Description of the main research directions investigated by the institute

The main research directions investigated by the institute followed the Research plan of the institute for 2015-2019, as defined in the previous evaluation. The research plan was updated and refined in 2017, and after discussion approved by the Institution Board until 2022. The main research directions of the institute were and still are primarily motivated by the versatile utilization of the Earth's crust, which represents a highly topical issue complying with the development of needs of human society. The research activities cover a relatively wide spectrum of interdisciplinary research areas, ranging from the characterization of geomaterials to the study of processes taking place in the Earth's crust, especially those induced by human activities, and their effects on the environment. Within this research, supporting disciplines, such as the applied mathematics and physics, chemistry, material disintegration, and environmental and social geography, have also been developed.

Generally, research activities of the institute were mainly focused on the development of geotechnologies for the extraction of minerals, where the rising prices had motivated the interest in innovation and creation of new, more efficient and more environmentally friendly mining processes. It also focused on solving issues related to the construction of underground structures, i.e. underground facilities of gas and other raw materials storage, on using geothermal energy and solving environmental problems important for the development of society.

From the point of view of the institute and its research potential, it is very important that activities of particular research teams are highly interconnected and complement one another. This is very advantageous as the present-day research of utilization of the Earth's crust is a very broad field requiring usage of both demanding and very expensive experimental equipment in close combination with high-level theoretical, computational, and modelling knowledge. From this point of view, the institute establishes itself as a nationally powerful and internationally recognized research unit.

The activities of the institute are financed from three sources: about ***58%*** comes from the Czech Academy of Sciences in form of the ***institutional support***; about ***32%*** from ***research projects*** of domestic and foreign providers and about **10%** from ***cooperation with industrial partners*** (see Fig. 1). The management of the institute together with the Institution Board made an effort to submit only those proposals of research projects that correspond with the main research directions of the institute.

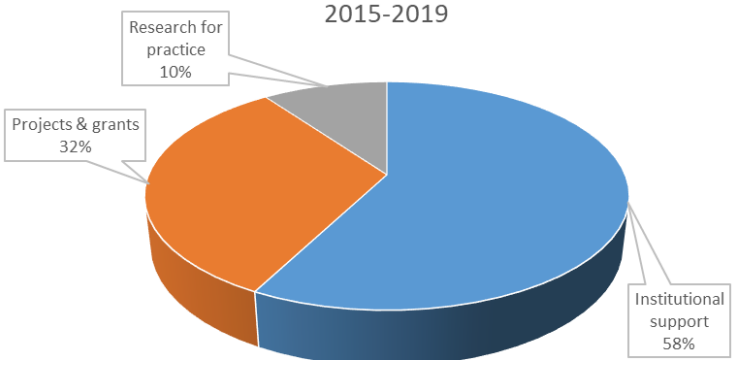

Figure 1. Sources of financing the research activities of the institute in the evaluated period 2015 - 2019.

The institute was successful in acquiring support from various grant agencies in the evaluated period. The researchers of the institute completed more than 50 grants and the overall subsidy for the evaluated period was over 4.3 million EUR (for more details, see part 3.2 "The list of all grant and programme projects").

Participation of the institute in projects with subsidies from the ***Operational Programmes and National Programs of Sustainability I and II*** contributed

substantially to the development of research activities of the institute enabling the engagement of both junior and senior researchers, including some researchers from foreign countries.

Moreover, the participation of the institute in the ***research infrastructure CzechGeo/EPOS*** leaded to the development of the MONET local seismic network monitoring seismic activity of the north-eastern part of the Czech Republic. Involvement of the institute in the research infrastructure ***Research INfrastructure for Geothermal Energy – RINGEN*** then stimulated research in the area of the deep geothermal energy exploitation.

It should also be noted that cooperation with industrial partners is traditional activity of the institute - the institute earned ***544 thousands EUR*** from the ***contract research*** and ***752 thousands EUR*** from the ***collaborative research***. In addition, the institute also gained ***37 thousands EUR*** from the ***technology transfer*** in the area of high-speed water jets. More details can be found in part 3.3 “Research for practice”. Apart from these monetary amounts, valuable results have been delivered to the industry; a part of them is naturally confidential and cannot be published. However, collaborative projects with some industrial partners enabled publishing results in scientific journals and presenting them at conferences.

A significant role played the participation in two phases of the ***Decovalex*** project devoted to the modelling of coupled thermo-hydro-mechanical processes associated with nuclear waste deposition and validation of the models against experiments. Two phases of Decovalex aimed at the formulation, implementation and validation of models for the analysis of coupled processes. The models were validated by the simulation of processes, which were monitored in three large, long-term, in-situ experiments: SEALEX (Tournemire, France); EB (Mont Terri, Switzerland); and FEBEX (Grimsel, Switzerland).

Another example of the collaborative research is a four-year contract which the institute concluded as a part of the consortium of the “***Research Support* for the *Safety Assessment* of a *Deep Geological Repository (DGR)*”- *Safety Support of the DGR***.

In practice, research activities of the institute are performed by five research departments which correspond to five teams selected for evaluation. The following table summarizes basic information provided on teams, their main field and field of research and development (FORD) and panels selected for the evaluation. The research teams are involved in various fields of research; however, they are also capable to perform research on complex areas using collaborative efforts, what is one of strengths of the institute.

Team			Main Field	FORD	Panel
No.	Name	Abbr.			
1	Laboratory Research on Geomaterials	LRG	2. Engineering and technology	2.7 Environmental engineering	7
2	Material Disintegration	MD	2. Engineering and technology	2.3 Mechanical engineering	7
3	Geomechanics and Mining Research	GMR	2. Engineering and technology	2.7 Environmental engineering	7
4	Applied Mathematics and Computer Science & IT4Innovations	AMCS	1. Natural sciences	1.1 Mathematics	1
5	Environmental Geography	EG	5. Social sciences	5.7 Social and economic geography	5

A brief overview of main research activities of individual teams is presented below. More detailed information on activities of teams and their main scientific achievements can be found in “Reports on the research activity of teams”.

Laboratory Research on Geomaterials

The main research topics of the LRG team were as follows: identification and characterization of geomaterials; strength and deformation properties of geomaterials under specific physical conditions; fracture properties and crack propagation in rocks; thermal behaviour of geomaterials; interaction between geomaterials and fluids; and interdisciplinary research.

In the field of identification and characterization of geomaterials, the activities were concentrated on natural and modified clay minerals and clay composites with specific properties, and on the development and application of analytical methods for their characterization in terms of structure, chemical composition and physico-chemical properties.

The newly-prepared composites exhibit structural changes associated with significantly higher sorption capacity, and also better thermal stability compared to the original clay materials. In addition, the polyethylene/vermiculite composites enriched with an active organic substance showed significant antimicrobial activity against bacterial strains Staphylococcus aureus, Escherichia coli and yeast Candida albicans, with long lasting effects.

The development and application of analytical methods for characterization of clay minerals and clay composites resulted in suggestion of an optimized procedure of Raman microscopy and specification of optimal measurement conditions with respect to the quality of sample preparation and the statistical reliability of the analytical data obtained. The procedure is based on the comparison of the measured Raman spectra with regard to the level of fluorescence and the presence of characteristic spectral bands.

Moreover, activities of the LRG team have also been focused on laboratory simulations of triaxial conditions, and on a comparative study of the deformational behaviour of rocks along specific paths in triaxial stress space. Special attention was paid to accurate measurement of deformations of rock specimens under loading.

Another part of the LRG team's research was oriented to the mechanical fracture parameters of rocks in relation to their mineralogical composition and internal texture features, and on the study of fracture initiation and propagation in quasi-brittle materials using X-ray computed tomography techniques.

In the field of research on thermal behaviour of geomaterials, a detailed analytical study was carried out on selected granitic rocks, focusing on the effects of rock composition and structure on residual thermal expansion and on the effect of phase transformations during the heat stress on the complex thermal behaviour of rocks. The research results confirmed that the methods of simultaneous thermogravimetric and differential thermal analysis, together with the methods of thermomechanical analysis, can be effectively used in the field of geomaterial research, especially in the study of the thermo-mechanical properties of rock.

Material Disintegration

The research activities of the MD team were focused on the high-speed water jet disintegration of materials and geomaterials. They contributed to the deepening of

knowledge about the basic physical processes occurring during the generation of high-speed liquid flows, their behaviour, their interactions with solid materials, and potential practical applications.

The main research areas investigated by the MD team are the following: intensification of high-speed water jet effects; the study of abrasive materials used in abrasive water jets (AWJ); numerical modelling of the water flow; topography and quality analysis of cut surfaces; and the search for new applications of water jets.

In the area of intensification of high-speed water jet effects, the research was oriented to the study of the basic characteristics of high-speed water jets (WJs), processes of generation and behaviour of WJ, and the effects of WJ on materials to be disintegrated.

Numerical methods of flow simulation and experimental verification of the results provided by numerical models were used for a study of fundamental processes of excitation and propagation of acoustic waves (and/or high-frequency pressure pulsations) in the pressure liquid in a high-pressure system, and their effects on the formation and properties of pulsating liquid jets. In addition, the numerical modelling significantly contributed to the creation and study of the so-called hydrodynamic nozzles generating self-excited pulsating water jets (SPWJs) of various properties.

In addition to pulsating water jets, the MD team focused on the improvement of the commonly-used concepts of an abrasive cutting head. Extensive analysis of the process of injection mixing of abrasives with a high-speed water jet and the subsequent numerical simulation revealed that the processes of mixing and acceleration provide great potential for improvements in the efficiency of the high-speed abrasive water jet, by a set of modifications and improvements in the existing cutting tool. Several Czech and international patents and patent applications protects the unique research results.

Within the research on abrasives, the MD team focused not only on the possibilities of improving the cutting capabilities of commonly-used natural abrasives by modifying their properties, but also searched for new materials suitable as abrasives which have not yet been used in the AWJ technology. The properties of abrasives and their behaviour in AWJs used in various operation modes were studied.

Equally, the study of the topography of cutting surfaces after the application of high-speed water jets is an integral part of the research of the MD team. In addition to the study of surface characteristics, suitable methodologies for surface assessment have been proposed and analysed. The parameters of these methods are clearly processed in databases of individual materials and individual water jet machining technologies (cutting, turning, milling, and drilling).

Significant research activities of the MD team are encompassed also in the area of search for new areas of high-speed water jet utilization. The scope of these activities is extensive, ranging from water jet machining processes, through water jet applications for concrete disintegration, to the use of pulsating water jets in medical applications.

Geomechanics and Mining Research

The activity of the GMR team includes basic research in the fields of the distribution of stress and seismicity in the rock mass, laboratory X-ray computer tomography research and development of measuring instruments. The team is also involved in targeted and applied research - mainly in situ - for the solution of various

geomechanical and geotechnical tasks. The targeted and applied research results in proposed measures, working methods and legislative outcomes.

The main areas of the research activities of the GMR team include: stress measurements in rock mass; resolving problems in the field of mining geomechanics and underground engineering, such as stability and reinforcement of underground workings, static and dynamic manifestations of RM pressures, and impact of mining on the earth surface; laboratory tomographic research methods on structures and the disintegration of geomaterials; and technical, induced and natural seismicity research.

The methods used, therefore, include field and laboratory research and they are particularly characterized by a large amount of demanding in-situ measurements.

Research activities in the field of geotechnical issues has focused on the detection and analysis of primary and induced distribution of rock mass stress fields in the vicinity of excavated underground structures in the construction process, and their use in terms of mechanical and functional stability during the life cycle of the work. Work is focused in this field on in-situ stress and stress changes measurement due to own-developed equipment (conical stress cells, dataloggers, system of measurement) and utilization of additional information about stress field, e.g. deformation of boreholes as well as underground openings due to stress release (back analysis), as well as paleostress analysis due to seismic data.

Significant attention has been paid to the evaluation of the level of safety in underground workplaces and the level of effectiveness of active and passive preventative measures used.

