Department of the Theoretical Geophysics

About

Scientific activity of Department of Theoretical Geophysics concentrated on the following issues: seismic source, fracture mechanics, fluid flows, stochastic models, time series modeling and monitoring of rotational effects.

Regarding to theoretical investigation of seismicity and seismic source two approaches were applied:

- The asperity fault model was proposed to find the relations of megathrust fault physical features with their seismicity patterns, such as fast and slow slip interplay and spatial and temporal variations of the b-value in the Gutenberg-Richter frequency-magnitude law. The model is based on the slip-dependent friction law with the stress dependent healing.
- For estimating the source time function from seismograms the time reversal technique was applied. The method can become competitive with regard to the full waveform inversion techniques or the Empirical Green Function method.

Fracture mechanics is associated with many geophysical and geological processes. Our research activity within this topic concentrated around analysis of various aspects of breaking brittle materials by the Discrete Element Method – the modern numerical simulation method which allows a detailed description of solid body fragmentation.

An important problem of hydrology is flow in channels with obstacles at the bottom or at walls of the channel. Two problems were solved by analytical methods - the problem of gravity driven flow over the sinusoidal bottom and the problem of steady flow through a tube with a wavy wall, have been studied by using the methods of asymptotic analysis.

The time series monitored by geophysical instruments reflects the complexity of phenomena under consideration. For modeling of p-order persistent time series the modified Langevin equation was proposed. In analysis of data the technique of transforming time series into graphs and the concept of HVG irreversibility with the Kullback-Leibler Divergence were used.

Monitoring of rotational effects in the ground was conducted in the Lower Silesian Geophysical Observatory at Książ by different types of rotational seismometers. In 2018 rock shooting works were done in immediately vicinity to the Observatory. This gave an unique occasion to study small shocks at close distance and testing the possibility of different devices.

Personel

Head of the Department
Zbigniew Czechowski
Professor

Włodzimierz Bielski
Associate Professor

Wojciech Dębski
Professor

Piotr Senatorski
Associate Professor

Roman Teisseyre
Professor

Krzysztof Teisseyre
Specialist

Research Project

- Development an adaptation of the Time Reversal Mirroring technique to analysis of full seismic waveforms.

  W. Dębski | NCN | 2016 -2018

- A network for Gravitational Waves, Geophysics and Machine Learning.

  W. Dębski | COST-EU | 2018 -2020

- Introducing the stochastic Langevin-type model and procedures of its reconstruction from persistent of order p geophysical time series.

  Z. Czechowski | NCN | 2017 -2020

- Complex network studies on natural and induced seismicity.

  Z. Czechowski | CONICYT Chile | 2018 -2020

- A network for Gravitational Waves, Geophysics and Machine Learning.

  Z. Czechowski | COST-EU | 2018 -2020

- Investigation of dynamical features of earthquake's temporal distribution based on the analysis of field, laboratory and simulated interevent data.

  Z. Czechowski | SRNSF Georgia| 2018 -2020

PhD Students

Piotr Klejment | Poland
supervisor: Wojciech Dębski

Alicja Kosmala| Poland
supervisor: Wojciech Dębski

Research activity and results

Modeling seismicity of subduction zones: seismicity patterns and fault parameters | P.Senatorski

The main purpose was an attempt to relate megathrust fault physical (material, structural) features with their seismicity patterns, such as fast and slow slip interplay and spatial and temporal variations of the b-value in the Gutenberg-Richter frequency-magnitude law. This has been done within the asperity fault model context. The asperity mechanical model has been based on the slip-dependent friction law with the stress dependent healing. The friction law depends on two independent parameters: strength and slip-weakening distance. The first parameter enables us to define asperities as regions with high strength value. The second one enables us to distinguish among different asperity types. Both parameters can be related to physical fault characteristics: topographic or structural heterogeneities, such as subducted seamounts, sediments, and released fluids. The healing has been interpreted within a subduction channel context as related to underplating or erosion processes at the channel roof.

Strong, coupled interface patches (asperities) and their weaker surroundings are modeled as respective distributions of frictional peak stresses and slip-weakening distances. Such an approach, which is an alternative for the commonly used rate and state friction law approach, has been justified by available observational and laboratory results.

The proposed model has been used to explain some debated observations concerning seismic and aseismic slips that occur at the same sites, hierarchical nature of the megathrust dynamics, and different roles played by subducted seamounts: whether they restrain or promote huge megathrust earthquakes. Two related effects, the changing fault stiffness and different slip-weakening distance values, provide the key to understand those findings.

