Seismic Activity Induced by Water Wells in a Fractured Aquifer in the Paraná Basin, Brazil: Five Years of Cyclic Activity

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ABSTRACT

Induced seismicity is commonly associated with deep water reservoirs or injection wells whereby water is injected at high pressure into the reservoir rock. However, earth tremors caused simply by the opening of groundwater wells are extremely rare. We present a clear case of induced seismicity caused by the drilling of water wells exploiting a confined fractured aquifer in the intracratonic Paraná Basin, SE Brazil. Shallow seismic activity, with magnitudes up to 2.9 and intensities V MM, has been observed since 2004 near deep wells (120-200m deep) drilled in early 2003 near Bebedouro town. The wells, drilled for irrigation purposes, cross a sandstone layer about 60-80m thick and extract water from a confined aquifer in fractured zones between basalt flow layers (Cretaceous Serra Geral Formation). Seismic activity has occurred every year since 2004 as swarms of events mostly during the rainy season when the wells are not pumped. During the dry season, when the wells are pumped almost continuously, the activity is very low. A seismographic network, installed in March 2005, has located more than 2000 micro-earthquakes. The events are less than 1 km deep (mostly within the 0.5 km thick basalt layer) and cover an area roughly 1.5 km x 5 km across. Migration of the epicenters away from the two closest wells (which also have the largest outflows, larger than 150 m3/h) was clearly observed in 2005 with a "seismic diffusivity" of about 0.3 to 0.6 m2/s. Some additional wells were drilled in the same area in early 2006 causing a third swarm of activity starting about one month after drilling. This 2006 swarm also showed a clear migration of epicenters with a "seismic diffusivity" of about 1.0 m2/s. The earthquake cycle repeated in the first months of 2007 and 2008. Geophysical and geothermal logging of several wells in the area showed that water from the shallow sandstone aquifer enters the well at the top, usually forming water falls, flows down the wells and feeds the confined fractured aquifer in the basalt layer at the bottom. Two seismic areas are observed: a main area around several wells which are pumped continuously during the dry season; and a second area near another well (about 10 km from the first area) not used for irrigation and which is not pumped regularly. The first area shows a cyclic annual activity whereas the second area is not cyclic. We propose that the earthquake swarms are induced by pore pressure diffusion in the fractured basalt layer, due to the extra pressure from the surface aquifer, reaching critically pre-stressed areas up to a few km away from the wells. During periods of continuous pumping, the reduction of pore pressure in the confined aquifer shuts down the seismic activity. Our study suggests that this kind of activity may be more common than previously thought, and many other cases of small tremors associated with drilling of water wells may have gone unnoticed.

Key words: Triggered seismicity, fractured aquifer, intraplate seismicity, intracontinental basin.

PRESENTER'S BIOGRAPHY

Marcelo Assumpção got his PhD at Edinburgh University in 1978. He worked in the University of São Paulo (1974-1982; 1988-present) and the University of Brasília (1982-1988). Main research interests are: intraplate and induced seismicity, lithospheric stresses, crustal and upper mantle structure with receiver functions and tomography.

Controls on the Maximum Extent of Mining-Induced Seismogenic Zones

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ABSTRACT

The public recognition that mining can induce local seismic events is growing. There have also been a number of recent examples where mining has been blamed for earthquakes that have occurred in close proximity to mining centres where causation is not so clear.

The causes, mechanisms and association between seismicity and mining have been investigated at several mines using calibrated, multi-scale, non-linear numerical models. A strong, non-linear relation between Dissipated Plastic Energy (DPE) and event probability was observed that describes the development, peak, and decline in seismicity as rock is deformed. Where sufficient data was available for a comparison, a relation between DPE and event probability consistent with the relation between event magnitude and frequency described by the Gutenberg Richter equation was found. In all cases, the maximum extent of the seismogenic zone was able to be statistically defined in terms of the energy changes induced by mining.

Key words: 1 to 5 key words in **10pt Times New Roman,** separated by commas; these will assist in the cross-indexing of the article.

Coal-mining induced events in the Ruhr area, Germany

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ABSTRACT

Induced seismicity in the Ruhr coal mining region, Germany, has been analysed since Mintrop opened the first seismological observatory in Bochum in 1908. Since 1983 seismicity in the Ruhr area induced by coal mining has continuously been monitored by Ruhr University Bochum and annual bulletins have been published. The regional distribution of epicentres shows a clear correlation with regions of active mining. About 1000 events with local magnitudes ML between 0.7 and 3.3 are recorded every year. Seismicity is of public interest as larger events with magnitudes ML ? 1.2 can be felt at the surface. Magnitude frequency distributions for the whole region will be shown and compared to distributions for single longwalls. b-values are calculated.

From June 2006 to July 2007 a dense local network was installed above a specific longwall in Hamm in the eastern part of the Ruhr region. The network provides a good dataset for detailed analysis of induced seismicity, e.g. precise localization and determination of source mechanisms. About 900 events up to a local magnitude of 2.2 were recorded each month. Localization accuracy is about 30 m. This allows a detailed analysis of the spatio-temporal distribution of seismic events. Epicentres move with the advancing longwall face at a velocity of about 100 m/month. Most seismic events occur up to 60 m ahead of and 60 m behind the face. Hypocentral depths are mainly located down to 50 m below and up to 100 m above the longwall. However, few events cluster at some hundred metres distance. In these locations coal was not extracted from layers above the active longwall by former mining. The overburden pressure may now lead to stress concentrations and seismic activity.

Smooth velocity models for monitoring of hydraulic fracturing experiments

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ABSTRACT

In oil and gas production, hydraulic fracturing is often used to increase the productivity of hydrocarbon reservoirs. Hydraulic fracturing involves pumping various types of fluids under pressure down a treatment well into the reservoir. The pressurized fluid enters the reservoir and fractures the reservoir rock. These fractures increase permeability and conductivity, and ultimately production. Creation of fractures and opening of pre-existing fractures generates microseismic events observed by geophones located in a monitoring borehole. The fracture geometry is then determined from locations of these events.

For the location of the microseismic events, a velocity model is one of the key inputs. All available data such as sonic logs, VSP traveltimes, crosswell or refraction measurements should be used to create the velocity model. The velocity model should not be too complicated to avoid multipathing, as we are usually unable to identify multiple arrivals for individual microseismic events and to include the multiple arrivals into the location procedure.

Layered 1-D velocity models composed of a set of homogeneous layers are broadly used in the geophysical community. If we use ray tracing as a forward modeling tool of our location procedure, layered models are a source of possible complications. The interfaces between the layers cause reflections and conversions of calculated seismic waves, and we thus need to specify precisely all the elementary waves which should be calculated. The layered models thus provide us with multivalued arrivals. Moreover, the thicknesses of the layers are usually comparable with the wavelengths of the calculated seismic waves, and the layered models are thus behind the limits of the validity of the ray method.

Homogeneous models are the simplest option. They provide single arrival, and there are no problems with the validity of the ray method. As the fractured rocks are usually sedimentary formations, homogeneous models are usually acceptable approximation of the horizontal properties of the structure, and they provide good estimation of the horizontal positions of the located microseismic events. For the vertical positioning of the events, the homogeneous models are usually insufficient.

Smooth velocity models appear to be optimal for the microseismic locations. If we apply the proper smoothing procedure, the models are suitable for ray tracing and provide singlevalued ray field. The velocity model should be obtained by simultaneous inversion of all available data, e.g., of sonic logs and VSP, crosswell, or refraction measurements, and the inversion should be restricted by minimizing simultaneously the Sobolev norm composed of the second velocity derivatives in the model. The resulting locations of the events using the smooth velocity model are better positioned in the depth compared to the locations in the homogeneous model.

Key words: ray method, velocity models, microseismic locations, induced seismicity, hydraulic fracturing

PRESENTER'S BIOGRAPHY

Petr Bulant was born December 7, 1970, in Prague, Czech Republic. He obtained his master degree from Charles University in Prague, 1994, in Geophysics, with diploma thesis on Two-point Ray Tracing in 3-D. He then obtained his PhD degree from Charles University in Prague, 1997, in Geophysics, with PhD thesis on Calculation of Multivalued Ray Theory Travel Times in 3-D Structures. Since 1997 he works as Research geophysicist at the Department of Geophysics, Faculty of Mathematics and Physics, Charles University in Prague. Areas of his research interests are: seismic wave propagation, computational seismology and theoretical geophysics, numerical modeling of seismic wavefields and their properties, especially construction of velocity models suitable for ray tracing, two-point ray tracing and travel time calculation, wavefront tracing, weak anisotropy.