In the field of the utilization of X-ray imaging techniques, research of the character of the pore space has been on-going, especially with respect to its influence on the properties of the monitored material. Processes during the mechanical loading of samples and internal rock structure by computational micro-tomography, in combination with petrographic methods, have been studied.

Moreover, the research in the field of geophysics has been focused on the study of seismic activity in the Silesian-Polish border region, based on seismological observatory activity and on the definition of the seismic load at potential sites of deep geological repositories. The MONET local seismic network is operated to monitor the seismic activity of the north-eastern part of the Czech Republic, which is characterized by the occurrence of stronger historical earthquakes, regionally anomalous levels of microseismicity and other manifestations of increased geodynamic activity. Since 2016, for the purposes of the CzechGeo/EPOS project, the KLOK, STEB and ZLHC stations of the IGN have also been assigned to this network. Seismological measurements and observations provide useful information for a variety of users from the public, state agencies, including rescue teams and the research community.

Applied Mathematics and Computer Science & IT4Innovations

The main activity of the AMCS team is focused on the numerical methods and applications motivated by geo-engineering and geo-environmental problems. The applications require elastic and elastoplastic models, flow in porous media and heat transport. The research of the AMCS team includes advanced topics, such as the coupling of these models (multiphysics), inverse analysis, limit load analysis and dealing with uncertainty, including the Bayesian inverse methods. Particular interest is paid to iterative solvers and high-performance computing methods for demanding applications.

A relatively broad scope of research interests of the AMCS team can be divided into three particular directions: analysis of mathematical models, development and analysis of suitable numerical methods; computer implementation and testing of numerical methods, including algorithms for parallel computing and developing new software tools; and mathematical modelling of problems arising in geo-engineering and geosciences.

Activities performed by the AMCS team attempt to encourage interactions between mathematical and engineering communities, and to benefit from the fact that engineering motivates the development or extension of many mathematical theories and, conversely, an advanced mathematical background can substantially improve engineering computations. This approach was applied, for example, in analysis of the safety and performance of the deep geological repositories for high-level radioactive nuclear waste, which requires simulation of coupled thermo-hydro-mechanical processes (multiphysics), and in the investigation of geotechnical stability requiring the solution of non-linear problems such as plasticity, limit analysis, and flow in unsaturated porous media.

Environmental Geography

The research activities of the EG team reflect some of the major current global environmental challenges (such as energy sustainability and security, urban sprawl, environmental restoration and the regeneration of brownfields, climate-forced drought, food security, etc.), as well as regional, socially relevant issues (e.g., energy poverty, traffic accessibility and transportation planning, regional and rural development, etc.).

The main research areas of the EG team thus include: transformation and recycling of urban spaces; renewable energy development and related land use and social conflicts; restructuring and diversification of agriculture and food production; and diversity of natural and cultural landscapes.

More precisely, the research activities in the area of transformation and recycling of urban spaces focus on the continuing changes in the socio-spatial aspects and positive and negative impacts of the transformation of urban spaces in regions of different types, including the phenomena of re-urbanization, urban space recycling and brownfields regeneration, the new patterns of space-time behaviours, spatial mobility, and accessibility problems.

In the field of renewable energy development and related land use and social conflicts, research activities focus on the socio-spatial aspects and the environmental, economic and socio-cultural impacts of the on-going ‘low-carbon’ energy transition.

Research activities in the area of restructuring and diversification of agriculture and food production encompass the geographies of agriculture and food, reflecting the current changes in farming and food production sectors.

The EG team's research in the area of diversity of natural and cultural landscapes is oriented to the diversity of living organisms in space, as well as processes and objects of an inanimate nature. The research further focuses on mapping the current state, changes and development of natural and cultural landscapes, including bio-monitoring, mapping and assessing natural hazards and geo-hazards, as well as their impacts and risk management.

Research activity and characterisation of the main scientific results

Research activities of the Team were carried out in accordance with the Research plan of the Team for 2015–2019, as defined in the previous evaluation. The activities were mainly connected with the objectives of the research projects, in which the Team members participated during the evaluation period. This concerns the following projects:

- MEYS LO1406 “Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use – Sustainability Program” (2015-2019);
- MEYS LM2015084 “Research INfrastructure for Geothermal ENergy – RINGEN” (2016-2019);
- MEYS EF16_013/0001792 “RINGEN – research infrastructure upgrade“ (2017-2020); and
- MC DG18P02OVV017 “Historical landscape on the border of Silesia and Moravia” (2018 – 2022). In this project, Team members conduct research on properties of building materials in archaeological monuments with a focus on detecting potential historical sources of raw materials for their production.

The main research topics were as follows: identification and characterization of geomaterials; strength and deformation properties of geomaterials under specific physical conditions; fracture properties and crack propagation in rocks; thermal behaviour of geomaterials; interaction between geomaterials and fluids; and interdisciplinary research.

1. Identification and characterization of geomaterials

This research project concentrated on natural and modified clay minerals and clay composites with specific properties, and on the development and application of analytical methods for their characterization in terms of structure, chemical composition and physico-chemical properties. Preparation of carbon precursors with potential applications in the field of industrial carbon was also investigated.

a) Modified clay minerals and clay-composites with specific properties

Research is focused on the structure and properties of clay minerals, especially smectites and structurally similar minerals. Smectites are currently being investigated intensively for their outstanding ability to absorb other substances of both organic and inorganic origin into their structure. In addition to their traditional role as sorbents, clay minerals are used in the development of nanomaterials and advanced composite materials, in which they act as a matrix or as one of the functional components.

Novel clay-composite materials have been developed by the Team members. Samples of montmorillonite and vermiculite were modified by alkylammonium cations with different carbon chains by a sorption procedure. Adsorption experiments were carried out in a batch mode with different masses of sorbents and initial concentrations and volumes of analgesic drugs. The organically modified clay samples exhibited high sorption ability for removing pharmaceuticals from aqueous solutions, as well as improved thermal stability. The thermal behaviour and stability of the organoclays were studied simultaneously by means of thermogravimetry and differential thermal

analysis, including thermal characteristics and the calculation of activation energy for the prepared composites.

The organically modified vermiculites were also used for preparation of polymer/clay nanocomposites. The set of polyethylene/vermiculite nanocomposites with different amounts of antimicrobial nanofiller has been prepared by a melt compounding procedure. The antimicrobial drug (chlorhexidine or ciclopiroxolamine) was loaded into the clay mineral structure and as organoclay nanofiller was incorporated into the polymeric matrix. The structure of prepared organoclays and nanocomposites was studied by X-ray diffraction analysis, Fourier transform infrared spectroscopy (FTIR) and thermal analysis.

The newly-prepared composites exhibit structural changes associated with significantly higher sorption capacity, and also better thermal stability compared to the original clay materials. In addition, the polyethylene/vermiculite composites enriched with an active organic substance showed significant antimicrobial activity against bacterial strains Staphylococcus aureus, Escherichia coli and yeast Candida albicans, with long lasting effects.

The research was conducted in cooperation with the VŠB-Technical University of Ostrava (hereinafter VŠB-TUO) and the Institute of Geotechnics of the SAS in Košice, Slovakia. The Team members designed the structure of organoclays and evaluated changes in their physico-chemical properties by FTIR and thermal analysis. They also performed the experiments on sorption processes of pollutants from the aquatic environment. Collaborators from VŠB-TUO participated in the sorption experiments, performed the enrichment of composites with polymers, created final forms of composites and tested their antibacterial activity. Collaborators from SAS performed X-ray diffraction analysis and specific surface measurements.

Project: MEYS LO1406
Outputs: papers in WOS and Scopus journals, conference papers

b) <u>Developments in infrared and Raman spectroscopy of clay minerals</u>

For many years, the Team has been dealing with applications of spectroscopic and microscopic methods in geomaterial analysis, focusing on the development and optimization of methodological procedures for laboratory measurements. In the evaluated period, special attention was paid to the use of Raman spectroscopy for the study of clay minerals. Raman spectroscopy of clays is often accompanied by fluorescence, an unwanted physical phenomenon that significantly affects the quality of the measured spectra. The Team members therefore focused on identifying the causes of fluorescence and finding ways to eliminate this analytical problem.

A series of measurements were performed on selected montmorillonite standards using dispersive Raman spectroscopy (excitation lasers of 532 nm and 780 nm), dispersive Raman microscopy (excitation laser of 532 nm), and Fourier Transform Raman spectroscopy (excitation laser of 1064 nm). A comparison of the measured Raman spectra with regard to the level of fluorescence and the presence of characteristic spectral bands was carried out. Based on the study, an optimized procedure of Raman microscopy has been suggested with the use of excitation lasers

of different wavelengths for specific types of materials. Optimal measurement conditions have also been specified with respect to the quality of sample preparation and the statistical reliability of the analytical data obtained.

The study was carried out in cooperation with VŠB-TUO. Analytical work was performed at the workplaces of both Teams using the available analytical equipment with different types of lasers. In addition, Team members prepared a sample base for the experiments and had a major part in evaluating the results. The results of the study have been published in the journal *Vibrational Spectroscopy*.
When designing, preparing and testing clay-composite materials, a detailed knowledge of the chemical structure of clay minerals is essential. The Team members conducted an experimental study aimed at finding the optimal combination of laboratory measurement methods and technical parameters to obtain comprehensive and accurate information about the composition and structure of clays. Vibrational spectra of clay mineral samples (different types of montmorillonites) were measured on a Fourier Transform infrared (FTIR) spectrometer and Fourier Transform Raman spectrometer in different spectral regions. The same clay samples were subjected to the XRD-powder diffraction analysis and chemical elementary analysis. The spectral data obtained by analytical methods used were compared in terms of their sensitivity to chemical composition, the isomorphic substitution of central atoms, and the layer stacking order of the clay minerals. The study showed what kind of information can be obtained from each spectral region and how it can be used to characterize particular clay minerals as raw materials for clay-composites. It was also confirmed that an appropriate combination of analytical methods represents an effective way to obtain sufficiently complex and accurate information about the composition and structure of clay minerals.

This research was carried out in cooperation with the VŠB-TUO. Most of the research work was done by Team members. The collaborators from VŠB-TUO provided spectral data from the dispersive Raman spectroscopy.

Results of the study have been published in the *Journal of Nanoscience and Nanotechnology* and at the 55th Annual Meeting of The Clay Minerals Society at the University of Illinois in 2018, as an Invited Lecture.

Project: MEYS LO1406
Outputs: papers in WOS and Scopus journals, conference paper

c) Carbon precursors

Another part of the analytical research program reflects current trends to find an efficient use of coal for "direct transformation" into carbon precursors with potential applications in the field of industrial carbon, as well as current endeavours to find other non-traditional raw materials for the preparation of industrial carbon.

Team members proposed and verified an innovative procedure converting selected fractions obtained from thermal processing of coal to higher molecular weight products, applicable as carbon precursors.

The extent of conversion and the ability to form anisotropic mesophase were monitored by determining the insoluble substances in selected organic solvents, and using the methods of thermogravimetric analysis, optical microscopy and Raman spectroscopy. The main parameters affecting the conversion process have also been defined.

The suitability of precursors for the above-mentioned applications is directly related to the formation of a high degree of textural anisotropy during the conversion process. Experimental results showed that the proposed conversion of the used fractions, including thermal treatment, intermolecular polymerization and polycondensation, leads to the formation of a sufficient amount of the anisotropic carbonaceous mesophase. It has been confirmed that the products obtained are suitable as precursors in high-technology carbon production, especially for sorbents or C/C composites. This research was realized in cooperation with the Department of Chemistry, VŠB-TUO. Most of the research work was done by the Team members. The collaborators from VŠB-TUO provided the results of additional analyses, such as optical microscopy or chemical elementary analysis.