The main results can be summarized as follows (Senatorski, 2018a).
- Complex processes within a subduction channel can be modeled by using the slip-dependent friction law with strength and slip-weakening distance as two model parameters.
- Slow or fast slip is more than the friction law problem only; it depends also on the changing system stiffness, which is related to the rupture area size.
- Relatively large slip-weakening distance value leads to a variety slip patterns with both small and large earthquakes possible.

The next problem to be explained in terms of the proposed asperity model and plate interface characteristics concerns observed earthquake statistics, such as variations of the Gutenberg-Richter law's b-value. To this end, several related concepts or ideas have been applied: the hierarchical asperity model, the slip budget and earthquake recurrence time, the stable and unstable slip conditions, and the MEP approach to the G-R law (Senatorski, 2017).

Two theoretical results are essential for solving the problem. First is relation between the b-value and the exponent in the rupture area vs. slip scaling (Senatorski 2017). It enables us to relate changing b-value with earthquake rupture dynamics and physical fault characteristics, so the link between earthquake statistics and physics is established. Second is the relation between system stiffness and its critical value. It enables us to explain the interplay between seismic and aseismic slips during earthquake cycle. Explanations of the following observations have been suggested by using these two results in the hierarchical asperity model perspective (Senatorski, 2018b, c, d):

- Large b-value for the largest global earthquakes,
- Decrease of the b-value before the largest earthquake,
- Increase of the b-value after the largest earthquake,
- Increase of b-value increase related to aseismic slip.

In general, the b-value increases when the asperities become more isolated, whereas it decreases when the asperities become more interconnected. This conditions change during an earthquake cycle, so the b-value variations can be used to recognized processes leading to huge earthquakes and, in this way, to the largest megathrust earthquakes forecasting task.

Significance of the obtained results is to contribute to the asperity megathrust model, which is the key to understand subduction zone seismicity and the largest earthquakes forecasting.

References:

Piotr Senatorski, 2017. Effect of slip-area scaling on the earthquake frequency-magnitude Relationship. Physics of the Earth and Planetary Interiors 267, 41–52.

Piotr Senatorski, 2018a. Effect of slip-weakening distance on seismic-aseismic slip patterns. Pageoph, DOI: 10.1007/s00024-019-02094-7 (in press)

Piotr Senatorski, 2018b. Megathrust large earthquakes: asperities and b-values, (poster). EGU General Assembly, Vienna, Austria, 8-13 April 2018.

Piotr Senatorski, 2018c. Gutenberg-Richter's b-value and earthquake asperity models (poster, paper published in the conference proceedings). Best Practices in Physics-based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations: issues and challenges towards full Seismic Risk Analysis. Cadarache-Chateau, France, 14-16 May 2018.

Piotr Senatorski, 2018d. Gutenberg-Richter's b-value and earthquake asperity models (submitted, under review).

Source time function inversion by the TRM method | W. Dębski, K. Waśkiewicz

The classical analysis of seismic data for seismic source characterization includes hypocenter location, moment tensor inversion and spectral analysis which lead to estimation of seismic scalar movement, source radius, static stress drop and apparent stress to name the most important parameters. Additional important source parameters like, for example, source duration, source directivity, rupture speed, and even a dynamic stress drop, can be inferred from seismic data provided a source time function - the function describing a seismic moment release from the source is known. Estimating the source time function is, however, a challenging task which new-days is accomplished either by using the full waveform inversion techniques or an approximate technique called the Empirical Green Function method. While the first approach in numerically demanding and requires high quality data, the latter one has limited accuracy. In this paper we propose yet another approach to estimating source time function. It is based on a principle of time reversal symmetry of a governing wave equation. The method is based on observation that when the far field seismograms are back propagated to the source foci according to the time reversal technique than a retrieved signal at the source location approximates the thought source time function. Thus, the source time function can efficiently be retrieved with only a few forward modeling needed by the time reversal techniques without any complex inversion or deconvolution. In this paper we explain basic mathematical and physical elements of the time reversal technique and show how it can be applied for the inversion of the seismic source time function. The proposed method is a cornerstone of the TRSTI algorithm and is illustrated with 2D numerical examples. In the following figure there are shown source-receiver configurations used in the experiment.