Monte Carlo inversion of seismic waveforms generated by mining induced seismicity

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ABSTRACT

Tremendous progress in seismology has been made in the past few years greatly due to the availability of high quality seismic waveforms.
The easy access to digital, multicomponent seismic data prompts to finding new mathematical and numerical algorithms for their efficient and detailed analysis. This analysis usually takes a form of an inverse task where we try to estimate some physical parameters of rock masses or seismic rupture processes from the seismic waveforms. For years this inference was understood as a simple optimization task: finding the ``best model". Currently, this classical approach is not sufficient any more as it has been recognized that knowledge of uncertainties in the final solutions is of the greatest importance for an interpretation of the obtained results. This task can hardly be dealt with in the framework of the classical inverse theory because an estimation of the inversion uncertainties requires not only finding the optimum model but also an inspecting its neighborhood. Nowadays only the probabilistic approach enhanced by the very efficient Markov Chain Monte Carlo sampling can deal with this task. This presentation reports the preliminary results of the collective afford headed towards the routine application of the probabilistic waveform inversion in mining practice. Our primary goal of the presented here numerical analysis was demonstrating the advantages of that the Monte Carlo analysis of the full elastic waveform inversion. For this purpose we have used synthetic waveforms (as ``observational data") resembling the seismograms of small earthquakes induced by mining at Rudna (Poland) copper mine . Forward problem (waveform modeling) was solved using elastic wave equation. For purpose of inversion the vertical and radial components of the wavefield were computed. The finite difference staggered grid (FDSG) algorithm was used to perform this modeling. As a model of the rock mass medium we have used an isotropic and stratified medium based on the detailed geological model of the Polish Copper Basin with elastic constants taken from the laboratory measurements. The sources of the earthquakes were located in places where the most of the seismicity in this area occurs e.a at depths ranging from 600 to 800 m. (in anhydrite and dolomite rocks). The different types of seismic sources were tested, from pure shear to explosive ones. Inversion was carried within the framework of the probabilistic (Bayesian) approach using the Markov Chain Monte Carlo sampling technique. Actually, since no special constraints was imposed on the inversion we used the simplest sampling technique based on the Hasting-Metropolis algorithm.

Key words: seismic waveform inversion, Hasting-Metropolis algorithm, staggered grid

PRESENTER'S BIOGRAPHY

Anna Pięta is lecturer in the Department of Geoinformatics and Applied Computer Science, Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Cracow. She is interested in geophisical field modeling and inversion of geophisical data. Over the years this interest has generated research activities in geothermal field modeling, vawe propagation, inversion of geoelectiral data and application of parallel computation in geophysics. Currently she is involved in the development and aplication of computer simulation metodology of three dimentional modeling of wave propagation in parallel computer environment using staggered grid finite difference method.

INDUCED SEISMICITY IN THE NETHERLANDS

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Induced seismicity due to gas exploitation is a long standing issue in the Netherlands. Since activity started in 1986, more than 540 earthquakes have been recorded of magnitude between -0.6 and 3.5. Due to their shallow depths, events of magnitude > 2.5 are causing light damage to structures close to the epicenter. Since 1995 a network of borehole geophones is operational for monitoring the region, extended by a network of accelerometers. Analysis of data coming from these networks begins to show patterns in the locations and allows a first interpretation with respect to the processes in the upper crust.
We will present results of ongoing research in this field.

The seismic safety of the Deep South African gold mines

A probabilistic Weibull frequency analysis

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ABSTRACT

Thousands of seismic events induced at the deep gold mines of South Africa as recorded by the Council for Geoscience's National Seismological Network have been used to estimate the conditional probability of not occurrence (safety) of rock-bursts above critical magnitudes at each of the four main gold mining districts. The Weibull distributions of the time intervals separating the occurrence of events above given magnitudes are presented.
This dynamic distribution of the time intervals allows to evaluate the **conditional probability** of occurrence of similar magnitude events within given periods of time such as days, weeks, months etc under the condition that not similar events took place for different previous periods of time. This probabilistic forecasting of seismic events is in some way similar to the meteorological ones. Graphs of daily, and monthly seismic hazard at the different gold districts will be presented as a function of the time elapsed since the occurrence of similar magnitude events. The results of the Weibull distributions will be compared to the ones obtained by the Poissonian distribution of the same events.
It is suggested that the careful application of the Weibull distribution to horizontal peak ground accelerations at critical points of the mines such as the working stopes, shafts, underground tunnels etc using the very accurate seismic data obtained by the dedicated networks of the mines could provide invaluable assistance to forecast and minimize the potential damage that could be caused by large rockbursts.

KEY WORDS : Seismic hazard, Weibull distribution, gold mines, conditional probability.

PRESENTERS BIOGRAPHY: Born in Spain (1925), M. Sc. Ph. D. (Geophysics) at St Luis University, USA (1961-1965), Sub-director of the Seismological Observatory "San Calixto", and Professor of the Geological Department of the National San Andres University, La Paz, Bolivia, (1965-19700, Chief seismologist in charge of the National Network of the S. A Council for Geoscience, (formerly the Geological Survey). Pretoria, South Africa (1971-1995), Part time assistance as Adjunct Director to the Regional Seismological Centre for South America (CERESIS). Lima, Peru. (1975-1995).

The effect of fluid injection to the increase of seismicity

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ABSTRACT

Recently the borehole fluid injections have in numerous cases triggered a macroseismically observed earthquake. This has opened the question what is the expected level of the induced seismicity and what are the physical mechanisms leading to larger induced earthquakes. In this study we examine this problem using the basic principles of earthquake physics and geomechanics to disclose the processes in-volved. The basis of the proposed approach is the comparison of the hydraulic energy supplied to the rock by fluid injection and of the total energy released during earthquake. We introduce the parameter seismic efficiency of injection which evaluates the conversion of the hydraulic energy to earthquake energy. It is The new parameter was evaluated for selected injection sites in soft and hard rocks during hydrocarbon exploitation and geothermal reservoirs. The resulting values ranged from close to zero up to those larger than one, which probably results from the different amount of aseismic creep and of the strain energy stored in rocks. We also review the possible mechanisms leading to rock failure due to fluid injection with respect to its impact to rise of seismicity. The analysis using Mohr-Coulomb diagrams indicates that gradually increasing pore pressure leads to a repeated failure of the same fractures at lower differential stress. This mechanism would result in gradual release of a large part of the accumulated strain energy in the vicinity of the injection and to accelerated energy release in the whole affected rock volume. However, the increased pore pressure can probably also result in generating larger events by smoothing the heterogeneities of the fault planes leading to interconnecting adjacent asperities and to simultaneous rupturing of larger fault patches. This mechanism would be probably manifested in the decrease of the b-value of the Gutenberg-Richter distribution. Based on the energy conservation of the induced events, we propose a quantitative model relating the change of b-value and of the maximum observed event magnitude. Both parameters, the seismic efficiency of injection and b-value, could be used during injection experiments to anticipate the change of magnitude level of induced events.
It appears that in low-seismicity areas the released earthquake energy comes mainly from the hydraulic energy of the injected fluid. However, in the areas with higher seismoactive potential, the hydraulic energy facilitates the release of strain energy stored in rocks and represents a trigger mechanism for generating larger earthquakes.

Key words: induced seismicity, fluid injection, triggered earthquakes.

PRESENTER'S BIOGRAPHY

Born: 1961 in Prague, Czechoslovakia

Academic history
1987 graduated in applied geophysics, Faculty of Science, Charles University in Prague
2005 PhD. degree in geophysics, Faculty of Mathematics and Physics, Charles University in Prague

Appointments
1993 - 1995 researcher at the Institute of Rock Structure and Mechanics, Czech Acad. Sci., Prague
1996 - 1999 programmer at Digital Equipment, later Compaq Computer
2000 .. researcher at the Institute Geophysics, Czech Acad., Sci., Prague
2008 .. researcher, lecturer at Faculty of Science, Charles University in Prague

Research interests
Swarm earthquakes – precise location, focal mechanisms, triggerring mechanisms; Automated processing of seismic data; Injection induced seismicity

Publications: Author or co-author of 18 scientific papers in IF journals. It can be found about 140 citations to his papers in geophysical journals

Triggered Earthquakes at Koyna, India

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ABSTRACT

Seismic activity in the vicinity of Koyna and Warna reservoirs, in western India has now continued for over 45 years. In 2005, we started examining the seismic data in near real time. We find that earthquakes of M ~ 4 are generally preceded by well-defined nucleations. We also showed that recognition of this nucleation phase in real time can lead to short term earthquake forecasts. Here we report that the current seismic activity in the Koyna region can broadly be divided in three zones. While the M ~ 4 earthquakes in Zone-A are preceded by well defined nucleation starting some 100 to 400 hrs before the main event, the same is not true for the earthquakes occurring in Zone-B and Zone-C. The paper presents the details of observation of occurrence / non-occurrence of the nucleation and offers some possible explanation.

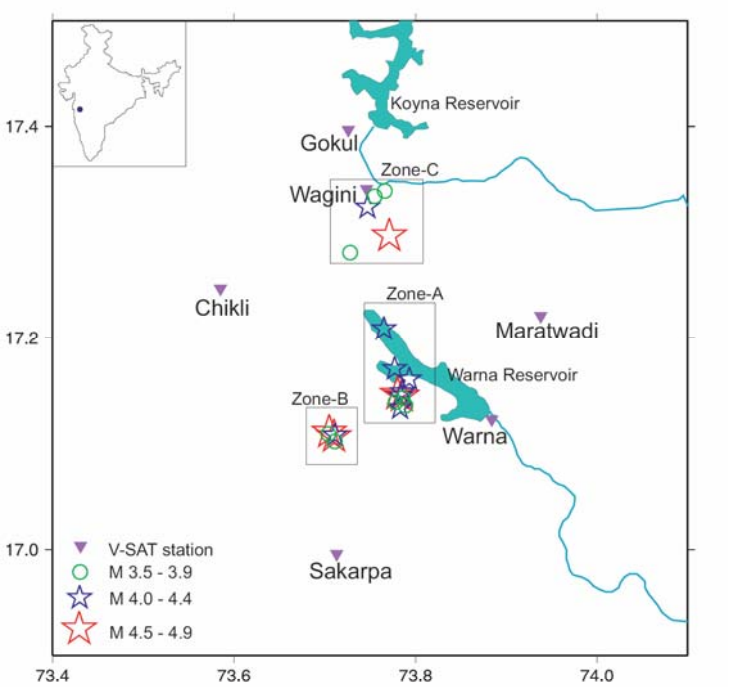

Figure: Shows the earthquakes of M ≥ 3.5 in the Koyna-Warna region, India from August 2005 to 23rd September 2008.