The issue of carbon-based sorbents was also investigated with a focus on modifications of carbon nanotubes to obtain materials with specific properties for various sorption processes. A procedure for purification of multiwall carbon nanotubes has been proposed, removing impurities and partly oxidizing the nanotubes to improve the sorption process. Sorption of two organic molecules of naphthalene and formaldehyde on both original and purified nanotubes was performed. The quantitative sorption of molecules was studied by thermogravimetric analysis, where the exact mass loss of organic molecules was observed on thermogravimetric curves. According to the obtained thermal data, the purified nanotubes absorb almost twice the amount of formaldehyde and slightly higher amounts of naphthalene compared to the original form. Molecular modelling was employed to predict the most advantageous position of adsorbed organic molecule. The computational study was conducted using Forcite and the Adsorption locator in the Biovia Materials Studio software environment. A series of total energy calculations using the adsorbate locator module for naphthalene and formaldehyde was performed. The process of geometry optimization was carried out using an iterative process, in which the atomic coordinates are adjusted until the total energy of a structure is minimized. Both the lowest total energy and the lowest adsorption energy was located at the centre of a nanotube.

This research was conducted in cooperation with the Nanotechnology Centre, VŠB-TUO. The Team members realized the experimental sorption study including thermogravimetric analysis and participated in the preparation of data for the molecular modelling. The collaborators from the VŠB-TUO provided the purification process of multiwall carbon nanotubes, scanning electron microscopy and the molecular modelling.

Project: MEYS LO1406
Outputs: papers in WOS and Scopus journals

2. Strength and deformation properties of geomaterials under specific physical conditions

The uniaxial compression test is commonly used to obtain information on the basic mechanical parameters of rocks, such as the strength and linear stiffness moduli. It is simple, quick and can be performed on standard commercial testing machines. In rock mechanics, however, uniaxial loading conditions are not always a suitable model, as most materials in the underground rock environment are exposed to a triaxial loading. In addition, the nonlinear deformation response of rock materials under triaxial conditions may not correspond in general to a superposition of linearized responses in uniaxial stress states. Therefore, the Team research activities have been focused on laboratory simulations of triaxial conditions, and on a comparative study of the deformational behaviour of rocks along specific paths in triaxial stress space. Special attention was also paid to accurate measurement of deformations of rock specimens under loading, and their quality sealing when testing in the triaxial mode.

a) Deformational behaviour of rocks along specific paths in triaxial stress space

An extensive experimental study was realized, focusing on the deformational response of rocks along several specific loading/unloading paths (IC - Isotropic Compression, CTC - Conventional Triaxial Compression, CTE - Conventional Triaxial Extension, RTC - Reduced Triaxial Compression, RTE - Reduced Triaxial Extension, and PS - Triaxial Pure Shear Extension). For measurements, a sophisticated multipurpose experimental device working with extremal loads (press with in-chamber detection of axial force limited by 2.6 MN, and triaxial cell with maximum confining pressure of 140 MPa) was used. Attention was focused on the non-linear behaviour of rocks and the variability of tangential stiffness moduli. Sandstone, with a relatively homogeneous structure, was selected as the test material for initial experiments. The experimental results showed that the deformation response of this rock differs from the predictions of the basic model, which describes the rock during its loading as an isotropic elastic medium with constant stiffness moduli.

The initial experiments have been subsequently augmented by cyclic variants of all the above-mentioned loading/unloading paths to analyse the evolution of irreversible deformation of the rock material. For reversible and irreversible strains, phenomenological description has been proposed based on the isotropic compression and triaxial pure shear experimental data, and on the assumption of an approximate transversal isotropy of the material. Model estimates have been verified through experimental data from other loading/unloading paths.

The assumption of approximate transversal isotropy of the sandstone has been confirmed by acoustic measurements, optical microscopy, X-ray computer tomography, and by water-jet abrasion of a real-cut surface followed by 3D optical scanning. Irregularities in the layered rock structure that are responsible for variability of measured stiffness moduli have been described in detail. An experimental base was created for preparing the constitutive models of the rock mechanical behaviour, including the material anisotropy and nonlinearities of reversible and irreversible strains.

With respect to the triaxial tests, the “ISRM suggested methods...” offer only recommendations related to the standard CTC test being used for determination of the failure envelope. Based on the above experiments, the Team members suggested a methodology for CTC/CTE and RTC/RTE tests. The methodology has been implemented for the triaxial device in the IGN laboratory as tuned control procedures, and verified by testing standard (metals, akulon) and rock materials (sandstones, granites).

Projects: MEYS EF16_013/0001792 ; MEYS LO1406; MEYS LM2015084
Outputs: papers in Scopus journals, conference paper

b) Developments in the methodology for rock deformation measurements

Laboratory research in rock mechanics continually requires activities aimed at developing test procedures and improving the measurement components of the test system. Extensometers in triaxial cell of the MTS testing system used by the Team provide only measurements of average strains along gauge-lengths defined by the construction of these detectors. Based on such limited data, it was difficult to investigate inhomogeneous rock samples or to study the localization of deformation on the tested rock specimens in detail.

Team members therefore focused on improving the measurement system to allow a more detailed strain mapping, e.g. at several local positions or on a selected area of the rock specimen surface. In cooperation with VŠB-TUO, the suitability of Digital Image Correlation (DIC) methods for analyzing the evolution of surface deformations on tested rock specimens has been examined and verified.

With the assistance of the GL Test Systems GmbH (Germany), the triaxial cell has been improved to allow its subsequent completion with a set of strain-gauges for detecting deformations. With the support of the MTS System Corp. (USA), the control system of the experimental device has also been updated.

In the above-described research activities, a new method of isolating cylindrical rock specimens for triaxial testing has been designed and verified. The method, using a painted coating on the specimen surface, eliminates the problems associated with the use of standard rubber or latex membranes or plastic shrinking tubes. It has been confirmed that the painted coats reduce the systematic error caused by the compressibility or degradation of standard insulation layers.

Projects: MEYS EF16_013/0001792 ; MEYS LO1406; MEYS LM2015084

3. Fracture properties and crack propagation in rocks

Another part of the Team's research was oriented to the mechanical fracture parameters of rocks in relation to their mineralogical composition and internal texture features, and on the visualization of the fracture propagation processes in rocks. The effects of various methodological and physical conditions on the values of rock fracture parameters have also been studied in detail.

a) Testing mechanical fracture parameters of rocks

Crack initiation in a rock material occurs when the stress intensity factor at a microcrack tip reaches its critical value, known as fracture toughness. From that point of view, fracture toughness represents an important mechanical parameter in the linear elastic fracture mechanics expressing material fracture resistance to the crack initiation and subsequent propagation.

During the evaluation period, measurements of rock fracture toughness using the Chevron bend test according to the methodology suggested by the International Society for Rock Mechanics and Rock Engineering, have been successfully implemented in the existing portfolio of laboratory tests conducted at IGN. At present, the Team is able to prepare test specimens with a special chevron (V-shaped) notch from the rock blocks to measure the rock fracture toughness and to evaluate the obtained experimental data. Experimental studies were carried out on selected sedimentary and granitic rocks. In cooperation with the Team of Professor Z. Keršner (Institute of Structural Mechanics, Faculty of Civil Engineering, Brno University of Technology), other mechanical fracture parameters (such as bending Young's modulus and fracture energy), have also been calculated from the obtained data. Within the IGN, the Team cooperates with the Department of Geomechanics and Mining Research in this field.

Project: MEYS LO1406
Outputs: papers in WOS and Scopus journals

b) Factors affecting rock fracture parameters

In cooperative research between the IGN and Kumamoto University (Japan), comparative experiments were carried out focused on the effects of various methodological and physical factors on the rock fracture parameters. A series of measurements on rock samples with different shapes, size, notch geometry and under different loading rates, were conducted at both IGN and Kumamoto University. In addition to methodological factors, attention was also paid to the mineralogical composition, porosity and water content in tested rocks.

Most of the experimental work was done by Dr. L. Vavro, who in 2018 completed her six-month Post-Doctoral Research stay at the Graduate School of Science and Technology of Kumamoto University, in the Laboratory of Rock Mechanics led by Professor Yuzo Obara. Professor Obara subsequently visited IGN in 2019.

Within IGN, the research was conducted in cooperation with colleagues from the Department of Geomechanics and Mining Research.

Project: MEYS LO1406; MEYS EF16_027/0008478
Outputs: journal paper, conference paper

c) Visualization of fracture propagation processes in rocks

Another element of our research program included the study of fracture initiation and propagation in quasi-brittle materials using X-ray computed tomography (CT)

techniques. In cooperation with the Institute of Theoretical and Applied Mechanics of the CAS (ITAM), a new laboratory loading device has been designed, constructed and verified. The unique device (patented by the ITAM team as Czech National Patent no. 307897) allows the capture of the 3-point and 4-point bending tests on rock specimens, while scanning the loading process using an X-ray CT scanner. A series of 3-point and 4-point bending experiments on chevron notched rock specimens with the CT scanning and 4D CT measurements were performed in both IGN and ITAM laboratories. The experimental results obtained provide important information in terms of the crack and fracture process zone (FPZ) development and propagation, as well as crack/FPZ length and shape identification.

Within the IGN, the Team cooperates with colleagues from the Department of Geomechanics and Mining Research in this research program.

Project: MEYS LO1406
Outputs: paper in WOS journal, conference papers

4. Thermal behaviour of geomaterials

The IGN has been extensively involved in scientific research in the fields of mining, underground engineering, underground waste and energy storage, etc. In recent years, applied research into the exploitation of deep geothermal energy has also been developed at the Institute. A specific part of the research in these areas is the influence of thermal changes on the behaviour of rocks and rock mass in underground structures (or in stone civil structures), whether these are thermal changes due to anthropogenic activities or as a result of extreme situations, such as tunnel or building fires. The influence of temperature on rocks is a complex and complicated process, as these effects depend on the composition and properties of rocks and are affected by external parameters of the thermal field. A temperature increase causes the phase and polymorphic transformations connected to thermal expansion, with the following appearance of tensions and cracks in minerals and in the rock structure. After consequential temperature decrease, developed tensions and cracks still influence the process.

In the evaluation period, a detailed analytical study was carried out on selected granitic rocks, focusing on the effects of rock composition and structure on residual thermal expansion and on the effect of phase transformations during the heat stress on the complex thermal behaviour of rocks.

A combination of laboratory analytical methods (thermomechanical analysis, thermogravimetry, differential thermal analysis, optical microscopy, X-ray powder diffraction, and FTIR spectroscopy) was applied for a detailed analysis of an experimental set of samples of granitic rocks. The methodology of measuring thermal expansion with respect to the measurement conditions (such as probe type, heating rate, final temperature, atmosphere) and sample preparation (grain size, orientation of sample according to the principal coordinate system) has been suggested. The characteristic thermal curves, as well as coefficients of thermal expansion, were determined and the thermal behaviour of particular rock types according to their composition and structure was predicted. Regression dependencies of the dilatation values on temperature have also been defined. The research results confirmed that

the methods of simultaneous thermogravimetric and differential thermal analysis, together with the methods of thermomechanical analysis, can be effectively used in the field of geomaterial research, especially in the study of the thermo-mechanical properties of rock.

Another part of the research was focused on the potential of thermal analysis methods for the identification of clay minerals in sedimentary rocks, where clays and especially mixed-layered or interstratified clay minerals can significantly affect their physical and mechanical properties, as well as their thermal properties. Identifying clay minerals in mixtures by means of thermal analysis is often complicated because of the similarity of thermal effects of individual clay components. The similarity in thermal behaviour is mainly connected with the origin, chemical variability and crystal structure of phyllosilicates. Therefore, a combination of methods of thermal analysis and infrared spectroscopy was proposed. The study has shown that such an approach makes it possible to determine detection limits of individual clay minerals or their mixtures, which can be effectively used to solve problems in the identification of clay minerals in sedimentary rocks.

The research was conducted in cooperation with VŠB-TUO. The Team members carried out substantial part of the analytical work. Colleagues from the co-operating institution provided additional analyses such as XRD-powder diffraction or chemical elementary analysis.