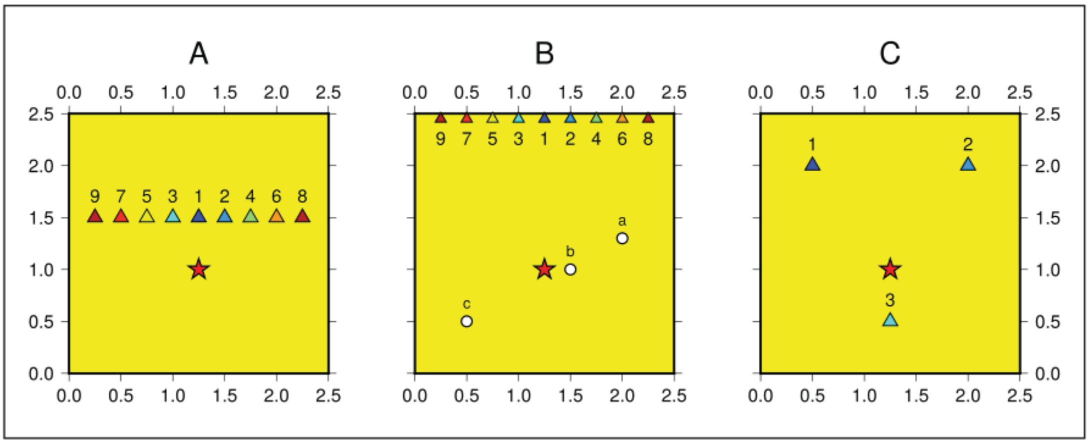


Figure 1: Three different configuration of receivers used in the acoustic TRM numerical experiment

We have considered homogeneous media with three different receiver arrangements and perfectly reflecting boundary conditions. The simulated waves were recorded, inverted in time and resent to medium from virtual sources located at receiver positions. The resend waves positively interfere at the true source position. The location and time of the maximum amplitude of this interference very accurately estimate the source position and its activation time. This is a very well known fact. However, we have also demonstrated another feature of the back projected signal, namely that the temporal variation of the collimated signals very well approximates the original STF. This a new and very important aspect of the TRM method unknown, until now. The retrived STF functions are shown below.

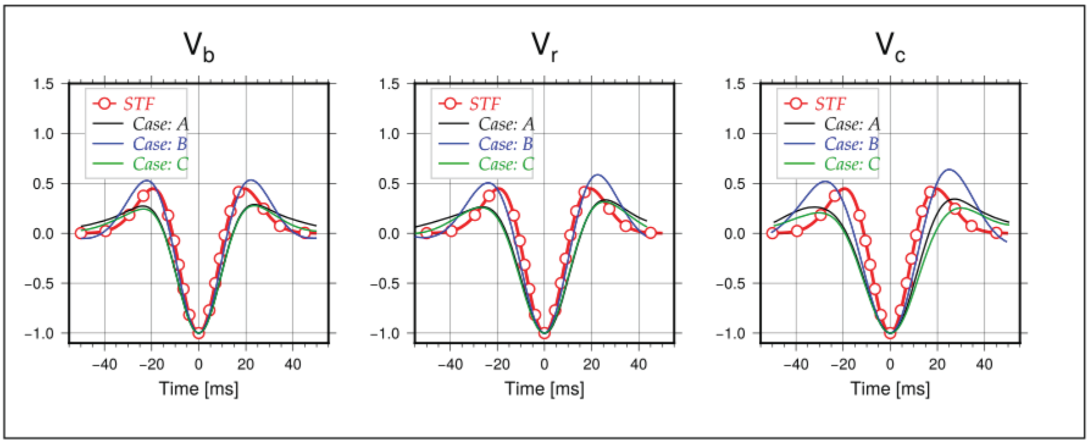


Figure 2: The original STF function (red) used for generating synthetic data (acoustic waves) which were subsequently used by the TRSTI algorithm. The retrieved STF functions were obtained using 3 different velocity models: a) the same as for synthetics generation (left panel), the velocity model with random (white noise) perturbations and the model with coherent noise (right panel). In both cases amplitude of disturbing noise was 10% of background velocity. The inferred functions very well approximate the original STF.

The obtained result opens a new way of an efficient retrieving source time functions for the real seismic events being the alternative to the classical full waveform inversion (accurate but extremely slow from computational point of view) and fast, but inaccurate approach based on the Empirical Green's Function approach. The achieved results become a part of the PhD thesis by K. Waśkiewicz, former PhD student at IGF PAS defended in 2018.