Key words: Koyna and Warna reservoirs; western India; nucleation; short-term earthquake forecast.

PRESENTER'S BIOGRAPHY

Harsh Gupta, Vice President of IUGG, is deeply involved with the mitigation of natural hazards, particularly earthquakes. Currently he is the Member CSPR of the ICSU, Chair of the ICSU Regional Office for Asia and Pacific's Group on Natural Hazards and President of Geological Society of India. He is well known for his work on artificial water reservoir triggered earthquakes. He has authored over 150 scientific papers and four pioneering books (all published by Elsevier).

Source mechanisms of microearthquakes induced during the injection experiment 2003 at the HDR site Soultz-sous-Forets

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ABSTRACT

Significant non-double-couple components of moment tensors (MTs) of intraplate earthquakes are often thought to be attributes of tensile forces due to pressurized fluids acting in the source. However, a question of interrelation between the non-double couple components and fluid-triggered earthquakes remains still unresolved. To clear up this issue we estimated and analyzed source mechanisms of microearthquakes induced by the fluid injection in the Soultz-sous-Forets geothermal field (Alsace) in 2003. During the injection with the flow rate of 30 to 50 liter/s and the well head pressure up to 16 MPa a cluster of several thousands of $M_L \leq$ 2.9 microearthquakes were induced at depths between 3 and 5.5 km.MTs of 50 selected M_L=1.4 - 2.9 events covering the whole 2003-seismicity in both 11-days duration and 3.2 km^3 focal volume were retrieved. We inverted the peak P-wave amplitudes of the ground displacement from 12 to 14 surface stations distributed uniformly on the focal sphere. A 1D isotropic P-wave velocity layered model of the Soultz upper crust were used for calculating Green's functions. To minimize errors due to mismodelling of the medium response the focal cluster was divided into cells in size of 400x 400x 400 m (comparable with the prevailing wavelengths), for each cell Green's functions were computed. Resultant MTs were decomposed into the double-couple (DC) isotropic (ISO) and compensated linear vector dipole (CLVD).
We found that source mechanisms of all the treated events possessed DC-components mostly larger than 90%, minor non-double-couple parts were found to be insignificant. Each of the resultant MTs were tested for stability to the reduction of the stations used, structure mismodelling, incorrectness of the amplitude readings due to distortion by noise, and weighting the input data. This way arising non-DC components >10% were evaluated applying the F-statistics on the MT and DC-constrained solutions; these tests also shown insignificancy of those non-DC components. Thus we can conclude that all the larger 2003-Soultz-microearthquakes (M_L>1.4), which were induced by hydrofracturing with the fluid pressure up to 16 MPa, were pure shear slips.

Key words: Microseismicity, moment tensor inversion, hydrofracturing, significance of non-double-couple components.

PRESENTER'S BIOGRAPHY

Josef Horálek

Josef graduated from the Czech Technical University, and holds the PhD degree from the Czechoslovak Academy of Sciences in geophysics. Since 1973 he has been working in the Geophysical Institute of the Academy of Sciences of the Czech Republic in Prague, in department of seismology; currently he works as a Senior Researcher. His major subject field in the last fifteen years has been intraplate West Bohemia/Vogtland earthquake swarms. His recent investigations have been mostly aimed at triggering mechanisms and driving forces of earthquake swarms, and at the role of crustal fluids in the earthquake origination. This is reason why he also deal with earthquake sequences induced during the injection and circulation experiments at the HDR site Soultz-sous-Forest in France.

Moment tensor inversion from linear array of receivers reveals non-shear events induced by hydraulic fracturing in sedimentary formation

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ABSTRACT

We developed a new method to invert source mechanisms of seismic events observed from a linear array of receivers. While a vertical (or near vertical) array of receivers in a 1-D isotropic medium does not allow a full moment tensor inversion (i.e. all six components), we can determine five components of the moment tensor in a specially orientated coordinate system. Then the full moment tensor for each event can be obtained by adding an arbitrary value of the sixth component, resulting in a set of possible source mechanisms. If additional information on a possible source mechanism is available, we may constrain the full moment tensor. Alternatively, we may test if a type of a source mechanism is consistent with the five constrained components of the moment tensor, i.e., if such source mechanism is part of a set of possible source mechanisms.

This technique was tested on a synthetic dataset and applied to a seismic dataset acquired during hydraulic fracturing of a sedimentary formation. We showed that a crack-opening seismic event recorded on a single vertical array can be inverted as a pure shear seismic event, indicating that the best fitting shear mechanisms inverted from seismic data acquired along a vertical borehole provide misleading information. We found that the majority of the analyzed source mechanisms of the induced events are not consistent with pure shear faulting as previously thought. The non-shear source mechanisms are required even when seismic noise, location uncertainty, and uncertainty in the attenuation structural model are considered.

Key words: Moment tensor inversion, non-double-couple mechanisms, hydraulic fracturing, induced seismicity.

PRESENTER'S BIOGRAPHY

Zuzana Jechumtalova – B.Sc. (Physics), M.Sc. (Geophysics), Ph.D. (Seismology)

Zuzana graduated at Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic, and holds the Ph.D. degree from the same faculty. During her studies she had been working in the Institute of Geotechnics within the Academy for two years, dealing with data from mining seismology. After finishing M.Sc. studies, she joined the Geophysical Institute of the Academy, where she works as a Researcher at the Department of Seismology. She has been dealing with inverse problems in seismology, particularly in determination of earthquake source mechanism, geodynamics and hazard assessment. She has been dealing with hydrofracturing data since collaboration with Schlumberger Cambridge Research in the framework EU project MTKI-CT-2004-517242 Induced Microseismics Applications from Global Earthquake Studies. She is author or co-author of 12 scientific papers.

Productivity of mine tremor aftershocks

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ABSTRACT

Mine tremors and their aftershocks pose a risk to mine workers in the deep gold mines of South Africa. The statistical properties and productivity of aftershocks were studied in order to assess the hazard and manage the risk. Data from two gold mines in the Carletonville mining district were used to analyse properties of stacked aftershock data. Mainshocks were stacked at the origin in time and space and aftershock sequences were studied. The mine tremor aftershocks were found to satisfy Gutenburg-Richter scaling, with a *b*-value close to 1. Aftershock activity diminished with time in accord with the modified Omori law, with p-values close to 1. However, the relationship between the mainshock and its largest aftershock violated Båth's law, with $\Delta M \approx 1.9$ and increasing for M>3 mainshocks. The aftershock density was found to fall-off with distance as $d^{-1.3}$. Aftershock productivity (K) was calculated from the modified Omori law. Productivity was then categorised into different subsets;

- Productivity in areas with high stress levels versus areas with low stress levels
- Productivity near geological features (faults and dykes) versus areas remote from geological features
- Productivity in active mining areas versus areas where no mining is taking place.

Initial analysis suggests that aftershock productivity is greatest soon after the mine blasts when the strain rates in the seismic source regions are at their highest, in agreement with the work in Lyakhovsky and Ben-Zion.

Key words: aftershock productivity, aftershock statistics, Omori law.

Thabang Kgarume

Born in Tshwane, South Africa, in 1984, Thabang Kgarume obtained his BSc (Honours) Geophysics from the University of the Witwatersrand in 2006. Thabang is currently pursuing an MSc degree in mine seismology studying mine tremor aftershocks and their implications on seismic hazard assessment. Thabang is member of the South African Geophysical Association (SAGA).

JAGUARS project: Frequency content of aftershocks of M2.1 event recorded with high-frequency network (100 Hz <f < 170,000Hz)

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ABSTRACT

To investigate the physics of earthquakes and link laboratory and seismological observations, the JAGUARS (Japanese-German Acoustic Emission Research in South Africa) Working Group was established. The JAGUARS project continuously monitors microseismicity and acoustic emission in a frequency range from 100 Hz to 170,000 Hz at 3.5 km depth in Mponeng gold mine, Carltonville, Republic of South Africa.

JAGUARS' network is located 90 m below the gold reef, where intensive mining is performed next to a dyke of 30 m width which acts as a stress concentrator. The major components of the network are currently 8 acoustic emission sensors, one three-component accelerometer and two strainmeters. The sampling frequency of the acquisition system is 500 kHz. The whole system works in triggering mode. The time window recorded for each is event is 65 ms. Since June 2008 the network recorded more then 500,000 microseismic events with magnitudes ranging from 0 down to -4 and smaller.