Projects: MEYS EF16_013/0001792 ; MEYS LO1406; MEYS LM2015084
Outputs: papers in WOS and Scopus journals, conference paper

5. Interactions between geomaterials and fluids

a) Filtration and pore properties of rocks

In recent years, IGN has been intensively engaged in the numerical modelling of coupled thermo–hydro–mechanical processes in the rock environment of nuclear waste repositories. In this context, an experimental evaluation of pore space characteristics and the filtration properties of granitic rocks in the Czech Republic, has been performed by the Team members. The main parameters of the pore system of rocks from five important geological regions were measured, and changes in their gas permeability during an increase in hydrostatic pressure were investigated using methodologies developed by Team members. The causes of the different behaviours of individual types of granitic rocks during hydrostatic pressure changes were determined and discussed in relation to their structural-textural properties.

Project: MEYS LO1406
Outputs: paper in WOS and Scopus journal

b) Physical interactions between rocks and water

From practice it is recognised that an inappropriate application of chemical agents commonly used for hydrophobization of stone in buildings and stone art objects, can cause damage to the surface layers of the stone and decrease its durability. The aim of the research was therefore to answer two main questions:

1. What is the impact of hydrophobizing agents on the dynamics of moisture exchange between the pore system of a building stone and surroundings? and

2. How will an addition of photocatalytically active nanoparticles affect the properties of the protective coating?

Poly(alkyl siloxane) containing photoactive nano-ZnO has been studied as a protective coating of glauconitic sandstone. The effects on visual appearance, hydrophobicity, porosity, water absorption/evaporation, and the self-cleaning ability of the sandstone were measured. The results were evaluated in comparison with uncoated and poly(alkyl siloxane)-coated sandstone.

The static contact angle of water reached 89° ± 3° and 128° ± 2° for poly(alkyl siloxane) and nano-ZnO/poly(alkyl siloxane) coating, respectively. Poly(alkyl siloxane) and nano-ZnO/poly(alkyl siloxane) coatings led to increased reduction in water absorption (>50%) for ~18 h and ~8 h, respectively, compared to the uncoated sandstone. The shorter time of reduction in water absorption is compensated by self-cleaning ability. Photodegradation of methylene blue on the nano-ZnO/poly(alkyl siloxane) coating after 5 h of UV irradiation was observed.

Significant reduction in water absorption together with photodegradation of artificial pollution on the stone surface gives this agent a potential for practical use in the protection of sandstone monuments.

This research was conducted in cooperation with the Nanotechnology Centre, VŠB-TUO. Photoactive nanoparticles were prepared at that workplace. Colorimetric and porosimetric measurements, as well as contact angle measurements, were performed there. At IGN, the sandstone test specimens were selected and prepared, petrographic analyses were performed, long-term absorption/evaporation experiments were carried out and evaluated, and the dynamics of moisture exchange between the stone and the surroundings on coated and uncoated samples has been described. The character of the pore space of the stone and its changes due to the agent used were analysed.

Project: MC DG18P02OVV017
Outputs: paper in WOS and Scopus journal

6. Interdisciplinary research

In addition to the previously described research activities and results, Team members also collaborated in research on interdisciplinary topics, with both IGN Teams and with partner institutions. These projects primarily involved the following topics:

- **Geotechnical characterization of the rock mass** (Department of Geomechanics and Mining Research of IGN; SÚRAO - Radioactive Waste Repository Authority; DIAMO, state enterprise);
  outputs: research reports, paper in WOS journal, conference papers.
- **Geology of the Upper Silesian Coal Basin** (Department of Geomechanics and Mining Research of IGN; Green Gas DPB Ltd.);
  outputs: conference papers.

- **Paleontology** (VŠB-TUO; Green Gas DPB Ltd.; Natuurhistorisch Museum Maastricht, Netherlands; Comenius University Bratislava, Slovakia; University of Granada, Spain);
  outputs: papers in WOS and SCOPUS journals, conference paper.
- **Material analysis of building materials** (VŠB-TUO);
  outputs: journal paper, conference papers.
- **Properties of materials in archaeological monuments and historical sources of raw materials for their production** (Silesian University in Opava; Palacký University Olomouc; VŠB-TUO);
  outputs: paper in WOS journal.

- **Machining and material analysis of hybrid metal matrix composites and wood-plastic composites** (Department of Material Disintegration of IGN; Indian Institute of Technology, Dhanbad, India; Technical University of Košice, Slovakia);
  outputs: papers in WOS journals.
- **Water jet cutting and machining of difficult-to-machine materials** (Department of Material Disintegration of IGN; Technical University of Košice, Slovakia; VŠB-TUO);
  outputs: papers in WOS journal, conference paper.
- **Visualisation and quantitative analysis of water jet structure** (Department of Material Disintegration of IGN; Technical University of Košice, Slovakia);
  outputs: paper in WOS journal, conference papers.
- **Characterization and modification of abrasives for water jet technologies** (Department of Material Disintegration of IGN);
  outputs: journal paper, conference papers.
- **Numerical modelling in quantum chemistry and chemical physics** (University of Paul Sabatier, Toulouse, France; VŠB-TUO);
  outputs: papers in WOS journals.

Research activity and characterisation of the main scientific results

The research activities of the Team were principally defined by the content of projects completed by the Team or projects in process. In particular, they were focused on the high-speed water jet disintegration of materials and geomaterials. Our research areas are interconnected, often overlapping and difficult to be clearly separated. Together, they contribute to the deepening of knowledge about the basic physical processes occurring during the generation of high-speed liquid flows, their behaviour, their interactions with solid materials, and potential practical applications. The following account briefly describes some of the results achieved by the Team in the evaluation time period. Significant results are then presented in more detail, with accompanying figures. The results are arranged by the research areas investigated by the Team in the evaluation period, and these have already been listed in the section: **Focus of the Team.**

I. Intensification of high-speed water jet effects

This research program was oriented to the study of the basic characteristics of high-speed water jets (WJs), processes of generation and the behaviour of WJ, and the effects of WJ on materials to be disintegrated. The objectives were to enhance the effectiveness of WJs used in a broad spectrum of applications, from traditional cutting and machining through to the removal of surface layers, to new and prospective application areas of WJs, such as in medicine, the food industry, etc.

a) Pulsating water jets

The collision of a high-velocity liquid mass with a solid material generates short high-pressure transients, which can cause serious damage to a surface and the interior structure of the target material. Therefore, some of our research activities focused on study of the possibilities of influencing the flow upstream from the nozzle outlet, in order to generate a water jet exploiting the above-mentioned physical phenomenon. A proprietary method of the generation of pressure pulsations in a high-pressure system to create pulsating water jets (PWJs) by means of an acoustic generator (proposed, designed and verified in previous evaluation periods) was further developed. **Acoustically-generated pulsating water jets** (APWJs) demonstrated a significant increase in disintegration effects on various types of materials in comparison to continuous jets. Currently, the protection of the acoustic generator of PWJs is granted by the US patent, Australian patent, European patent validated in 20 countries, the Canadian patent and the Japanese utility model.

Numerical methods of flow simulation and experimental verification of the results provided by numerical models were used for a study of fundamental processes of excitation and the propagation of acoustic waves (and/or high-frequency pressure pulsations) in the pressure liquid in a high-pressure system, and their effects on the formation and properties of pulsating liquid jets. In addition, the numerical modelling significantly contributed to the creation and study of the so-called hydrodynamic nozzles generating **self-excited pulsating water jets** (SPWJs) of various properties.

Influencing physical and mechanical properties of surface layers of materials by APWJs

Comprehensive experiments were aimed at comparing the effects of continuous and acoustically-generated pulsating water jets with traditional methods of surface hardening of metals (for example, peening as a process of working a metal surface to improve its material properties, usually by mechanical means - by blasting with shot, etc.). The application of APWJs demonstrated effects comparable to those of conventional methods. The results showed that the APWJ process is a new possibility of surface cold-working treatment. The hardened surface layer was thinner than in the case of shot peening; however, the beneficial effect on fatigue life was comparable. (Surface treatment was performed by the Team; fatigue

tests, SEM microscopy and microhardness measurement were realised at the Institute of Physics of Materials of the CAS in Brno).

Hydrodynamic nozzle as a tool for surfaces treatment and material disintegration

Based on a detailed study of the phenomenon occurring in the fluidic nozzle, a hydrodynamic nozzle was designed using numerical flow modelling. This nozzle enables the generation of pressure and velocity/flow pulsations of the liquid, which are significant enough to break up effectively the outgoing continuous liquid jet into bunches of liquid. Sufficiently high amplitudes of pressure and flow oscillations can be achieved at frequencies from units up to hundred thousands of Hertz, depending on the value of the supply pressure, i.e., the fluid flow rate and type of nozzle.

Low-frequency hydrodynamic nozzle with a stabilizer

Promising research in the area of hydrodynamic self-resonating nozzles follows from previous research using an innovated nozzle with low-excitation frequency, which has been approved for the removal of surface layers.

The design of a hydrodynamic nozzle with low-excitation frequency and with a stabilizer was realised theoretically and verified experimentally. In addition, the designed tool was fitted with a stabilizer which allows the water jet energy to be transported to greater distances. The design of the tool was based on the mathematical modelling of a compressible water flow inside the tool and at the outlet. The flow of fluid in the inner space of the tool evokes self-excited pulsations of pressures and velocities. This phenomenon creates a self-excited pulsating water jet (SPWJ) at the outlet of the tool (see Figure 1). The SPWJ generates a large dynamic stress on the surface of the disintegrated material due to a large and fast change of the impact pressure over time. The tool generates self-pulsating oscillations in the full operating range of the feeding water pressure, i.e., from almost zero (0.01 MPa) to 300 MPa.

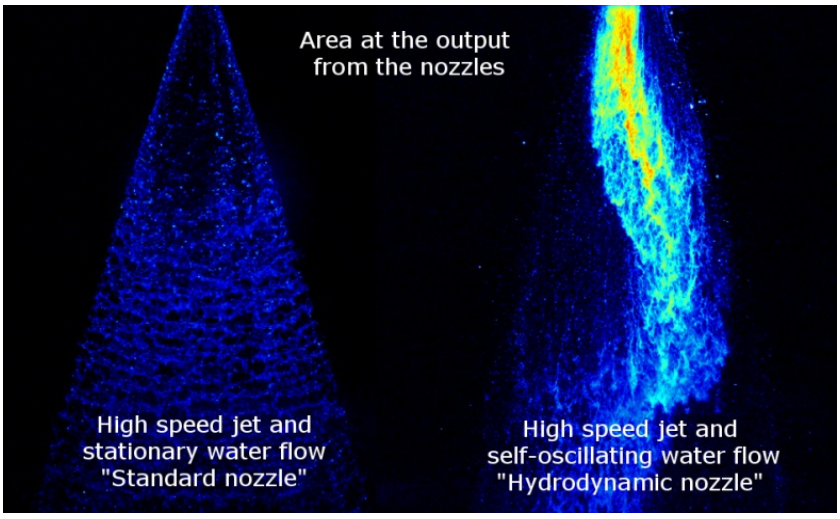

Fig. 1. Visualisation of real flows of high-speed water jets at outlets from the standard and hydrodynamic nozzles (Source: Photo by M. Zeleňák, Institute of Geonics)

The tool has been tested for de-scaling hot-rolled sheet surfaces. Compared to a standard flat jet nozzle, the low-frequency and low-pressure hydrodynamic nozzle achieves the same erosive effect. The SPWJs can be synchronised and the jets do not collide on the cleaned surface (when simultaneously applying more nozzles placed side by side). The different load of water jets along their width is thus eliminated and a better quality of the cleaned surface is achieved using the hydrodynamic nozzle with the same input energy as the standard nozzle.