References:

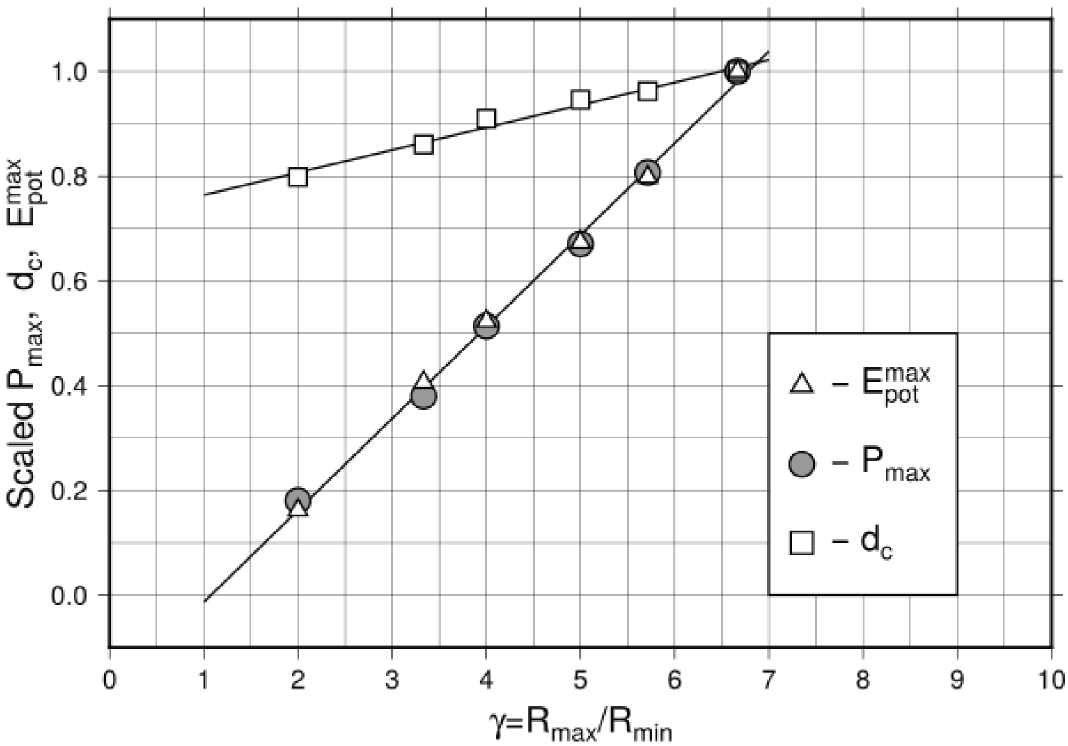
K. Waśkiewicz, Zastosowanie, techniki skal czasowych do modelowania i inwersji akustycznego pola falowego, PhD thesis, IGF PAN, 2018.

Discrete Element Simulation of brittle material failure | W. Debski, P. Klejment, A. Kosmala

The research activity within this topic concentrated around analysis of various aspects of breaking brittle materials by the Discrete Element Method – the modern numerical simulation method which allows a detailed description of fragmentation solid bodies. Three issues were analyzed:

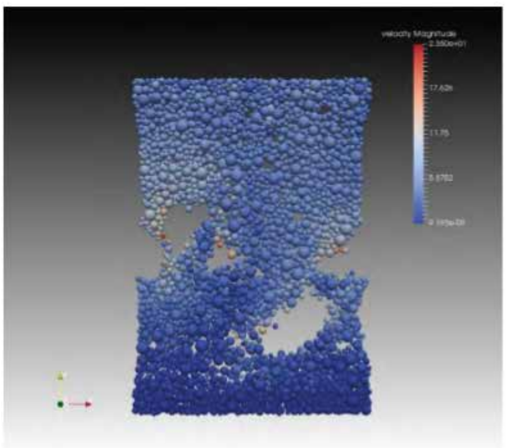
1. Brazilian test

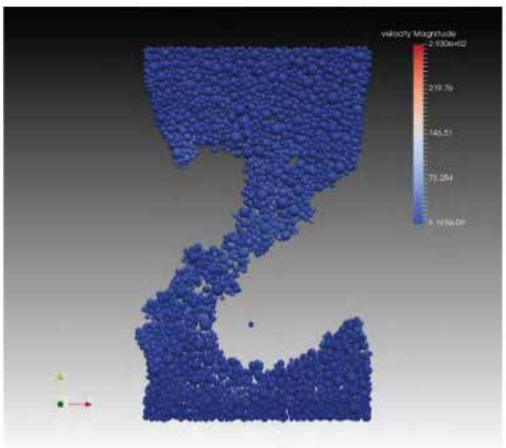
The tensile strength of solid materials is one of the most important parameter describing a behavior of the material under external mechanical loading and thus its knowledge is of great practical importance. However, the direct measurement of tensile strength especially for brittle materials is quite difficult and only limited results are available. To cope with this situation various methods of indirect measurements have been proposed among others the so called Brazilian test is the most popular. The method relies on diametrically loading of disc-like sample of the brittle material until it splits apart due to a induced tensile stress. In this paper we report our effort to describing the fracturing process during the Brazilian test from the "microscopic" point of view. For this purpose we use an advanced implementation of the Discrete Element Method - the ESyS-Particle software. We represent rock specimen as a set of interacting spherical particles which mimic grains of real rock material. We have observed that the maximum loading force which sample can withstand almost linearly scales up with a ratio of maximum-to- minimum particles diameters. This is shown if figure below where maximum load, accumulated potential energy and deformation at which sample breaks are shown as function of grain size.