On December 27th, 2007, a M2.1 event occurred 15 m from our network. More than 25,000 aftershocks were recorded and approximately 13,000 were successfully localized with an automatic localization procedure (Yabe2008). Here the aftershocks are analyzed with regard to their frequency content and compared to the regular seismic activity within the area of our interest. Analyzing the frequency content is necessary to analyze the nature of these events, their source characteristics as well as estimating the networks limitations.

We classify the events recorded with JAGUARS network into three groups: (1) events with energy at frequencies below 1 kHz, (2) events with energies between 1 kHz and 25 kHz and (3) events with energy above 25 kHz. We study the spatial and temporal distribution of the three groups comparing aftershocks and regular seismicity as recorded with JAGUARS network.

We find that high frequency records are restricted to small magnitudes and short source-receiver distances because of damping. Thus e.g. events with energy above 40 kHz could not be observed from distances further than 50 m. Nonetheless some events reach the network limit and display dominant frequencies up to 170 kHz. In the aftershock sequence a significant increase of group 3 events is observed. The total number of events recorded increase from a few/hour to several hundred/per hour. The percentage of group 3 events in the recordings increases from 15% in the days before Christmas to 40% in the aftershock sequence. Corner frequencies show that source radii of events are on the cm to m scale.

Key words: high-frequency seismic network, mining-induced seismicity, corner frequency, JAGUARS project.

PRESENTER'S BIOGRAPHY

I am currently a Phd-student at GFZ German Research Centre for Geosciences in the group "Deformation and Rheology" of Professor Dr. G. Dresen. My work is part of JAGUARS-project with a special focus on source analysis.
I received my Diploma (Masters) in Geophysics in 2006 from the University of Karlsruhe/Germany. The diploma thesis was supervised by Tom Jordan and Thorsten Becker both from the University of Southern California, Los Angeles/USA, where I was visiting researcher in 2005 and 2006. In my diploma thesis I studied the uncertainties of stress inversion methods using a numerical boundary element approach. I worked several years as a research assistant for the World Stress Map project.
My scientific interests are mining induced seismicity, source physics of earthquakes, global and local stress field.

Coseismic and Aseismic Deformations of the Rock Mass Around Deep Level Mining Excavations

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ABSTRACT

Underground sites in several deep gold mines in South Africa were instrumented with tilt-meters and closure-meters integrated with seismic monitors in order to understand the rock mass behavior around deep level mining. The rate of tilt and closure, defined as quasi-static deformations, was analysed in combination with the seismic ground motion, defined as dynamic deformations, for different geotechnical areas and different mining situations.

A good correspondence between the dynamic and quasi-static deformations was found, indicated by rapid changes in tilt and closure during seismic events and blasts. Both tilt and closure show time-dependent behavior of the coseismic and aseismic deformations.

The post-blast deformations show Omori type behavior similar to the rate of aftershocks.

Much of the quasi-static deformations, however, occurred independently of the seismic events and are described as 'slow' or aseismic events.

An interpretation of the different types of deformation in the light of the fracture regions around the mining openings is presented.

Key words: mining seismology, aseismic and coseismic deformations, underground monitoring.

PRESENTER'S BIOGRAPHY

Dr Alex Milev is a principal scientist at CSIR - Natural Resources and the Environment, Johannesburg, South Africa. He has a PhD is in physics and mathematics and extensive experience in conventional and mining seismology. He is author and co-author of more than 100 scientific reports and papers.

Modeling the interaction of seismic waves with rock fracture

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ABSTRACT

Fracture in rock mass plays an important role in determining fluid transport and rock strength, inducing elastic anisotropy and influencing other geophysical phenomena. Wave velocity is often applied in geophysical exploration to estimate the existence of rock discontinuities, and to evaluate rock mass quality. Compared to wave velocity, wave amplitude is more sensitive to the existence and properties of fractures. It is therefore important to be able to predict wave attenuation across fractured rock mass. There is an extensive literature on the subject, much of it treating an individual fracture as an interface conforming to generalized boundary conditions (BCs) in which the displacement field at the interface is allowed to be discontinuous, and the traction forces at the interface are treated as continuous and proportional to the displacement discontinuity. In this paper we undertake a somewhat more realistic modeling of a plane fracture surface, with effective BCs for displacements parallel and normal to the surface of the form

$$\frac{\eta(x)}{2}\left[u(+)-u(-)\right]-\left[1-\eta(x)\right]t(\pm)=0.$$

These relate the components of the displacement discontinuity $\left[u(+)-u(-)\right]$ at the interface to corresponding components of the traction force $t(\pm)$, and incorporate a coupling parameter $\eta(x)\in[0,1]$ which we suppose to be a smoothly varying periodic function of position x of spatial period D. Where there is perfect bonding between the adjacent fracture surfaces, $\eta=1$, while the limit $\eta=0$ corresponds to completely free surfaces. Using these BCs and a Fourier series representation of the wave field, we calculate the transmission and reflection coefficients for incident P and S seismic waves as a function of their wavelength λ, with particular attention given to the range $\lambda>D$. We further establish the existence and nature of a guided interfacial wave at the fracture interface, which in the long wavelength limit degenerates into an S wave propagating along the surface. With decrease in the average value of $\eta(x)$ and/or increase in D/λ, in general there is a decrease in transmission and increase in reflection at the fracture interface, and greater confinement of the interfacial mode near the interface and lowering of its velocity. Our model, on a larger wavelength scale, is also applicable to seismicity at mine stopes, where it predicts resonant behavior of standing interfacial modes.

PRESENTER'S BIOGRAPHY

Clifford Ndiweni works for the power utility company ESKOM as a Chief Physicist in the Nuclear Fuel Department. He graduated with an MSc in Physics from the University of the Witwatersrand in 1997. He then joined the Nuclear Analysis Section of Koeberg Nuclear Power Station, where he worked in criticality safety, heat generation, radiation shielding and source terms. He currently works for the Nuclear Fuel Department, where his interests are in site characterization of a spent fuel geological repository. He is presently also working with Professors Every and Durrheim on a PhD project that involves modeling seismic waves in fractured rock.

Strain change in rock mass in M~2 mining-induced seismicity

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ABSTRACT

Collaborating with South African gold mines and ISS International ltd, the research group for SeeSA has been attempting to elucidate rock mass response at the closest proximities of M~2 seismic sources, which should help us to understand seismogenic physics. In the paper, we review the outcome obtained specifically by the strain monitoring in a few mines over few-year periods, highlighting slow events and forerunners. We usually use a 3-component Ishii borehole strainmeter that detects a diameter change of a borehole in three directions that are angled 60 degrees from each other with a ~10^{-9} resolution and a ~10^{-3} dynamic range. We drill holes in host rock near a normal fault in subparallel with its strike, monitoring the strain to drive shearing the target faults for potential M<3 earthquakes and the normal strain in host rock clumping the target faults continuously at sampling rates of 25-50 Hz.

The strain changes in buildup periods were associated with mining and those in release periods associated largely with largest induced earthquakes (M<3), which causes strain change exceeding 10^{-4} at the maximum. At each experimental site, from tens to hundreds of catalogued seismic events caused co-seismic strain steps, but they were not preceded by perceivable forerunning phases for the events without a foreshock. During relatively seismically active periods, we found slow strain steps lasting for tens of seconds or for minutes, changing in the different manners from the strain changes in blasting hour. The clearest slow strain step was greater than 10^{-6} strain in the largest component of one strainmeter; this was dominant in shear change; small, but perceivable corresponding change was detected with the other strainmeter ten and several meters apart from the one. Interestingly, a clear, forerunning phase preceded the slow event. Although no clearer than this example, some other slow strain changes were preceded by forerunning phases. Although not dominant, it seems that such slow events prevail in seismically active area in active period at least in some South African gold mines.

Recently it is getting widely recognized that major plate boundaries accommodate slow earthquakes or very slow events at the specific regions as well as great earthquakes at the complementally other specific regions. To more accurately predict great earthquakes, we have to understand in more detail about the behavior and/or interaction of seismic and aseismic regions. Our monitoring covers the ranges in source size and duration that have never been covered with the monitoring for larger natural earthquakes. We also have successfully monitored the details of slow events. These might lead to further understanding of great earthquakes at both plate boundaries and hazardous tremors in deep mines.

Key words: monitoring very close to hypocenters, strain, forerunner, slow event, South African gold mines.

PRESENTER'S BIOGRAPHY

Hiroshi Ogasawara is a professor of Ritsumeikan Univ. and one of the representative researchers of the research group for SeeSA that consists of members from Japanese universities (Ritsumeikan, Kyoto, Tokyo, Tohoku, Nagoya and Kagoshima) , Tono Res. Inst. Earthq. Sci. and AIST Japan on Japanese side, and Witwatersrand Univ., ISS International ltd., OHMS cc, Geohydroseis cc, Seismogen cc on South African side. He has been studying mining- or flooding- induced rock mass deformation and seismicity in a Japanese silver mine over a period of 1989-1995 and six South African gold mines since 1994 with SeeSA. He has been collaborating with ISS International ltd to monitor the rock mass response at the closest proximity of hypocenters in the mines, attempting to compare the mining-induced earthquakes with natural great earthquakes, elucidating underlying physics. He has been also working in JAGUARS project.