This tool has been also tested for the surface cleaning of hot-rolled wires. Huge energy savings with a significant increase in the quality of cleaned surfaces have been achieved, compared to the standard cleaning method by means of the continuous flat water jet. While

the input pressure of 40 MPa was used for the standard flat nozzle, only 4 MPa were needed for the hydrodynamic nozzle. During testing, both nozzles generated the same value of the volumetric flow. It has been demonstrated that the SPWJ is more effective during surface cleaning processes, even at significantly lower input hydraulic energy than the stationary flat water jet.

The pulsating water jet created by self-excited oscillations can use all of its energy at a given time for only a very small area compared to the stationary flat water jet. The difference between the effect of the stationary water jet and the effect of the SPWJ is more significant at a greater spraying angle of both jets, e. g., at 30°. The effect of the SPWJ is further enhanced, as the impact area is subjected to a greater change of pressure in a very short time. Due to energy savings during operation, less mechanically resistant materials can be chosen for the tool manufacturing. In addition, an important side effect is the considerably lower impact on the environment.

The technical solution of the hydrodynamic nozzle is protected by a Czech patent No. 305370: **Tool and hydrodynamic nozzle for generating high pressure pulsating liquid jet without cavitation and saturated vapours** (granted in July, 2015). Subsequently, a licence agreement was signed with a strategic partner from Germany - Hammelmann GmbH. On this basis, the protection of the solution was extended by submission of patent applications in the EU and USA. European patent No. EP3068543: **A device and Hydrodynamic Nozzle for Generation of a High Pressure Pulsating Jet of a Liquid without Cavitation and Saturated Vapour**, has been granted (in June, 2020).

b) Abrasive water jets

In addition to pulsating water jets, the Team focused on the improvement of the commonly-used concepts of an abrasive cutting head, and increases in its efficiency during the disintegration of materials. Extensive analysis of the process of injection mixing of abrasives with a high-speed water jet and the subsequent numerical simulation, revealed that the processes of mixing and acceleration provide great potential for improvements in the efficiency of the high-speed abrasive water jet (AWJ), by a set of modifications and improvements in the existing cutting tool.

Unified high-speed abrasive water jet

AWJ is the most widely-used type of water jet applied in material machining technology. Currently, the AWJ consists of a single water jet. The new solution is based on the concept of several water jets which meet in a particular place, get unified and form the so-called unified water jet (Figure 2). The jet is consequently enriched with a mixture of air and abrasive. The newly-formed mixture (water + abrasive + air) is further accelerated and applied for material machining in the same way as the tool in current use. The new AWJ enables the creation of a completely unique distribution of the mixture of water, air and abrasive particles in the flow cross-section.

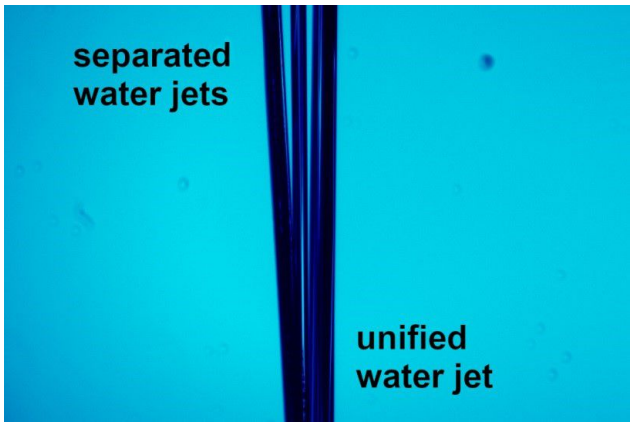

Fig. 2. Visualisation of three water jets being unified into a single water jet (Source: Photo by M. Zeleňák, Institute of Geonics)

The newly-developed device was carefully tested and compared with the existing commonly-used AWJ tool under the same input energy conditions. Numerical flow modelling and completed experiments have shown that even though the unification of water jets causes loss of their hydraulic power, the resulting cutting power is higher by approximately 20% compared to the commonly-used AWJ. It is clear that the magnitude of the hydraulic power of the mixture of water, abrasive particles and air at the tool outlet, is not crucial in assessing the cutting efficiency. The magnitude of the cutting power thus mainly depends on the distribution of the mixture in the flow cross-section at the tool outlet. This conclusion represents a breakthrough in the field of the design of tools for the generation of AWJs. It seems that the efficiency of the currently-used tools can be significantly improved.

This new type of the unified water jet provides new possibilities of important energy savings during machining operations. The unique research results were protected by a Czech patent No. CZ 307860: **Multi-jet abrasive head** (granted in May, 2019), and a utility model: **Abrasive jet cutting tool with multiple water jets and intake air**.

Abrasive head with inserted nozzle and clean air infeed

In the abrasive cutting head, more precisely at the water nozzle outlet, the pressure energy of water is changed into kinetic energy, forming a narrow water jet. Subsequently, abrasive particles are infed into the jet and the abrasive is accelerated. This created AWJ is then used for cutting very hard materials and other machining operations. Unfortunately, using existing solutions, an uncontrolled movement of abrasive particles inside the mixing chamber occurs when mixing the jet with the abrasives, which often results in undesired contact of particles with the water nozzle. This usually leads to the early destruction of the water nozzle and its total replacement.

Data obtained from the numerical analysis of the 3D multiphase turbulent flow of water, air and abrasive particles, have shown that the given inner shape of the standard abrasive head causes undesired wear of the orifice by abrasive particles. The results correspond to practical observations. This has demonstrated that the existing shape of the fluid flow has to be changed in order to guarantee sufficient orifice protection.

The resolution of this problem by the Team is based on the hypothesis that when the inner space between the water nozzle and the mixing chamber is supplemented with a clean air in-feed and another (inserted) nozzle, then the fluid flow is changed, which eliminates the orifice wear caused by the impact of abrasive particles. The hypothesis was consequently validated by fluid flow numerical modelling. Of note, this solution does not influence the cutting efficiency of the tool. The unique solution is relatively simple and can be installed in any existing commonly-used abrasive head (see Figure 3). It improves the lifetime of the cutting tool, reduces energy consumption, and less resistant and cheaper materials can be used for manufacturing the water nozzle.

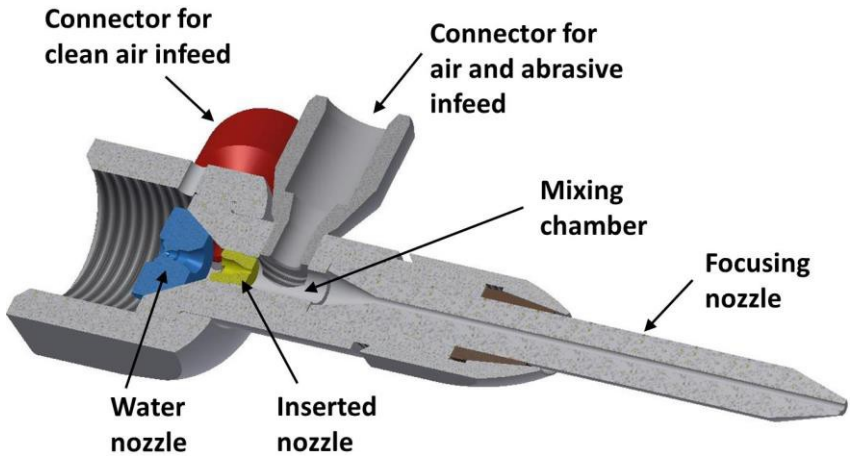

Fig. 3. CAD model of a modified abrasive head with inserted nozzle and clean air infeed (Source: Model by Z. Říha, Institute of Geonics)

The technical solutions described above were protected by Czech patents No. 307862: **Abrasive head with inserted nozzle** (granted in May, 2019) and No. 307863: **Pure gas intake abrasive head** (granted in May, 2019), European Patent Applications No. 3 572 186 A1: **Abrasive Head With Clean Gas Infeed** and US patent Applications No. 2019/0366508 A1: **Abrasive Head With Inserted Nozzle** and No. 2019/0366509 A1: **Abrasive Head With Clean Gas Infeed.**

Projects related to **research area I:** LO1406, FV10446, FV30233 and GA19-00408S.
Outputs related to **research area I:** patents (see above), utility models, papers in WOS and Scopus journals, conference papers.
Examples:

1. Srivastava, M., Hloch, S., Tripathi, R., Kozak, D., Chattopadhyaya, S., Dixit, A. R., Foldyna, J., Hvizdoš, P., Fides, M., Adamčík, P. Ultrasonically generated pulsed water jet peening of austenitic stainless-steel surfaces. *Journal of Manufacturing Processes*. 2018, 32(32), 455-468. **IF (2018) 3.462, Q2 according to QAIS;**
2. Lehocká, D., Klichová, Dagmar, Foldyna, Josef, Hloch, Sergej, Hvizdoš, P., Fides, M., Botko, F. Comparison of the influence of acoustically enhanced pulsating water jet on selected surface integrity characteristics of CW004A copper and CW614N brass. *Measurement*. 2017, 110 (November 2017), 230-238. **IF (2017) 2.218**, **Q3 according to QAIS.**

II. Abrasive materials for abrasive water jets

When cutting or, more generally, machining materials by means of the AWJ technology, a suitable abrasive material (abrasives), which is accelerated by the water jet and transported to the place of interaction with the disintegrated material, has to be used. Abrasive materials are thus an integral part of the technology and significantly affect the efficiency of the whole machining process.

Within the research on abrasives, the Team focused not only on the possibilities of improving the cutting capabilities of commonly-used natural abrasives by modifying their properties, but also searched for new materials suitable as abrasives which have not yet been used in the AWJ technology. The properties of abrasives and their behaviour in AWJs used in various operation modes, were studied. By means of numerical modelling, modifications of the inner geometry of high-pressure systems were proposed, including the parts of mixing water jets with abrasives, in order to significantly increase the efficiency of the existing cutting heads.

Abrasive materials for the abrasive water jet turning and milling

Problems related to the determination of suitable types of abrasive materials for the technology of AWJ **milling** and **turning**, which would increase the efficiency of the machining process and

the quality of cutting surfaces, while preserving existing economic parameters and price ratios of the technological process, were resolved. A detailed study of selected properties of abrasives was motivated by the need to understand the behaviour of a particular abrasive material during the process of milling and turning by AWJ. The data that were obtained were further processed and used to create a database of all studied abrasives. In addition, the scientific knowledge and experiences gained in this process were used for an intentional treatment of the properties of abrasive materials. It was considered appropriate to use a particular type of abrasive for a particular type of material to be cut. An abrasive material suitable for one type of material to be machined was usually ineffective for another material. Due to this finding, the machining ability of a particular type of abrasive material can be significantly increased.

In this research area, the Team cooperated with the Department of Laboratory Research on Geomaterials, which principally resolved the issues related to the mineralogy and properties of abrasive grains.

Special abrasives for machining hard-to-machine materials by AWJ technology

Finding new suitable abrasives for the **cutting** and **machining of hard-to-machine materials** using the AWJ technology, is one of the traditional activities of the Team under evaluation. Unlike work on the commonly-available almandine-type garnet concentrates, this research has focused on a promising abrasive of the so-called pyrope-almandine type from localities in Tanzania, the excellent cutting abilities of which were confirmed in our experiments. The Team also studied a garnet-type abrasive - andradite, the cutting abilities of which have not been examined to date. The last of the studied abrasives is the barite mineral ($BaSO_4$), with deposits in the Czech Republic. Due to its biocompatibility and easy sterilisation, it is a very promising abrasive for the application of abrasive water jets for cutting tissues and bones in medicine.

Determination of abrasive particle velocities in injection and suspension abrasive water jets

The proposed method allows for the detection of supersonic speeds of abrasive particles in the injection and suspension water jet at the nozzle outlet. The measurement of abrasive particle velocities is based on the Particle Image Velocimetry (PIV) method, combined with the Laser-Induced Fluorescence (LIF) technique. A special procedure for the coating of abrasive grains has been developed for measurements of particle velocities. The data acquired in this process are used for the study of the generation process of abrasive water jets and for verification, with numerical models used for the optimisation of new designs of cutting heads.