2. Crack nucleation in tensional regime

Cracking of materials is an extremely complicated process that includes processes in scales from atomic (breaking intermolecular bonds) up to a scale of thousands of kilometers in the event of catastrophic earthquakes (in the energy scale from individual eV to 10 24 J) [1]. Such a large span of the scale raises a lot of questions, in particular about scalability of cracking processes, existence of factors determining the final size of the fracture area (on a macroscopic scale), course of the preceding and occurring processes during material destruction, etc. [2]. The aim of this research was to try to look at the cracking processes on a scale typical for engineering and seismology (millimeters to meters) using micro-physics methods. The proposed research methodology was based on large scale simulations using the Discrete Element technique. We mainly focused on cracking hypothetical three- dimensional materials subjected to uniaxial stretching with constant velocity and sample deformation. The above assumptions underlying the simulations may seem quite unrealistic. In fact, however, they quite well allow to describe the behavior of cracking structures such as thin films (eg. biological structures), metal coverings (eg. aircraft fuselages), tailoring materials, crack propagation [2]. The well-known fact is that cracking solid bodies are determined by the structure of a given material, its atomic and micro-structural structure, but also by the way of applying external forces leading eventually to its destruction and fragmentation [3]. Usually, the rupture source is described by a single crack or dislocation, following the pioneering vision of Griffith [4]. The dynamic crack propagation causes a relaxation of stresses and energy release, leading in the consequence to material failure. It was shown experimentally that the micro-destruction leads to macro-destruction. Correct analysis of complexity of the fracture process or/and interactions of micro-cracks at big concentrations typical for pre-fracture state is possible only in terms of statistical models. The kinetic model of evolution of crack population was introduced by Czechowski [5] and developed in [6, 7]. It lies at a level intermediate between the purely statistical approach and the fully microscopic treatment. The elementary objects are micro-cracks which can nucleate, propagate and coalesce. The problem of crack interaction and fusion is faced in its simplest aspects (binary interaction) but avoids its most delicate features by introducing extra mechanical probabilistic assumptions. The kinetic approach operates on crack size distribution function that evolution is governed by the modified coagulation equation (mesoscopic level). Relations with the macroscopic picture, concerning the stress field evolution and the relationship between the time to fracture and the applied stress, were derived. Figures below demonstrate two observed fracture modes.





References:

[1] Teisseyre R. (ed.) Theory of Earthquake Premonitory and Fracture Processes, PWN, Warszawa, 1995.

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[6] Czechowski Z., A kinetic model of nucleation, propagation and fusion of cracks, J. Phys. Earth, 41, 127-137, 1993.

[7] Newman W., Gabrielov A., Durand T., Phoenix S.L. and D. Turcotte, An exact renormalization model for earthquakes and material failure: statics and dynamics,Physica D 77, 200-216, 1994.
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Flows of viscous fluids in non-typical open and closed channels. Theoretical modeling and perspectives | W. Bielski

An important problem of hydrology or geohydrology is flow in channels with obstacles at the bottom or at walls of the channel. The bottom may be uneven, rough, sloped, wave, with vegetables, plants and so on. Then the velocity field is drastically changed in comparison with the flow over plane bottom. The problem of resistance is one of the important in hydrology. Particularly, corrugated tubes are an example of such problems and have an application to the technical and medical sciences. Similarly, a such kind of phenomenon occurs in the propagation of gravity (or density) currents.

In our research activity we have solved some problems of the flows by analytical methods, which stands for a start point to further study and obtaining numerical results to compare the compatibility of the experiment with the results of theoretical modeling.

First, the problem of gravity driven flow over the sinusoidal bottom is studied by using the methods of asymptotic analysis including expansions in the Taylor and Fourier series, accordingly to sinusoidal shape of the channel bottom, what leads to a cascade system of equations to be solved (Wojnar and Bielski , 2018).

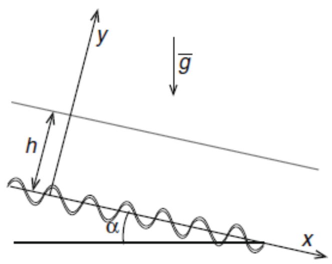

Figure 1: The gravity driven flow past a wavy bottom with the mean slope alpha to the horizontal plane. The vector g denotes the gravity acceleration. The depth of the stream in subsequent calculations is taken as h = 1. The proportions of the bottom waviness are exaggerated.