Non-stationarity and internal correlations of the occurrence process of mining-induced seismic events

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ABSTRACT

A fully random stochastic process is stationary and internally uncorrelated. Fully random processes are inherently unpredictable. Therefore, studies of the dependence on time of the seismic process and its internal interrelations are important both for the understanding of the process as well as from a practical point of view. In the present work we investigate stochastic properties of the occurrence process of mining-induced seismicity.

Seismic activity in mines is associated with and partially controlled by changing in time mining works. Thus, its dependence on time is expectable and has already been investigated elsewhere. Detailed studies of the nature of this dependence require, however, an uncertainty analysis of the test results, which is difficult to perform due to the fact that seismic series from mines are incomparable, hence in fact only unisample tests are carried on. We overcome this difficulty complementing the standard tests results with their significance determined from bootstrap replicas of the original seismic series.

A level of deviation of the mining seismic event occurrence process from the Poisson process is investigated using the Matsumara's coefficient of randomness and the difference between the empirical cumulative distribution of interevent time and the best fit of the exponential distribution. The latter studies make it possible to determine the interevent time ranges in which these deviations are significant. Six series of mining seismic events from Rudna copper mine from Poland are analyzed. The data comprises events of magnitude range from 1-4.2, recorded in different mining stopes. In order to recognize the structure of the dependence on time of mining occurrences, the complete series of events, the subseries from shorter time periods and the subseries consisting of only stronger events are studied separately. These studies show that the mining seismic event occurrence process is the Poisson process for shorter time periods about 100 and 50 days. Secondly, this process becomes the Poisson process for subseries consisting of only stronger events. The left-hand threshold values of discrimination of event energy depending on the tested sample. In the second part of the analysis we investigate internal correlations among event occurrences. For this purpose we carefully select such fragments of the original event series which are apparently stationary. Their analyses reveal that Matsamura's coefficient of randomness is closer to 0.5 which is value Matsamura's coefficient for random process. Next, the left-hand threshold values of discrimination of event energy for fragments of the original event series were smaller that for the original event series. Finally, the mining seismic event occurrence process becomes the Poisson process for shorter time periods in particular in time periods of fragments of the original event series. That why the mining seismic event occurrence process for those fragments of the original event series is closer to the Poisson process than for the original event series.

This work was prepared within the framework of the research project No. PBS-Grecja/10/2007, financed by the Ministry of Education and Science of Poland during the period 2007 to 2009.

Key words: mining-induced seismicity, occurrence process, time-dependence, internal correlations.

PRESENTER'S BIOGRAPHY

Dorota Olszewska

Dorota Olszewska is a final year PhD student of geophysics in the Faculty of Geology, Geophysics and Environmental Protection in AGH University of Science and Technology in Krakow, Poland. Her research is connected with mining-induced seismicity and engineering seismology on mining areas, being strongly supported by mathematical statistics. In her already prepared and positively reviewed PhD dissertation Dorota undertakes the problem of estimating and incorporating site effects into attenuation relations of ground motion caused by mining seismic sources. She is an author or co-author of 12 research papers and conferences presentations from the field of mining seismology.

Significance of Static Stress Transfer in Mining-Induced Seismicity Generation Process, the Case Study of Rudna Mine in the Legnica-Głogów Copper District in Poland

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ABSTRACT

Rudna Mine is one of three copper ore mines belonging to the Legnica–Głogów Copper District (LGCD), located in the south–west Poland. The long lasting mining activity has perturbed the stress field in the rock mass, resulting in intense seismic activity. Due to its link to mining works this seismicity is generally time-dependent, and often has memory. Several authors have provided the evidence for interrelations among mining seismic events It has been suggested that the occurrence of mining-induced seismic events can result in some probabilistic triggering for the subsequent seismicity. Based on the premise that one possible cause of interactions among seismic events can be a static stress transfer, we investigate its effects for the mining induced seismicity from Rudna Mine.

We consider events of energy greater than 10^5J (ML≥2.0) with known focal mechanisms, which occurred in Rudna Mine from 1993–2006. Mining-induced seismicity is transient and depends on time-variable anthropogenic factors hence we focus on the influence of the cumulative static stress changes due to seismicity from only 1 month back. We examine the possible triggering checking correlation between event locations and the stress–increased zones, expressed by the proportion of events in dataset consistent with increased Coulomb failure function (CFF) areas.

We find that the coseismic stress changes caused by mining induced seismicity, expressed in terms of CFF are at least one order smaller than those for earthquakes. Secondly, it turns out that more than 50 per-cent of the analyzed seismic events occurred in areas where stress was enhanced due to the occurrence of previous events. Most of these events were located in regions of positive CFF changes greater than 0.01 MPa. Although the rest of the considered events were located in areas of negative CFF changes, for the majority of them the modeled rupture zone was located partially on areas of positive CFF changes.

In order to recognize the significance of the effect we test the null hypothesis stating that there is no influence of CFF changes due to previous events on the subsequent event. This hypothesis is equivalent with the hypothesis that the proportion of events located inside positive CFF areas obtained for the original event series is not greater than this proportion obtained for the series in which the events are reshuffled. To attain the significance of this null hypothesis we estimate the distribution of the mentioned proportion from 2000 results for random permutations of the original series of events. For CFF changes ≥ 0.02 bar the null hypothesis was rejected at the 95% confidence level. This result indicates that the static CFF triggering in Rudna Mine exists and this effect is statistically significant.

This work was prepared within the framework of the research project No. PBS-Grecja/10/2007, financed by the Ministry of Education and Science of Poland during the period 2007 to 2009..

Key words: LGOM, Rudna Mine, induced seismicity, Coulomb stress changes.

PRESENTER'S BIOGRAPHY

Beata Orlecka-Sikora graduated from AGH University of Science and Technology in Cracow, Poland, with Eng and MSc Degree in Prospecting and Environmental Geophysics in 2000 and a Ph.D. in Earth Science in 2005. She is presently an Assistant Professor in the Department of Geophysics at the Faculty of Geology, Geophysics and Environmental Protection. Her research activities mainly focus on the evaluation of the uncertainties in the magnitude distribution estimation for the probabilistic seismic hazard analysis, earthquake interaction and modeling the static stress transfer. The results of her work have been published in refereed journals and conference materials. She has been engaged in several projects in the fields of induced seismicity and seismic hazard financed by Ministry of Science and Higher Education, European Union, Polkowice Municipality and KGHM S.A. Enterprise.

Full waveform modeling of earthquakes induced by mining activities at Rudna Copper Mine

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ABSTRACT

Seismicity induced by mining is dangerous for people, mining excavations and surface infrastructure. Damages caused by seismic vibrations are also important from the economic point of view because of compensation payments.

In this presentation, vibrations caused by mining-induced tremors in the "Rudna" copper mine, Poland are modeled and analyzed. For people and buildings the most harmful are surface vibrations. Likewise vibrations at the exploitation level, they are dangerous for miners and mining equipment in the vicinity of excavations. The damages are especially serious if a mine is located under densely inhabited area. From economical point of view costs of damages are also large if mine is equipped with modern mining machinery. Even an approximate assessment of the energy of seismic vibrations can increase the safety of miners and reduce the costs of damages.

Copper deposits in western Poland are located in Permian sandstone and limestone sediments that form a monocline. Geological structure of this region is fairly good recognized because a large number of drilling from surface to crystalline basement. Petrophysical parameters of the rocks in this region are also known. Exploitation is carried on at a depth between 800 to 1200m where copper shells are located. Most seismicity occurs above those layers in dolomite and anhydrite rocks. They are rigid and favor the creation of seismic tremors of high energy. There were 38 seismic events of energy larger than 10e8 J registered in years of 2000 – 2005. The energy of the strongest events was greater than 10e9 J.

We estimated the energy of seismic vibrations on surface using numerical modeling of wave propagation. We used the detailed model of geological strata from the vicinity of the "Rudna" mine with randomly distributed inhomogeneities in surface watering layer. We started modeling using source mechanism of tremors related to direction of the regional tectonic stresses. It was taken from the analysis of the archival tremors registered in this area. Then we changed orientations of nodal planes of the seismic source around this direction. It helped us to analyze the influence of source orientation on the amplitude of registered vibrations. In the presented numerical modeling wave dumping was taken into consideration.

The staggered grid finite difference method was used to solve the wave equation. The large number of modeling and huge size of each model forced us to use a parallel computer cluster for model evaluation. The calculated results allow the relative estimation of vibration energy in places on the surface, which are susceptible to destruction. These places were located in highly populated towns and settlements. This allows some prevention activities in places where hazard of strong vibrations is largest to be undertaken. It is also possible to approximate the energy of the vibration in places where sensors are not located.

Key words: induced seismicity, wave field modeling, staggered grid

PRESENTER'S BIOGRAPHY

Anna Pięta is lecturer in the Department of Geoinformatics and Applied Computer Science, Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Cracow. She is interested in geophisical field modeling and inversion of geophisical data. Over the years this interest has generated research activities in geothermal field modeling, vawe propagation, inversion of geoelectiral data and application of parallel computation in geophysics. Currently she is involved in the development and aplication of computer simulation metodology of three dimentional modeling of wave propagation in parallel computer environment using staggered grid finite difference method.