Development of a Smart recycling line based on Industry 4.0 principles

As part of the TH04020218 project of the Technology Agency of the Czech Republic, an advanced unit for the recycling of abrasives is being developed in cooperation with industrial partners. The operation and control of the unit is based on Industry 4.0 principles. The **Smart Recycling Line** of abrasives for AWJs is a comprehensive technological system for the recycling of abrasives with complex processes, the behaviour of which can only be described by methods of virtual simulation of material flows, taking into account random phenomena and all significant external and internal relations. Machine learning with elements of artificial intelligence is used for the development of intelligent algorithms (neural networks) in order to optimise the entire process of the recycling line. The implementation of advanced control methods results in significant energy savings in the whole recycling technology, an improved recovery ratio and quality of recycled abrasive concentrates and acceleration of the recycling process.

Within this concept, an **Internet Knowledge Portal of Abrasives** has also been created. The portal is already used by project researchers for an easy and intuitive storage of acquired data, and it enables access to the results of analyses of properties and cutting capabilities of abrasives. The portal will soon provide the ordinary users of the AWJ technology with information on an abrasive material suitable for the required application and material to be cut

or machined, on the basis of an expert system. Other important functions of the portal are the processing of data acquired during the operation of the abrasive recycling unit, and the control of the Smart Recycling Line technology by means of the newly-developed algorithms.

Projects related to **research area II:** LO1406, FV10446, FV30233 and TH04020218.
Outputs related to **research area II:** papers in WOS and Scopus journals, conference papers.
Examples:

1. Zeleňák, M., Foldyna, J., Linde, M., Pude, F., Rentsch, T., Fernolendt, J., Poort, H. U. Measurement and analysis of abrasive particles velocities in AWSJ. *Procedia Engineering*. 2016, Vol. 149, July 2016, 77-86.
2. Nag, A., Ščučka, J., Hlaváček, P., Klichová, D., Srivastava, A. K., Hloch, S., Dixit, A. R., Foldyna, J., Zeleňák, M. Hybrid aluminium matrix composite AWJ turning using olivine and Barton garnet. *International Journal of Advanced Manufacturing Technology*. 2018, 94 (5-8), 2293-2300. **IF (2018) 2.496, Q n.a. according to QAIS**
3. Cárach, J., Hloch, S., Petrů, J., Müller, M., Hromasová, M., Nag, A., Čuha, D., Hlaváček, P., Hatala, M., Kratochvíl, J., Ruggiero, A. Evaluation of physical phenomena and surface integrity during hydroabrasive disintegration of the rotating workpiece with feedback loop control. *Measurement*. 2019, 134 (February 2019), **IF (2019) 3.364, Q3 according to QAIS**

III. Numerical simulation of flow

This topic is closely related to other research areas systematically studied by the Team. The philosophy of the Team is to implement numerical modelling and simulation of a high-speed flow to currently resolved issues. The modelling, based on thorough experimentally-verified data, is a powerful tool in our water jet research and a crucial part of innovations and modifications of the standard high-pressure systems. A significant time savings enables us to extend the research scope of the Team, as well as to shorten the time needed for the completion of topics currently under investigation.

Due to the interrelationships of topics, the issues resolved by means of numerical simulation of the flow are only listed at this point: they are presented in more detail in other parts of the Report describing the activities of the Team. These results are, for example: research into hydrodynamic nozzles; modifications of the abrasive head in order to increase its efficiency and lifetime; analysis of the distribution and behaviour of abrasive particles in a high-speed flow; and the development of special equipment enabling the water jet application in new areas (cavitation chamber development for research into the cavitation wear of concrete by fast-flowing liquids, etc.).

CFD simulation of a free surface jet of a high-pressure nozzle

Besides such basic research, the knowledge and skills of the Team in the field of numerical simulations of the flow are used in contract research. An important contribution is, among others, flow analysis for the renowned German manufacturer of high-pressure equipment - Hammelmann, GmbH.

This included Computational Fluid Dynamics (CFD) modelling and the subsequent description of the two-phase flow of water and air. The problem of a high-speed water flow (jet) impinging onto a planar surface at various angles was resolved. The objective was to find out how the impacting water flows over this surface using an advanced CFD model. Three cases with various flow inclination angles to the impacted surface (90°, 85° and 75°) were studied. The calculation was performed as a calculation in steady-state. This result has been applied in concepts and constructions of high-pressure devices. It also represents important information for the arrangement of multiple nozzles in a common workspace.

Projects related to **research area III:** LO1406, FV10446, FV30233 and GA18-25035S.
Outputs related to **research area III:** papers in WOS and Scopus journals, conference papers.
Examples:

1. Zeleňák, M., Foldyna, J., Ščučka, J., Hloch, S., Říha, Z. Visualisation and measurement of high-speed pulsating and continuous water jets. *Measurement*. 2015, 72 (August 2015), 1-8. **IF (2015) 1.742, Q3 according to QAIS**
2. Zeleňák, M., Říha, Z., Souček, K., Pude, F. Analysis of Micro Continuous Water Jet Based on Numerical Modelling and Flow Monitoring. In. Hloch, Klichova, Krolczyk, Chattopadhyaya, Ruppenthalova (eds.) Advances

in Manufacturing Engineering and Materials, ICMEM 2018, *Lecture Notes in Mechanical Engineering*, 2019, pp. 144-155.

IV. Study of the topography and quality of surfaces

Due to increasing demands on the surface quality of components and detailed knowledge of their topography and integrity, the analysis of surface characteristics is not only an important phase in evaluating the qualitative aspects of a particular technology used in machining, but it also contributes to the improvement of knowledge about the physical principles of the interaction of cutting tools with a material. The study of the topography of cutting surfaces after the application of high-speed water jets is an integral part of the research of the Team under evaluation. In addition to the study of surface characteristics, suitable methodologies for surface assessment have been proposed and analysed. The parameters of these methods are clearly processed in databases of individual materials and individual water jet machining technologies (cutting, turning, milling, and drilling).

Methodology for the topographic evaluation of Al-composites machined by the AWJ

Based on a series of laboratory experiments with AWJ machining of aluminium-based composites, a methodology for the quantitative and qualitative characterisation of surfaces created by this technology has been developed. Experiments were carried out at the Institute of Geonics on composites developed at the Indian School of Mines in Dhanbad. The methodology combines techniques of optical and confocal microscopy and optical profilometry. It evaluates the basic topographic and morphological parameters of a surface in terms of its roughness, integrity and homogeneity.

Creation and usability of a database of parameters and results of AWJ machining

In cooperation with partners, an extensive database of surface characteristics after cutting, turning and milling of technical materials by the AWJ, was clearly processed in a user-friendly manner in the form of the previously-mentioned **Internet Knowledge Portal**. The portal serves as a tool for: (i) the further development of the water jet technology; (ii) for an easy determination of material machinability and other parameters in commercial cutting available to end-users of the AWJ technology; and (iii) as a summary of data for the optimal setting of the cutting processes of cutting machines which apply the AWJ technology.

Projects related to **research area IV:** LO1406, FV10446, FV30233 and GA19-00408S.
Outputs related to **research area IV:** software, papers in WOS and Scopus journals, conference papers.
Examples:

1. Lehocká, D., Klichová, D., Foldyna, J., Hloch, S., Hvizdoš, P., Fides, M., Botko, F. Comparison of the influence of acoustically enhanced pulsating water jet on selected surface integrity characteristics of CW004A copper and CW614N brass. *Measurement*. 2017, 110 (November 2017), 230-238, **IF (2017) 2.218**, **Q3 according to QAIS.**
2. Hloch, S., Adamčík, P., Nag, A., Srivastava, M., Čuha, D., Müller, M., Hromasová, M., Klich, J. Hydrodynamic ductile erosion of aluminium by a pulsed water jet moving in an inclined trajectory. *Wear*. 2019, 428-429 (June 2019), 178-192. **IF (2019) 4.108, Q2 according to QAIS.**
3. Lehocká, Dominika, Klich, Jiří, Botko, F., Simkulet, V., Foldyna, Josef, Krejčí, L., Storkan, Z., Kepič, J., Hatala, M. Comparison of ultrasonically enhanced pulsating water jet erosion efficiency on mechanical surface treatment on the surface of aluminum alloy and stainless steel. *International Journal of Advanced Manufacturing Technology*. 2019, 103(5-8), 1647-1656. **IF (2019) 2.633, Q3 according to QAIS.**

V. New areas of high-speed water jet utilisation

Significant research activities of the Team under evaluation are encompassed in this program. The application of water jet technology in fields that would have been until recently unimaginable, is a great challenge. Of note in this area, the Team takes advantage of its extensive domestic and foreign contacts with the world's leading water jet research institutes, manufacturers and end-users of the high-pressure equipment. Since the range of these activities is extensive, only a brief overview is presented below.

a) Water jet machining processes

Beside the traditional water jet cutting technology, the Team focuses on application of the water jet in other processes of machining materials, especially in turning, milling and drilling. Influencing the resulting material properties of a workpiece by means of water jets (for example, in peening) can also be included in this group of the Team's interests.

AWJ as an effective tool for turning hard-to-machine materials and optimisation of the AWJ turning process

Water jet turning is similar to the conventional single-edged turning with a mechanical tool on a universal lathe, in that a workpiece is rotated and the tool is continuously fed parallel to the axis of rotation and incrementally fed toward the centre of rotation. Unlike conventional turning, the water jet can be moved in all directions and in much larger increments. The jet forces on the workpiece are negligible, and the material is removed from the workpiece in the form of very small debris, compared to the continuous or discontinuous chips formed during conventional turning. In addition, turning by means of the water jet incorporates all the advantages of the conventional water jet cutting: practically zero thermal effects on the cutting surface of the workpiece; the possibility to realise several different operations with the same tool with one workpiece clamping; and a uniform technological production process applicable for different workpiece shapes and different materials (see Figure 4), etc.

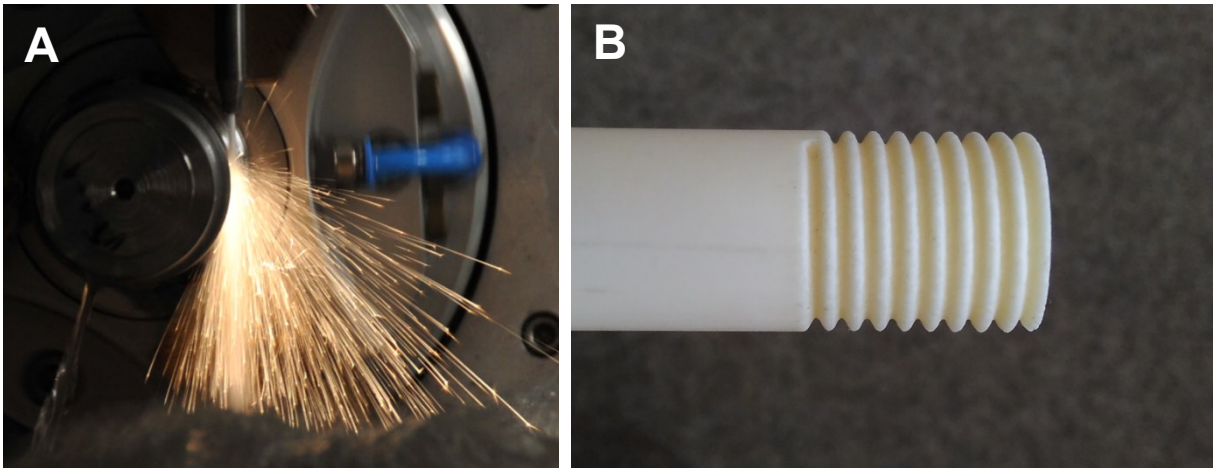

Fig. 4. (A): The turning of titanium alloy with AWJ (The interaction of abrasive grains with the material being turned causes the generation of sparks. This lighting effect is typical for the turning of titanium and titanium alloys. The same effect can be observed when turning some rock materials). (B): A thread in corundum ceramics formed by AWJ turning (Source: Photos by P. Hlaváček, Institute of Geonics)

Application of the AWJ procedures for the turning of materials difficult to be machined by conventional methods were investigated. The research was focused on the turning of rocks, technical ceramics, titanium and nickel alloys, and composite materials. It has been found that any material can be turned with the AWJ with an accuracy up to ±0.1 mm. The technology of turning with the AWJ is especially suitable for rough turning of difficult-to-machine materials, and for the turning of non-rotational semi-finished products where the material removal process is interrupted.