Second is the problem of steady flow through a tube with a wavy wall. This is related to geophysical problems of stream flows past the channels with rough walls in Karst phenomena (appearing as a result of the dissolution of soluble rocks such as limestone, dolomite). To account this phenomenon the effect of small amplitude wall waviness on the steady flow in a tube is examined. We consider a Stokesian pressure driven flow in tube with a wavy wall as the axially-symmetric problem. Thus, we are dealing with two dimensional steady problem described by two position co-ordinates r and z.

The problem is solved again by means of analytical methods involving the asymptotical analysis. We assume that the radius R of the pipe cross-section is a periodic function of the z variable, what means that the wall shape is described by a surface periodic along the z-axis, R = R0 + ⌧ a cos(Kz). Here R0 is the mean value of the pipe radius, ⌧ is a dimensionless small parameter, a is the amplitude of the wall wave, and K = 2⌧⌧, where ⌧ denotes the length of the wall wave, see Fig.2.

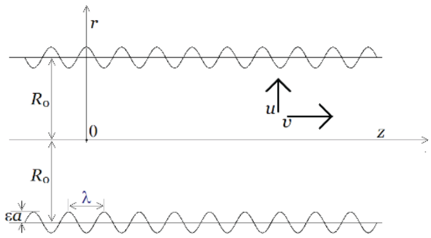

Figure 2: Cross-section of the considered axially-symmetric tube. Here Ro is the mean value of the pipe radius, epsilon is a dimensionless smallness parameter, a is the amplitude of the wall waveness, and lambda denotes the length of the wall waveness.

The solution was obtained by expanding the stream function in a Fourier series and expanding the boundary surfaces in Taylor's series. Even in the first order approximation O(⊠), new results are obtained (Bielski and Wojnar, 2018).
The obtained solution for the velocity v belongs to the class of periodic functions with period ⊠ in z. Thus, a study of Stokesian flow is performed on base of the asymptotic analysis and a correction to Hagen-Poiseuille's type flow is found.

The methods of asymptotic expansion and averaging (homogenization) are fruitful tools in solving many physical problems.
The results obtained currently will be verified by a numerical method, and next will be applied to the description of gravity currents propagating in channels with rough bottom, what is to be a subsequent step in our activity.

References:

R. Wojnar, W. Bielski, Gravity driven flow past the bottom with small waviness, in: P. Drygaś S. Rogosin, Eds. Modern Problems in Applied Analysis, Birkhauser, Cham 2018, pp. 180-202.

W. Bielski, R. Wojnar, Stokes flow through a tube with wavy wall, in: J. Awrejcewicz Ed., Dynamical Systems in Theoretical Perspective, Springer 2018, pp. 379-392.

Time series analysis and modeling | Z. Czechowski

The time series monitored by geophysical instruments reflects the complexity of phenomena under consideration and its important features; nonlinearity, multifractality and non-Markovian properties. Typical non-regularity of geophysical data induces us to accept the assumption about stochastic basis of geophysical time series.

Therefore, for the modeling, nonlinear models of the Langevin-type was taken into account. In our approach the standard Langevin equation had to be modified to describe some non-Markov processes – persistent of order p (Czechowski 2018). For this goal the additional random factor was introduced to the diffusion term, i.e., a function c, which determines a sign of the term and is dependent on signs of p previous jumps. The main task of modeling, besides choosing the proper mathematical model, is to propose a reconstruction procedure of the model from data. However, for the modified Langevin equation typical reconstruction procedures fail. Therefore, the novel procedure was introduced and tested on synthetic data. The results showed good efficiency of the procedure.

Recently, scientists have shown growing interest in the process of transforming time series into graphs (and vice versa). This creates a very attractive relation which enables to use simultaneously well-developed methods of time-series and graphs (complex networks) theories to the examination and discrimination of data sets. Basing on this idea spatiotemporal analysis of the dynamical system of seismic area was performed (Pasten, Czechowski, Toledo, 2018). The complex network for earthquakes is built according to the location of hypocenters and the network nodes are marked by their final connectivity given by the time sequence of the seismic events. Then, the procedure of transforming the graph into connectivity time series follows the time sequence of the occurrence of seismic events. Therefore, some features of both, the constructed complex network and the appropriate connectivity time series, can be examined. The procedure was applied to four data sets in Chile with different levels of seismic activity. It was shown that the multifractal properties of connectivity time series are different - the multifractality is diminishing with the occurrence of large earthquakes. It is reflecting the spatiotemporal organization of these seismic systems.