JAGUARS project: Attenuation, scattering and instrumental effects of events recorded by a high-frequency seismic network as seen from seismograms and their frequency content

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ABSTRACT

JAGUARS (Japanese-German Acoustic Emission Research in South Africa) project aims to investigate the physics of microseismicity and close the gap between laboratory fracture studies on rock samples and seismicity recorded in natural environments. For this purpose, a seismic network, sensitive for very high frequencies (100 to 170,000 Hz) was established at 3540 m depth in Mponeng gold mine, South Africa. The seismic network is located about 90 meters below the gold reef, where exploitation takes place and induces a large number of small to medium seismic events. The study area is intersected by a dyke of about 30m width, which acts as a local stress concentrator in the area of our interest. The seismic network is composed of one 3C accelerometer, 8 acoustic emission sensors and 2 strainmeters. The sensors are located in long boreholes to limit the effect of damaged rocks around the tunnel. The sampling frequency is 500 kHz. Since June 2007 the network recorded more then 500,000 microseismic events with moment magnitudes M_W ranging from ~0 down to -4 and lower.

In order to perform detailed source analysis and investigate e.g. source properties or scaling relationships, the comprehensive analysis of both instrumental and path effects is of great importance, since complex travel paths, recording bandwidth and attenuation have a strong influence on the recorded waveforms. Here, various factors are analyzed:

1. Seismograms displaying different scattering patterns in dependence on their travel path are shown and analyzed. We find that reflections from the dyke, tunnels and stope are very well pronounced.
2. A rough estimate on damping is given by comparing recordings in terms of their frequency content. Furthermore, the maximum source-receiver distances are shown for high-frequency events. The correction for attenuation is addressed by comparison of different Q models (constant and frequency-dependent) obtained with different methodologies e.g. transmission tests. We observe Q values between 200 and 400.
3. The response of acoustic emission sensors is matched against the accelerometer to investigate the instrumental effects related to high-frequency piezoelectric sensors.

Our study shows that, as usual in seismology, our recordings are strongly influenced by the different factors described above. On the other hand, these factors can be sufficiently well described due to the fact that the study area is well defined and accessible. Thus not only the sensor characteristic and the geometry of boundaries (both from geology and from the mine's layout) are known, but also e.g. the elastic parameters of the present rocks can be analyzed in details.

The gathering of all information available together with careful selection of appropriate events will allow us to correct the recordings for both path and instrument effects. As a result, future analysis on the properties of seismic source will be possible.

Key words: high-frequency seismic network, mining induced seismicity, JAGUARS project, attenuation, scattering

PRESENTER'S BIOGRAPHY

I completed my doctorate in seismology in 2007 from the Institute of Geophysics, Polish Academy of Sciences, under the mentorship of Prof. S. J. Gibowicz and Assoc. Prof. W. Dębski. My PhD thesis was related to the kinematic source tomography of mining-induced seismic events recorded in Polish copper ore mines.
Currently, I am researcher at the GFZ German Research Centre for Geosciences in the group "Deformation and Rheology" leaded by Prof. G. Dresen. My research centers on seismic source characteristics including spectral parameters - scaling relationships, seismic moment tensor and seismic source tomography.

An application of the double difference relocation technique to the mining induced seismic events at Polish copper mines

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ABSTRACT

Precise location of mining tremors is of the great importance not only from the mining and engineering point of view but is also crucial for some advanced seismological analysis of the mining induced seismicity like velocity and attenuation tomography, source time function analysis, or source tomography to name a few. Since the mining seismicity tends to cluster in space the location techniques which takes this particular feature into account are favorable in the advanced data analysis processing. The double-difference relocation technique meets this criterion. It allows not only to reduced the location uncertainty of the different events in a cluster, thus providing some insight into the spacial cluster structure but it also reduces the influence of the velocity structure on the location results. In this presentation we demonstrate another, less obvious, but also very important feature of the DD algorithm, namely the decoupling of the events origin time from the events depth. The consequence of this is an increase of the depth location accuracy with respect to the classical location algorithms.

Key words: induced seismicity, double – difference, location.

Seismic crisis caused by water infiltration in the Mila region east of Algeria.

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ABSTRACT

Hundreds of micro seismic events (Ml=-0.4 to Ml=2.7) have been recorded in December 2007 during more than 1 month by a permanent and the portable digital network installed in the epicentral region few hours after. The micro events were felt in one locality called the village of the Ain Kerma about 8 km south of the Beni-Haroun world's largest gravity dam. After field investigation the seismicity seems to be triggered by water infiltration in the ground. The water to be transferred from the huge dam of Beni-Haroun to the reservoir of Oued Athmania passes through a tunnel under the Jebel Akhal a small mountain located between the two dams. No pipe existed into the tunnel to conduct the transferred water. Water leak observation downstream the jebel confirms the circulation of some of the transferred water into the suspected fractures system of the jebel. The preliminary analysis of the first set of data showed that the epicenters extent in about ten kilometers and are centered in the jebel Akhal. The seismic crisis stopped when the local authorities decided to interrupt the water transfer. This induced seismicity phenomena was the first one observed in Algeria. On the basis of the regional tectonics we propose that this seismicity results from collapsed blocks into the Jebel after water infiltration. Indeed focal mechanisms showed normal faulting.

Key words: induced seismicity, water transfer, microseismicity

PRESENTER'S BIOGRAPHY

Dr Fethi SEMMANE seismologist, Research Assistant at the CRAAG Algeria, at the department of seismology in charge of strong ground motion modeling and seismic hazard assessment. After a basic education in geophysics at the university Houari Boumediene, I got a Ph.D in geophysics at the LGIT (an earth science laboratory) Grenoble France (2005) the principal focus of my research is the seismic source characterization using near field data. The project I am leading is the study of the Bam seismic source. I am a coauthor of about 10 papers published in international journals.

Resolution of non-double-couple mechanisms: Simulation of noise contamination, hypocenter mislocation and velocity structure mismodeling

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ABSTRACT

Mechanism of earthquakes and induced seismic events has been searched in the moment tensor description rather than as the traditional double-couple (DC), as it allows describe also non-shear source phenomena. However, the non-DC source components are sensitive to noise contamination of the data and to factors that violate the set-up of the data inversion, namely the event mislocation and inexact velocity model of the crust. They generate spurious non-DC components in the mechanism, which may mask the true source mechanism, and thus should be taken into account during the interpretation. We performed a synthetic case study simulating seismic observation at Soultz-sous-Forêts, Alsace HDR site. Synthetic P and S amplitudes for several shear-tensile source models in a few levels of the noise contamination were inverted, assuming hypocenter mislocation and velocity structure mismodeling in several types of station coverage. Satisfactory reconstruction of the source was achieved assuming a low noise superimposed on the data, except a rather extreme mismodeling and extremely poor station coverage. The threshold of the noise contamination was determined, above which the tensional component in the shear-tensile source is masked by spurious non-DC parts of the retrieved mechanism due to the noise.

Key words: induced micro-earthquakes; hydro-fracture experiments; shear-tensile mechanism; separation of source and spurious non-double-couple components of the mechanism

PRESENTER'S BIOGRAPHY

Jan Sileny – BSc (Physics), MSc (Geophysics), PhD (Seismology)
Jan graduated at Charles University, Prague, Czechoslovakia, and holds the PhD degree from the Czechoslovak Academy of Sciences. For several years he has been working in the Institute of Geology and Mining within the Academy, dealing with mining seismology (event localization, modeling the source of mining tremors). Then, he joined the Geophysical Institute of the Academy, where he works as a Senior Researcher, currently heading the Department of Seismology. He has been dealing with inverse problems in seismology, particularly in retrieval of anisotropy of continental lithosphere, and determination of earthquake source mechanism.

Rapid changes in water level and reservoir-induced seismicity

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ABSTRACT

A "rapid response" of seismicity to reservoir loading is related to the changes in the depth of water in the reservoir. Observations at Nurek reservoir in Tadjikistan and elsewhere have shown that rapid (daily) changes in water level can impact the level of seismicity, even for small (meter) changes in water level. Interactions between changes in load (rapid and directly related to water level) and pore pressure (delayed and related to diffusion) can be invoked to explain this effect.

In spite of the large number of high dams and large reservoirs constructed in the United States, the incidence of reservoir-induced seismicity in the US is relatively low. It is interesting to consider whether construction or regulatory practices, established independent of concerns for seismicity, might influence the occurrence of reservoir-induced seismicity. Anecdotal evidence suggests that in some cases, constraints on the rate of water level changes in US reservoirs are imposed to prevent landslides and slope failure. This level of control does not appear to be imposed at all reservoirs and may be a factor in controlling the rate of induced seismicity. If this effect is to be studied, it is important that accurate and rapid (at least daily) measurements of water level be available.

Key words: induced seismicity, reservoirs, water level

PRESENTER'S BIOGRAPHY

David Simpson has been President of the IRIS Consortium since 1991. IRIS manages facility programs, funded by the US National Science Foundation, that provide instrumentation, field services and data management to support seismological research. Prior to IRIS he was a research scientist and Associate Director at Lamont Doherty Earth Observatory of Columbia University, where he led research projects related to induced seismicity, nuclear monitoring and the tectonics and seismicity of Central Asia.

Modeling of Transient Processes in Seismicity

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ABSTRACT

Regularities of excitation and relaxation of the failure process in rocks were revealed after a series of laboratory experiments for modeling of transient processes in seismicity; processes similar to swarms and aftershocks was found and dependence of their parameters on the acting stress level was obtained. Similar regularities are revealed for field experiment of a high-rate water injection in borehole; a physical idea and its mathematical simulation are proposed for interpretation of obtained laboratory and field experimental results.