Based on extensive experiments with the turning of difficult-to-machine materials, the optimal setting of water jet machining parameters for individual tested materials was determined. An efficient and accurate tool for the meaningful and economically appropriate turning of semi-finished products was also created.

Abrasive water jet milling

A series of experiments with AWJ milling was realised in order to design a predictive model suitable for AWJ technology applications in milling. Accurate milling procedures enabling creation of non-through kerfs (pockets) with an accuracy up to ±0.2 mm have been elaborated for various materials. Based on extensive laboratory tests, a method of AWJ milling of technical materials suitable for industrial applications was developed. In cooperation with an industrial partner, the method has been implemented in software, allowing an easy input of technological parameters and cutting conditions so that it is straightforward to use for operators of the equipment. This software has significantly increased the automation of the entire milling process and improved the quality and accuracy of the results.

b) Water jet applications for concrete disintegration

Another important activity of the Team is the study of the interaction of different types of water jets with building materials, especially with concrete. Analysis of the process of deterioration of inhomogeneous brittle materials caused by high-speed water jets, has significantly contributed to extend the application potential of water jets for the pre-treatment of surfaces of concrete structures prior to their repair.

Possible pre-treatment of concrete surfaces affected by high temperatures by means of water jets during repair works

A detailed analysis of individual components of cement-based composites (concretes) exposed to high temperatures resulted in the determination of a suitable composition of concrete from basic raw materials commonly available in the Czech Republic. The recommended composition has to be sufficiently resistant to high temperatures, as concrete structures are often exposed to fires in tunnels, underground garages, etc. The use of the recommended components will significantly reduce the production costs of concrete mixtures resistant to high temperatures, as well as the subsequent treatment of the already-degraded concrete layers. At the same time, various methods of removing surface layers damaged by high temperatures using high-speed water jets during repair work, were tested and analysed. An optimal variant has been determined that enables the selective removal of damaged concrete and the preservation of the undamaged parts of building structures, for the subsequent application of repair mortars.

Concrete resistance to fast-flowing liquids

The objective of this research activity was the design of a suitable method for an accelerated simulation of effects of fast-flowing liquids on concrete surfaces, using various types of high-speed water jets in order to best simulate the process of mechanical degradation of surface layers of cement-based composites by fast-flowing liquids. Concrete of various compositions were prepared and their erosion, abrasion and cavitation resistances to fast-flowing liquids were analysed. Several suitable types of water jets were selected and various methods of their application for the removal of surface layers were tested. Results of the accelerated simulation using the high-speed water jets were compared with the real effects of fast-flowing fluids on real concrete structures, using CFD modelling and micro X-Ray Computed Tomography (CT) methods. A so-called cavitation chamber was designed in order to analyse the cavitation effects caused by the fast-flowing liquids on concrete surfaces. It has been found that the proposed methods appropriately simulate the specific properties of real degradation processes.

c) Pulsating water jets in medical applications

A pulsating water jet-based surgical dissector was developed and tested. The achieved results confirmed a high potential of pulsating water jets for special medical applications. Orthopaedic applications in the area of the extraction of cemented knee and hip replacements was revealed. Results of the disintegration of bone cements have motivated the creation of an international

research team of professionals, discussing all aspects of the development of a new technology for re-implantation of joint replacements.

On-line monitoring of bone cement disintegration using pulsating saline solution at the pressure of 7 – 10 MPa

Recently, the number of revision operations of big joints is constantly increasing. Revision (i.e. replacement of the original joint implant) is a more complicated medical procedure than the primary total knee/hip replacement. The use of liquid jets for implant revisions is more advantageous than the use of conventional instruments, in that no thermal or mechanical damage is caused to the tissue. So far, a relatively high volume flow at high pressures has been used for the bone cement cutting. This often caused complications due to overpressure in the surrounding tissues. The use of a pulsating physiological jet at low pressures opens new avenues for a low-invasive non-thermal selective technique for surgical applications.

Projects related to **research area V:** LO1406, FV10446, FV30233, GA15-23219S, GA18-25035S, GA19-00408S, PAN-17-21, TH04020218, 15_PA07-C1, RFSR-CT-2014-00010 and 02574/2014/RRC.
Outputs related to **research area V:** patents, patent applications, prototype, validated technology, software, papers in WOS and Scopus journals, conference papers.
Examples:

1. Srivastava, A. K., Nag, A., Dixit, A. R., Ščučka, J., Hloch, S., Klichová, D., Hlaváček, P., Tiwari, S. Hardness measurement of surfaces on hybrid metal matrix composite created by turning using an abrasive water jet and WED. *Measurement*. 2019, 131 (January 2019), 628-639. **IF (2019) 3.364, Q3 according to QAIS.**
2. Hloch, S., Nag, A., Pude, F., Foldyna, J., Zeleňák, M. On-line measurement and monitoring of pulsating saline and water jet disintegration of bone cement with frequency 20 kHz. *Measurement*. 2019, 147 (December 2019), 106828-106837. **IF (2019) 3.364, Q3 according to QAIS.**

Research activity and characterisation of the main scientific results

The activity of the team includes all types of research with respect to our research objectives – from basic research (especially in the fields of the distribution of stress and seismicity in the RM, laboratory X-ray computer tomography research, and the development of measuring instruments) to targeted and applied research, mainly in situ, for the solution of various geomechanical and geotechnical tasks, which result in proposed measures, working methods and legislative outcomes.

The research activities of the team currently include a wide range of topics. The main areas include:

- Stress measurements in RM;
- Resolving problems in the field of mining geomechanics and underground engineering (stability and reinforcement of underground workings, static and dynamic manifestations of RM pressures, impact of mining on the earth surface);
- Laboratory tomographic research methods on structures and the disintegration of geo-materials; and
- Technical, induced and natural seismicity research.

The methods used therefore include field and laboratory research and they are characterized particularly by a large amount of demanding in situ measurements. The eight major results that the Department achieved in the reporting period are reported below.

1. The complete monitoring of the pilot project Approval of a new mining method “Roadway-Pillar” – a modified “Room and Pillar” mining method with left stable coal pillars

Considerable amounts of coal reserves are located in protection pillars that lie under built-up areas in actively mined regions in the Czech part of the Upper Silesian Coal Basin (USCB). The commonly used controlled caving longwall mining method is not applicable in these areas, because significant deformation of the surface is not permitted. For this reason, the modified “Room and Pillar” method (“Roadway-Pillar”) with stable coal pillars has been tested in order to minimise strata convergence. The four-year pilot project of the new mining method “Roadway-Pillar” was completed at the underground coal mine at a depth of 900 m, which is the deepest trial test of the method in the world (Fig. 1). The monitoring included stress and deformation changes in pillars and roof strata, loading of roof and pillar rockbolts and deformation of the surface. The results of this wide-ranging monitoring of the stress-deformation state of RM, verified numerical models (Fig. 2), and other analyses confirmed the stability of left coal pillars and effectivity of roof bolting in the conditions of highly stressed RM.

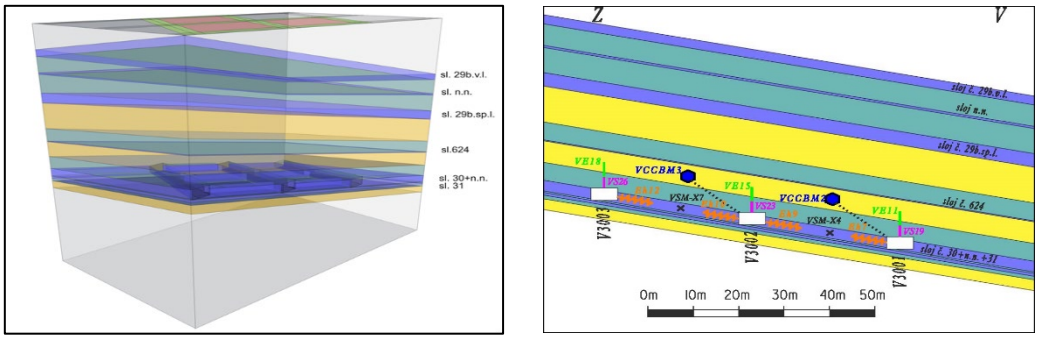

Fig. 1 3D model of monitored locality (left) and arrangement of monitored equipment (right)

Minimal subsidence effects on the surface were also demonstrated. These results, together with verified technological procedures, were the main sources for approval procedure of the new mining method by the mining authority. With regard to the mining depth up to 900 m, the results are significant not only from the point of view of Czech mining, but also worldwide.

Outputs of this research were summarized in six technical and final reports, two contributions to impacted journals, as well as in the following three other WOS indexed journals and/or five prestigious rock mechanics and rock engineering conferences.

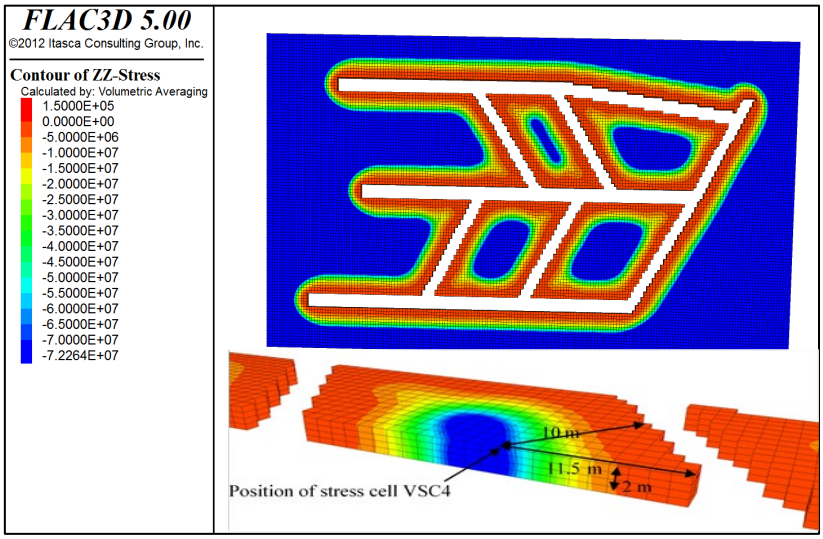

Fig. 2 The vertical stress in the monitored pillar inferred from verified FLAC 3D numerical **model**

Selected references: 7, 20, 21

2. Rockbursts prevention

Rockbursts are a natural risk in mining and underground constructions. They are determined by stress/strain state changes in RMs. The results of our research are an improvement in their prediction and prevention, mainly the localization of stress concentration and the successful decrease in rockburst risk level (Fig. 3).

The system of rockburst prevention was improved and verified. It covers the prediction methods and the measures against rockburst and/or reduction of their consequences. The system is based on the analyses of their causes and on long-term experiences in the monitoring stress/strain behaviour of RM in the coal mines. The results are applied in the coal mines of the Czech Republic. International cooperation with Poland, Canada, India, China and Australia was carried out in the same time period.

An improvement in the understanding of stress and stress changes development in rock mass during mining is the main benefit of the research, with clearly high social relevance. The main contributions of the research to the development of rockburst prevention were:

- an on-line stress change monitoring system, which has been certified for use in underground coal mines with methane and coal dust explosion risk (ATEX - explosive atmosphere EU guidelines and related standards – ATEX 2014/34/EU Guidelines); and
- improving our understanding of stress release in the rock mass due to the rockburst mitigation technique, mainly due to destress blasting (Fig. 4) which is connected

with improving the Seismic Effect methodology and its verification due to seismic moment tensor inversion analysis of seismic events corresponding to destress blasting.