Unlike typical deterministic systems stochastic differential equations have a built-in direction of time flow. This directly leads to the problem of reversibility/irreversibility of time series that can be treated as a realization of a stochastic process. Our next task corresponded to finding a direct relation between time irreversibility and memory (namely, a persistence) of time series (Telesca and Czechowski, 2018). To this aim, HVG irreversibility with the Kullback-Leibler Divergence as a tool for estimating the level of time irreversibility of persistent/antipersistent time series was applied. The HVG irreversibility concept is based on Visibility Graph method of transformation time series into graphs. The modified Langevin equation was utilized as a generator of time series with different levels of time persistence. A non-trivial relationship, characterized by a non-symmetric shape, between the degree of irreversibility and the level of persistence was found - time irreversibility increases with the level of persistence or antipersistence.

References:

Czechowski Z., Modelling of persistent time series by the nonlinear Langevin equation, pp.141-159, [in] Complexity of Seismic Time Series: Measurements and Application, Chelidze T., Vallianatos F., Telesca L. [Eds.], Elsevier 2018.

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Pasten D., Czechowski Z. and Toledo B., Time series analysis in earthquake complex networks, CHAOS 28, 2018, 083128.

Monitoring of rotational effects | K.Teisseyre

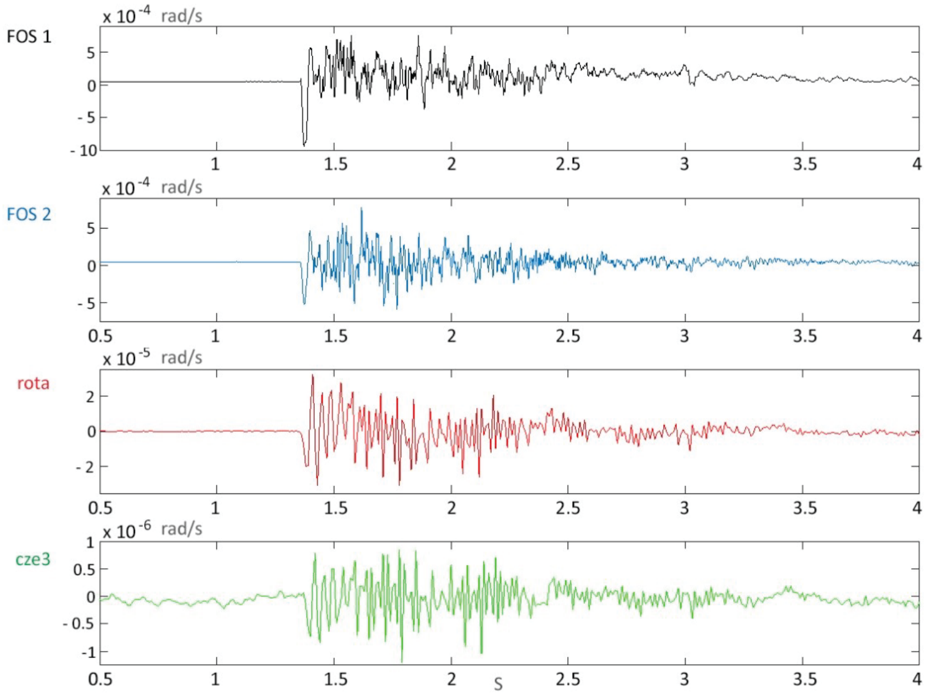
Rotational effects in the ground are monitored in the Lower Silesian Geophysical Observatory at Książ by the following types of seismometers: fiber optic Sagnac gyroscopes (FOGs, manufactured and maintained by the Military University of Technology WAT in Warsaw); a set of two TAPSES – Twin Pendulum Antiparallel Seismometers (manufactured in our Institute) and two rotational sensors of lower sensitivity (prototypes, made in the Czech Academy of Sciences).

There are two reasons to record rotation with various sensors collocated. First, each equipment has its own shortages, therefore comparing the results allows for better data understanding and cleaning; second – different families of seismic sensors are under development, which is facilitated by practical testing.

Studies on seismic rotations and strains are relevant to seismology, the technologies of architecture and care of the buildings' safety. The technological aspect of rotational seismology is nowadays especially important, because some experiments show that rotational motions can be dangerous to man-made constructions, but tests for these motions are not comprised in the routine.

In 2018 year, rock shooting works were done in immediately vicinity to the Observatory - two new entrances to the huge Książ undergrounds were cleaved. This gave to seismologists an unique occasion to study small shocks at close distance – about 80 m in case of so far mentioned sensors; various distances to the temporary network of seismometers. Unfortunately, the broadband seismometer was blocked in the time of these works, for its safety. The blasts differed in strength and details of location; each blast embraced several explosions in adjacent places and controlled, very small retardation. First data processing concentrate on comparing simultaneous recordings from the six mentioned rotational seismometers, next step will include comparison with the results from the temporary network.