Transient sequences of acoustic impulses in sandstone cylinder samples, diameter of 30 mm and height of 60 mm, was monitored during axial step-like deformation and under confining pressure of 40 to 70 MPa as well. The step-like load regime was used to investigate the regularities and patterns of acoustic emission (AE) response structure under different strain rate of step. The data obtained from experiments with big blocks of marble and limestone (0.25 cubic meters) are also analyzed. It was shown that under relatively low stress and small strain rate of step-like deformation the AE intensity increases gradually and time of AE maxima is occurred before the end of increasing stress stage. These maxima are shifted toward the end of respective sub-cycles of loading with increasing of stress level. The moment of activity decay onset began later as stress increases. With sharp step-like loading of a sample when the stress abruptly increases the acoustic decay could be described with Omori power law. Omori law parameters depend on the stress level for aftershock-like activity.

The data of September, 1993 of field experiment at the Soultz-sous-Forêts hot dry rock (HDR) system were analyzed. High-rate injection of water in granite on depth about 3 km lead to excitation of induced seismicity. Water injection in experiment was realized as step-like series with increasing levels of injection rates and, consequently, under different pressure of water. Swarm-like seismic activity is induced by each step of injection. Maximum of seismic activity is delayed relative to injection step and relaxation starts after finishing of initiating loading. The value of delay time increases with increasing of water pressure (i.e. with increasing of local stresses). Obtained results are similar to ones from laboratory experiments.

It is supposed that low-rate step of load generates groups of acoustic pulses similar to swarm earthquakes while the sharp step produces the sequences like aftershock series in seismology. The hypothesis of competition between processes of excitation and relaxation was developed to explain obtained experimental results on qualitative level. Relation between intensities of processes of excitation and relaxation seems to be different for different level of acting stress. Excitation is week under relatively small stresses and relaxation mode starts earlier. Excitation under larger stresses is much more intensive, it overcomes relaxation significantly, and relaxation mode starts later, sometimes after finishing of initiating loading.

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Key words: acoustic emission, induced seismicity, triggering, transient processes, modeling.

A. PONOMAREV'S BIOGRAPHY

Alexander V. Ponomarev, born in 1946, Moscow. Graduated from Moscow State University in 1971, geologist-geophysicist. Work in IPE RAS (researcher, head of laboratory, deputy director). Doctor of sciences in geophysics and applied geophysics. Member of scientific council of IPE RAS, member of the section of seismology and Earth's interior physics of the National Geophysical Committee of Russian Federation. Research and familiar fields: geophysics (seismology), earthquake physics, induced seismicity, field multidisciplinary research for earthquake prediction, laboratory fracture experiments, acoustic emission, modeling of earthquakes, data processing. International scientific cooperation: France, Germany, USA, China, Greece, India, NIS, projects INTAS, Copernicus and ISTC. Publications: more 120, 1 book.

Automatic Location of Mining Induced Seismic Events

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ABSTRACT

Mining induces large numbers of seismic events that are recorded by mine-wide seismic networks installed underground. The large number of events and the continually changing stress environment result in inaccurate locations and source mechanisms. For example, the spread of seismic locations around the planar South African gold and platinum reefs is much larger than the fracture zone created by these events. Locations and moment tensor solutions are rarely sufficiently accurate to attribute events to particular structures or to shear zones created by failure of intact rock. In addition, data sets can be large, sometimes exceeding a thousand events a day. There is clearly great need to automatically calculate robust locations and source mechanisms.

This study extends on earlier work on waveform comparisons and on hybrid locations. Waveforms are compared using cross-correlations as well as the shape of energy envelopes. The hybrid location method uses double difference locations stabilized with absolute locations based on events located using hand-picked P- and S-wave arrival times.

Events located by this automatic procedure compared well with locations obtained using manually-picked arrival times. In addition, ensembles of events with similar waveforms overlapped one another, facilitating interpretation according to plausible source mechanisms of events associated with mining faces, stationary abutments and geological features.

It is suggested that this methodology can provide a robust way of locating and simultaneously estimating the source mechanism of a large number of events based on manual phase picks on a much smaller data set.

Key words: automatic location, source mechanisms, mining induced seismic events

PRESENTER'S BIOGRAPHY

From 1970 to 1978 he was at the Bernard Price Institute for Geophysical Research (BPI) at Wits University in South Africa. From 1978 to 1984 he installed and ran the underground seismic system at Blyvooruitzicht Gold Mine. This system was the first system to be owned and operated by a mine in South Africa. Since 1986, he has been at the Chamber of Mines Research Organization (COMRO), now called part of the CSIR in a number of leadership capacities.
He has authored / co-authored more than 70 scientific papers on rockbursts and mine seismicity.

His current activities and research interests include combining seismology and mine modeling to better understand the mechanisms that drive mine seismicity; seismic source mechanisms; strong ground motion recording and analysis; rock and support behaviour during seismic events and studying the behaviour of highly-stressed mine pillars

Memory effects in parameterizations of mining-induced seismic process

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ABSTRACT

The mining-induced seismic process is controlled by mining works and, as such, is time-varying. Estimation of the process parameters in moving time widows can reveal history of its variations. The trend of this history can, in turn, suggest a probable future development of the process. Such reasoning has formed a background for many various attempts that aimed at determining and predicting the seismic hazard in mines. In an approach like that a series of seismic events parameter values from a certain time window is treated as a statistical sample with no stochastic coupling. Fewer studies have investigated internal correlations of mining seismic series. Their relatively little number is partially due to complexity of this problem in the specific mining conditions: the mining seismic process is intrinsically non-stationary whereas most of the methods to analyse the stochastic coupling require stationarity of the studied process. On the other hand, however, the problem is of paramount importance because non-stationarity or/and memory of the process implies its predictability and determines grounds for prediction.

In the present work we study memory of selected parameterizations of the mining seismicity. The considered parameters are the interevent time, the interevent distance and the logarithm of seismic energy of event that parameterizes the event size. Memory properties are studied with two methods. Long memory in the parameter processes is investigated by means of the Hurst rescaled range analysis (R/S analysis), and the autocorrelation function estimate is used to test for short memory. Both methods are complemented by a detailed uncertainty analysis. Estimates of the Hurst coefficient from permutations of the original samples serve to reproduce distributions of the Hurst coefficient estimators under the no-memory condition. Confidence of the long memory effect is determined from location in this distribution of the Hurst coefficient estimate obtained from the original sample. Interval estimates of the autocorrelation function are attained using the block of blocks bootstrap resampling technique.

The analysed data comprises events recorded by a mine-wide seismic network in Rudna copper mine in Poland. The magnitude range of these events is from 1.0 – 4.2. The analysis is performed on eight more or less stationary event series from different mining regions. The series are in general long, the shortest consists of 480 events and the longest comprises 2250 events. The memory studies show that the interevent time and interevent distance processes have both long and short memory. The mining induced seismicity occurrences and the locations of mining seismic events are internally interrelated. The autocorrelation function of the interevent distance has a peculiar form; the first order correlation coefficient is much larger than all other terms. This suggests that the interevent distance process could be a Markov chain. Internal relations among the sizes of mining induced seismic events are apparently weaker and are limited to long term interactions.

This work was prepared within the framework of the research project No. PBS-Grecja/10/2007, financed by the Ministry of Education and Science of Poland during the period 2007 to 2009.

Key words: mining-induced seismicity, process memory, internal correlations, clustering.

PRESENTER'S BIOGRAPHY

Stanislaw Weglarczyk

Stanislaw Weglarczyk is an Assistant Professor of Hydrology in the Faculty of Environmental Engineering, Cracow University of Technology, Krakow, Poland. Graduated in physics from Jagiellonian University in 1975, since then he is involved in hydrology with a particular activity in stochastic hydrology. His main research interest is the application of statistical methods in modeling hydrometeorological processes. He has authored or co-authored over 60 research papers concerning mainly stochastic properties of extreme events, especially floods, and the problems of parametric and nonparametric methods of estimation and hypothesis testing.

Aftershock activity of an M2.1 earthquake in a deep South African gold mine observed by a high frequency seismic network

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ABSTRACT

Fracture tests of rocks in laboratories are closely investigated to understand faulting processes of earthquakes. However, their scales differ more than several orders in space and time and fracturing is inherently scale dependent phenomena. Therefore, applicability of laboratory knowledge to earthquakes needs to be tested by examining faulting process of intermediate-scale (~100 m) rock mass. For this purpose, we developed a high-frequency (up to 200 kHz) seismic network at a depth of 3550 m in a deep South African gold mine. The extent of network is about 50 m. A vertically intruded dyke (called PG dyke) of 20-30 m thick exists in the network. The PG dyke consists of hornblende gabbro. Mining activity beside the dyke is high, though the PG dyke will be left as a pillar. Therefore, stress in the PG dyke increases with time and it is expected an earthquake of M2-3 occurs on the contact between the PG dyke and the host rock where stress concentration should be enhanced by contrast of material properties.

