenic impact. Under these circumstances the prediction of exact time, energy and focus position of seismic events is almost impracticable. Choice of *predicted quantity Y* has to be carried out with regard to the properties of input data. In practice it means that only integral quantities are predicted, for example the total amount of radiated seismic energy during one day, or the number of mining tremors during one day, average energy of tremor, etc.

As *prediction methods*, both linear and nonlinear methods of extrapolation of time series are usually used. The linear method is based on the Wiener approach. This practically determines the prediction filter with utilizing of correlation analysis. The nonlinear method is mainly based on using neural networks. An example of prediction of cumulative, seismic recorded, amplitude is demonstrated in Figure 3.

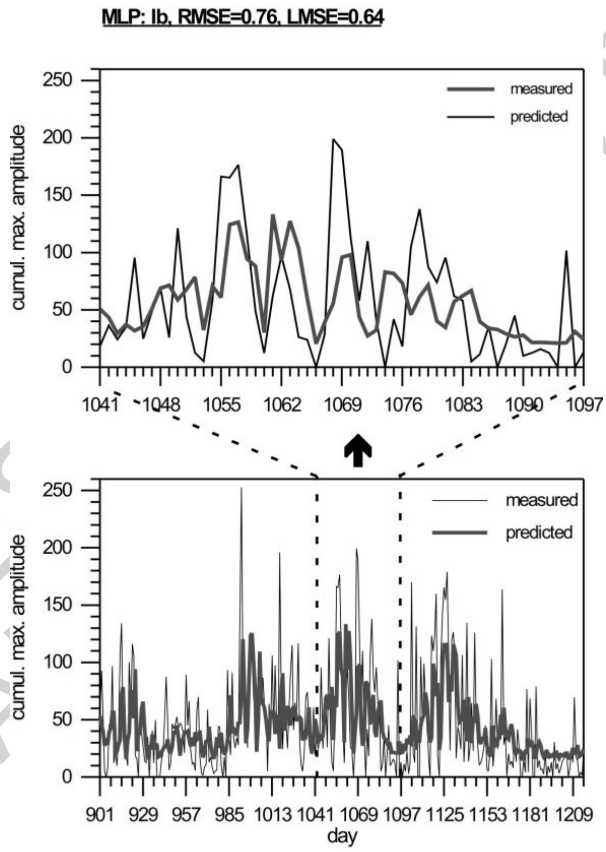

Figure. 3. Predicted quantities of cumulative seismic amplitudes by neural network method.

Success of prediction was tested by two methods:

- ratio of dispersion of series, predicted by neural network method, to dispersion of series, predicted by average value of previous data RMSE

- ratio of dispersion of series, predicted by neural network method, to dispersion of series predicted by the last value of LMSE.

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Biographical Sketch

Vladimir Rudajev,was born in November 1938, in Prague. In 1961 he graduated in geophysics at the Faculty of Mathematics and Physics of Charles University in Prague, and in 1966 he was a Candidate of Technical Science degree (PhD) from the Czechoslovak Academy of Sciences. In 1988 he was awarded his Doctor of Technical Science degree (DrSc) from the Czech Technical University. He has been employed since 1962 in the Mining Institute of the Czechoslovak Academy of Sciences, later called Institute of Geotechnics (1990-1993) and now the Institute of Rock Structure and Mechanics of the Academy of Sciences of the Czech Republic. He worked as senior scientist from 1978, since 1991 as deputy director, since 1992 as director, and since 2001 again as deputy director. His areas of research interests cover monitoring and processing of local seismic data, induced seismicity, mechanism of rockbursts foci, extrapolation of non-stationary seismic processes, prediction of rockbursts, seismic hazard, laboratory testing of brittle fracturing, and criteria of stability of rocks. He has published 132 scientific papers and 39 research reports.