The figure presents an example of simultaneous blast recordings, showing signals from two FOGs (FOS1 and FOS2), rotation obtained from the set of TAPSes (rota) and the signal recorded by Czech sensor (cze3). General conformity of results is seen, but differences caused by the characteristics of instruments are visible too.



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Jaroszewicz, L.R., A. Kurzych, Z. Krajewski, P. Marć, J.K. Kowalski, P. Bobra, Z. Zembaty, B. Sakowicz and R. Jankowski (2016). Review of the Usefulness of Various Rotational Seismometers with Laboratory Results of Fibre-Optic Ones Tested for Engineering Applications, Sensors 2016, 16, 2161, 22 pp., DOI: 10.3390/s16122161.

Jaroszewicz, L.R., A. Kurzych, K.P. Teisseyre, Z. Krajewski (2018). Measurement of Rotational Events In Regions Prone to Seismicity: A Review, in Geophysics, A. Okiwelu, Editor. IntechOpen, 19-39, (http://dx.doi.org/10.5772/intechopen.72169).

Seminars and teaching

Seminars and lecture outside of the IG PAS

- Z. Czechowski | *Reconstruction of the modified Langevin equation from p-order persistent time series* | Lecture
  University of Chile, Department of Physics | Santiago, Chile

- K. Teisseyre | *Henryk Arctowski i Epoka Odkryć – Henryk Arctowski and The Discoveries Epoch* | Invited lecture
  Polish Academy of Sciences | Warsaw, Poland

Completed PhD thesis defense

- K. Waśkiewicz | *Zastosowanie techniki skal czasowych do modelowania i inwersji akustycznego pola falowego* | Supervisor: W. Dębski

- P. Klejment | *The microscopic insight into fracturing of brittle materials with the Discrete Element Method* | Supervisor: W. Dębski

Visiting scientists

- T. Matcharashvili | Institute of Geophysics of Ivane Javakhishvili Tbilisi State University | Tbilisi, Georgia

- S.Pradhan | Porolab Excelence Center, Physics Department, NTNU | Trondhaim, Norvay

Meeting, workshop conferences and symposia

EGU General Assembly | Vienna, Austria
P. Senatroski | *Megathrust large earthquakes: asperities and b-values* | poster

P. Klejment | *The microscopic insight into calving process in grounding tidewater glaciers – the Discrete Element Method numerical approach* | poster

A. Kosmala | *Investigation of fracturing fluid penetration with the Discrete Element Method* | poster

P. Klejment, W. Dębski | *Application of the Discrete Element Method for analysis of fundamental psrticle interactions during rupturing seismic sources* | poster

W. Dębski, K. Waśkiewicz | *Estimating Source Time Function by Time Reversal Method* | poster

P. Klejment, A. Kosmala, W. Debski | *High-performance computing in geophysics: Application of the Discrete Element Method to materials failure problem* | poster

Best Practices in Physics-based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations: issues and challenges towards full Seismic Risk Analysis | Cadarache-Chateau, France
P. Senatroski | *Gutenberg-Richter's b-value and earthquake asperity models* | poster

ISCPS2018 International Summer Conference on Probability and Statistics | Pomorie, Bulgaria
Z. Czechowski | *Reconstruction of the modified Langevin equation from p-order persistent time series* | oral

ICCS 2018 The Ninth International Conference on Complex Systems | Cambridge MA, USA
Z.Czechowski, A. Budek, M. Białecki | *Bi-SOC-states in one-dimensional random cellular automaton* | oral

The 7th International Conference on Complex Networks and Their Applications COMPLEX NETWORKS 2018 | Cambridge, United Kingdom
D. Pasten, Z. Czechowski, B. Toledo | *Time series analysis in earthquake complex networks* | oral

Conference on Complex Systems 2018 | Thesaloniki, Greece
M. Petelczyc, Z. Czechowski | *Time irreversibility of persistent time series generated by discrete Ito equation* | oral

2nd Workshop on Porous Media | Olsztyn UWM, Poland
W. Bielski, R. Wojnar | *Plane flow through the porous medium with chessboard-like distribution of permeability* | oral

Solmech 2018 | Warsaw Poland
W. Bielski, P. Kowalczyk, R. Wojnar | *Two Temperature Heat Transfer and Thermal Stresses* | oral

Fatigue-2018 | Poitiers, France
P. Klejment, W. Dębski | *Crack nucleation in solid materials under external load - simulations with the Discrete Element Method* | poster

Supercomputing Frontiers 2018 | Warsaw, Poland
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