An earthquake of M2.1 occurred close to our network on December 27, 2007. The hypocenter was located at center of dyke and about 15 m above our network. We succeeded to locate about 13000 aftershocks in 150 hours following the M2.1 event. The aftershocks distributed on a plane dipping to east. The strike of aftershock plane is close to that of the contact between the PG dyke and the host rock. The lower edge of the aftershock plane is at a depth of our network and coincides with the east contact. On the other hand, the upper edge is about 50 m above our network and seems to consist with the west contact, though event detectability should degrade by increasing hypocentral distances. Further, the dip of aftershock plane differs by about 30 degree from dip of the near-vertical contact. Since the aftershock plane should represent the fault surface of the M2.1 event, these suggest that the M2.1 event did not occur on the contact but fractured the PG dyke itself, opposing to our expectation.

The occurrence rate of aftershocks decayed with time by obeying the modified Omori's law with the *p*-value of 1.4. We calculated a relative magnitude from the maximum amplitude or duration of waveform. The distribution of the relative magnitude obeys the Gutenberg-Richter's relation with *b*-value of 0.6-1.2. These statistical parameters are within a range of those for natural earthquakes.

A mine-wide ordinary seismic network equipped by the mine also detected the aftershocks. However, the number of aftershocks located by the mine-wide network was less than 10 suggesting vast majority of aftershocks are smaller than detection limit of the network (Mw~ -0.5). If we assume the Gutenberg-Richter's relation with unity *b*-value would hold for the aftershock sequence, about 3.5 order difference in the number of located events implies that we could detected aftershock with magnitude down to about M -4.

Key words: faulting process, high-frequency seismic network, mining-induced seismicity, scaling law

PRESENTER'S BIOGRAPHY

I am working for Tohoku University as an assistant professor since 1997. My research interest is the faulting process of earthquake.

Reservoir Induced Seismicity in the Three Gorges Area, China

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One of the world's largest hydroelectric projects is now completed at the Three River Gorges site on the Yangtze River in China. The construction of the dam will impound the river, where the water level is being raised in three stages from about an elevation of 65m to 175m above sea level. When completed (Sep.2008), the elevated water level along the river will extend for more than 660km.

The dam is located in a granitic core lying between karst terranes on either side.

Upstream along the river, the granitic core extends for about 15km to the Miaohe area, then nearly 100km in the karst terrane to the Badong province, and into sandstones and clay stones, further upstream. A preliminary evaluation of the seismicity reveals the following:

In the first filling stage, which began in May 2003, the water level rose to 135m in less than a month. It was followed by intense seismic activity in the karst terrane along the river. The seismicity spread along a belt from Wushan- Badong-Zigui-Yichang-Changyang, with 34 events with M>2.0 and the larges being M 3.6. Intense activity (59 events with M>2.0, Mmax 3.8) continued in 2004, although there was no further increase in the water level until 2006. In 2005 also, the seismicity level (69 events with M>2.0, Mmax 3.5) did not decrease. There was an abrupt increase in seismicity following the rise in water level from 135m to 156m in September-October, 2006.

A comparison of focal mechanisms of $M_L \geq 2.5$ events before and after impoundment shows that the style of faulting for the tectonic events, primarily compressional (reverse faulting with strike slip component, and P-axis parallel to the direction of maximum horizontal compression), has changed to dilatational (normal faulting with strike slip component, and a vertical P-axis) for the induced events. The focal mechanisms and field evidence suggest that the induced seismicity was caused by increases in pore pressures and the additional load of water, and is primarily related to the dissolution of karsitic rocks and slumping of the dissolved rocks along glide planes.

The adaptation of Eurocode 8 to mitigate rockburst effects on structures

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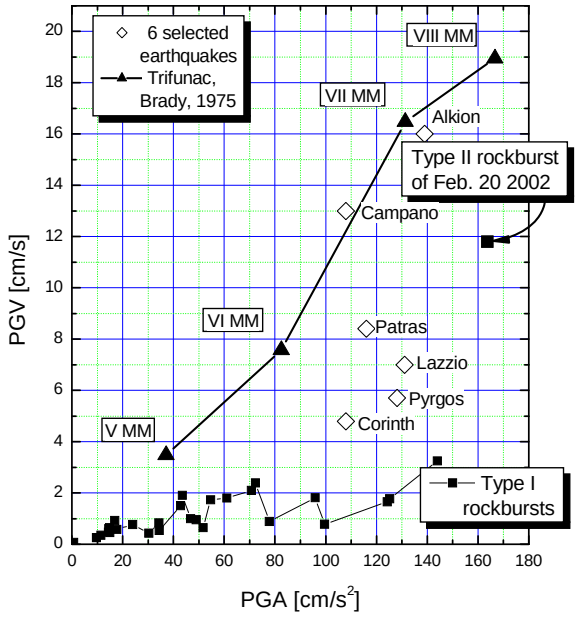
(abstract)

Deep mining often takes place near or below habited areas, sometimes even below cities. The rockbursts generate surface ground motion similar in some respects to small earthquakes which then may cause some damages to the buildings and equipment (e.g. Knoll 1992). Deeper analyses show however some qualitative differences too. The research on the nature of ground motion induced by rockbursts in the copper basin LGOM in Poland (Zembaty 2004) revealed two characteristic patterns of the generated surface vibrations:

- Type I rockbursts occurring with return period of 3-6 months, very short duration (1-2s) and usually high frequency spectral content, similar to strong surface blast effects.
- Type II rockbursts occurring with 5-10 years return period, longer duration and low frequency content with surface ground motion characteristics similar rather to small, shallow earthquakes.

The differences in the spectral content affect the maximum surface Peak Ground Accelerations (PGA) as well as velocities (PGV). The figure below presents dependence between measured horizontal PGA & PGV for typical, type I ground motion and one, rare event of type II, as well as six selected low intensity earthquakes (PGA=0.1g) and averaged peak values correlated with Modified Mercalli intensity by Trifunac and Brady (1975).



The plots in this figure indicate distinctive nature of the two types of rockbursts, particularly with respect to their surface intensity.

This classification, based on the surface ground motion characteristics, is similar to the one proposed earlier by Jonston (1992), which took into account the overall, seismological description of the rockbursts. Each type of the ground motion causes different structural effects and requires different approach in mitigating the eventual resulting structural damage.

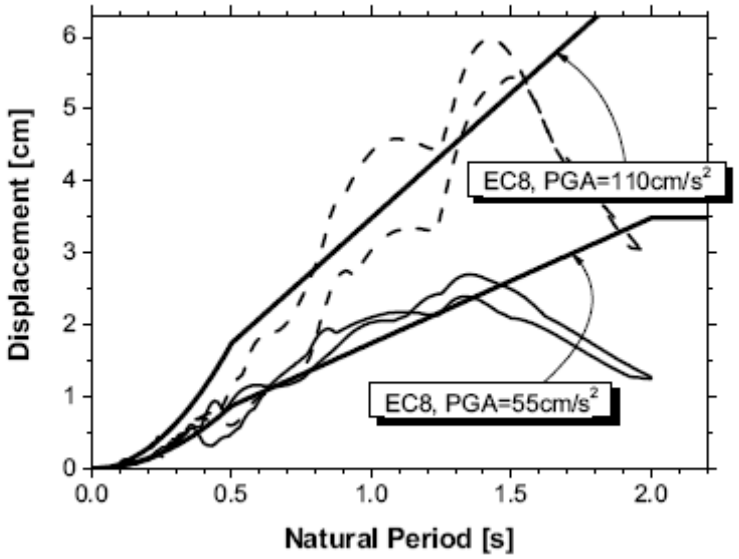
Since the mine authorities are responsible for any damages caused by rockbursts to the civil infrastructure (buildings, lifelines, equipment etc.) a need for a design code similar to seismic codes appeared. Such code shall serve as a tool when building new structures in the area affected by rockbursts. The structure designed using such the code should, on the one hand, prevent any serious damage and, on the other hand should also minimize minor, so called cosmetic damages to the structure.

The main obstacle in a direct adaptation of typical seismic code (e.g. Eurocode 8) derives from two main sources:

- different return period of type I and II rockbursts compare to natural earthquakes
- the differences in ground motion characteristics mentioned above (Zembaty 2004).

The first obstacle requires redefinition of the ultimate and serviceability limit states of the structure under rockburst ground motion compare to the effects of the natural earthquakes. The second one needs to formulate a link between typical earthquake measure of intensity formulated in terms of design seismic acceleration and an appropriate measure of rockburst intensity. As it was shown in the paper by Zembaty (2004) the usual way of applying PGA measured during rockbursts can be particularly misleading due to a shift in the spectral content of surface rockburst ground motion.

In the paper proposed to be presented during the IASPEI General Assembly, a concept of applying PGV as a measure of rockburst intensity and displacement response spectrum as a measure of the structural seismic effects will be presented. The idea of correlating design acceleration with rockburst PGV is presented briefly in the figure below.



The value of design acceleration minimizing the difference between design displacement response spectrum and the actual rockburst displacement response spectra leads to the ratio between design acceleration and rockburst peak ground velocity (intensity measure). The analyses carried out so far lead to the value of this ratio at about 8 to 10. When this value is obtained the rockburst design response spectrum is defined in terms of expected surface particle velocity during rockburst.
In the paper for the IASPEI General Assembly, other details of the adaptation of Eurocode 8 covering design rules for specific structures (masonry, reinforced concrete etc.) will briefly be presented and commented.

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