The improvement of rockburst prediction in Czech hard coal mines is the main benefit of the research, which augments mining safety work and the economic conditions of excavation of coal deposits. Our research results have a high potential for applications, mainly in countries with large hard coal extraction, e.g., China and Australia, as well as in underground constructions in very unfavourable conditions (great depth, high horizontal stress, etc.). This high research potential is utilized in international project preparation.

Outputs of the research in the field of rockburst prevention have been published in 6 respected impacted journals, in 2 books [*23, 24*] (rated as “excellent results, the practical utilisation of which will bring about a change with international economic impact or a change with significant impact on society” in the national R&D evaluation) as well as in 8 prestigious rock mechanics and rock engineering conferences.

Fig. 3 Rockburst consequences (left) and continuous rockburst prognosis – drilling tests (right)

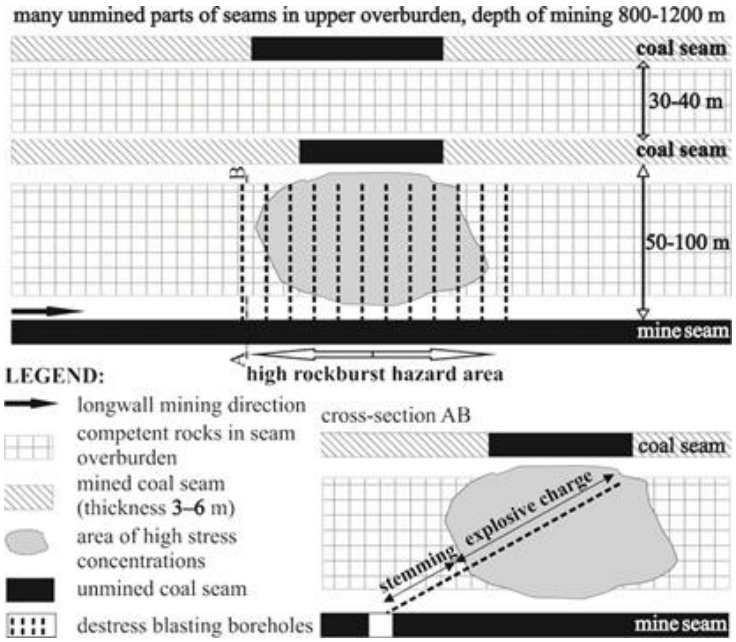

Fig. 4 Conception of destress blasting as a rockburst mitigation technique

Selected references: 5, 6, 11, 13, 23

3. Using 3D laser scanning technology in the field of geotechnical monitoring and its full implementation for the purpose of monitoring spatio-temporal changes of mine workings

3D laser scanning technology (TLS) has a crucial potential for the description and subsequent modelling of the real shape of spatially complex underground mining works. Besides other techniques, 3D laser scanning has been successfully deployed during the construction of the research facility URF Bukov (Fig. 5).

This technology was also shown to be very beneficial in determining spatio-temporal deformations in the mining environment. It can be called “ground-breaking” in its application in the pilot deployment of the new mining method ‘Roadway & Pillar’ at the CSM Mine (Fig. 6). Traditional measurements of deformations in the mine workings are carried out using permanently installed control points, but this does not allow for a comprehensive assessment of the area under investigation. TLS eliminates these shortcomings: the change in the size of the mine profile is fully characterized by an accurate spatial model based on a captured point cloud. Anomalous movement sites can be easily separated from overall trends due to the high density of the output spatial data. From the acquired knowledge, it can be stated that laser scanning is a new, verified and fully functional method applicable in the field of geotechnical monitoring, both in the case of current mining operations and the monitoring of deformations after the termination of mining activities.

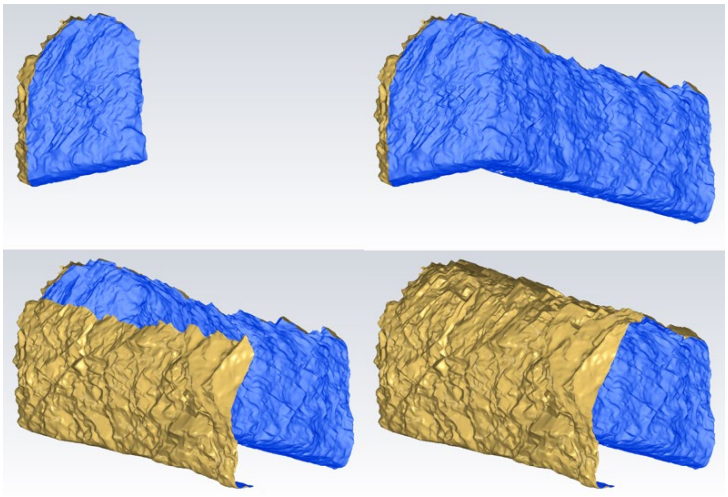

Fig. 5 A part of real shape model (URF Bukov)

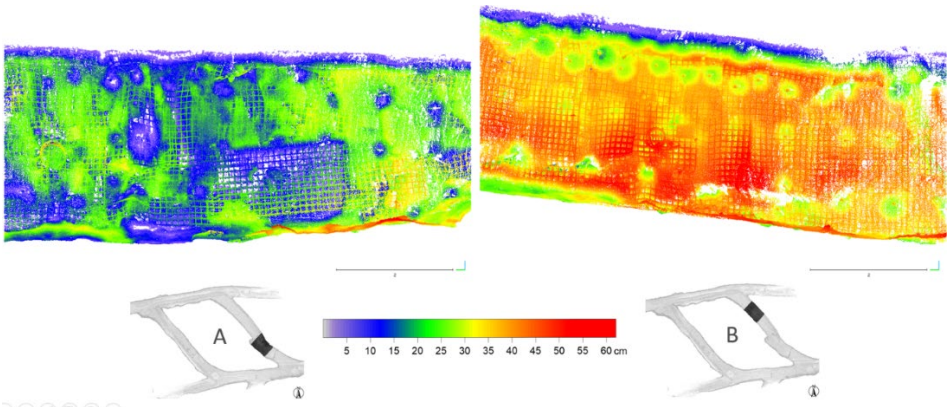

Fig. 6 Development of coal rib deformations on selected parts of mine workings (CSM Mine, Roadway & Pillar trial)

Selected references: 2, 3

4. Complex geotechnical characterization of the Bukov Underground Research Facility - contribution to knowledge and evaluation of the rock environment in the process of preparation for the construction of the deep geological repository in the Czech Republic

Bukov Underground Research Facility (Bukov URF) is designed to operate as a test site to assess the properties and behaviour of the rock mass analogous to selected candidate sites in the Czech Republic. It is situated at a depth of about 550 to 600m beneath the Earth's surface, which corresponds with the proposed storage depth of the final locality for the national deep geological repository (DGR).

Fig. 7 Structural-geological mapping of mining facility walls for the purposes of determination of the rock mass quality (left) and convergence measurement (right)

Within the four-year period of the complex geotechnical characterization of the Bukov URF, the Institute of Geonics (IGN) carried out a series of laboratory and field works in order to provide a detailed description of the geotechnical and geomechanical properties and quality of the RM. These works included: (1) the determination and assessment of the physical-mechanical properties of the rocks sampled from the walls, boreholes and ground surface in the locality; (2) the determination of stress state using the methods of hydrofracturing of borehole walls or/and special methods based on strain gauges measurement such as "Compact Conical Borehole ended Overcoring" (stress relief technique), or "Compact Conical Borehole ended Monitoring" technique for investigation of tensor stress changes; (3) the determination of deformation properties of the RM in-situ using Goodman Jack – field device for borehole testing (press) ; (4) determination of the RM quality based on selected index geo-mechanical properties (Fig. 7 left); (5) periodic, long-term strain-gauge measurements and convergence measurements (Fig. 7 right); and (6) the assessment of the effect of technical and mine-induced seismicity on the RM of interest.

The implemented set of research activities provided a sufficient and integrated account of the geotechnical and geomechanical knowledge vital for the subsequent implementation of extensive research experiments, focused on the long-term safety and technical feasibility of the future national DGR of high-level radioactive waste. It follows from the above that this result is of extremely high social relevance.

The results of the research were summarized in six technical and final reports, two contributions at non-WoS indexed conferences, as well as in the following impacted journal articles and/or WoS indexed conference proceedings.

Selected references: 1, 15, 18

5. Preliminary assessment of the candidate sites suitable for the location of a future Czech deep geological repository in terms of their long-term safety

Between 2016 and 2018, a comprehensive assessment of the suitability of nine potential candidate sites selected for the location of the DGR of a high-level waste and spent nuclear fuel) was carried out in the Czech Republic in terms of its long-term safety. Sites were evaluated according to the following criterion categories:

(1) geological characteristics of the site; (2) hydrogeological characteristics of the site; (3) transport characteristics of the site; (4) site stability; (5) factors, increasing probability of human intrusion into the site; and (6) acceptability of engineered barrier properties under site conditions. The rating of individual sites was based on 36 selected criteria and sub-criteria. IGN was responsible for the results of the assessment of seismic stability and the geomechanical properties of localities. A number of other renowned Czech scientific and professional institutions, such as the Czech Geological Survey Prague, Nuclear Research Institute Řež, Czech Technical University in Prague, Masaryk University Brno and the Technical University of Liberec, took part in the entire process of expert assessment of the suitability of individual candidate sites.

The larger majority of evaluated potential candidate sites, namely Březový Potok, Čertovka, Čihadlo, Hrádek, Horka, and Magdaléna are situated in plutonic rocks of predominantly granitic composition. Two other sites, i.e., Kraví Hora and Temelín-south, consist of high-grade metamorphosed rocks. The last of nine potential candidate sites, Dukovany-west, is located along the contact between plutonic and metamorphic rock sequences.

The evaluation criteria were derived from the requirements of the State Office for Nuclear Safety (SÚJB Decree 378/2016) and the International Atomic Energy Agency (SSG-14 Geological Disposal Facilities for Radioactive Waste, IAEA 2011; NS-R-3 rev.1 Site Evaluation for Nuclear Installations Safety Requirements, IAEA 2016) and are in line with the Czech Radioactive Waste Repository Authority (RAWRA) methodological guidance (MP.22, version 3, Vokál et al., 2017).

Based on the literature review, a database evaluation and numerical modelling, it is possible to conclude that the impact of seismic events (vibration) on the stability of rock mass at the depth of 500 m, and on the deep geological repository, in the horizon of 100,000 years will be very low. The maximum estimated vibration effect did not exceed the surface acceleration of 0.518 $m.s^{-2}$, and the underground acceleration is 0.22 $m.s^{-2}$ at the depth of 500 m. It is not possible to include in the estimation additional related information, such as the degradation of the RM, type of the fill around the containers and the containers themselves as a result of on-going geochemical processes and ageing. It cannot be expected from these studies that earthquakes exceeding the magnitude of 5 or more could occur at any one of the sites, and therefore the load on the underground structures in question by vibrations obviously will not be substantial or damaging.

Basic sub-criteria of geo-mechanical suitability of the rock mass within individual candidate sites was represented by: (1) uniaxial compressive strength of intact rock (more than 100 MPa); (2) Young´s modulus of intact rock (between 10 and 80 GPa); (3) Poisson´s ratio of intact rock (between 0.10 and 0.30); and (4) stress state of the rock mass, represented by the value of the major horizontal stress component which must be lower than 70 MPa. Using these geo-mechanical properties sub-criteria, it was

found that there are no disqualifying assessment indicators in any locality, and that is why each site can advance to the further stage of exploration and assessment.

It follows from the previous account that the results of the whole process is to build an order of sites for the purposes of the subsequent selection of the four most suitable localities for further exploration. The result is of extremely high social relevance.

The results of the expert assessment of the nine potential candidate sites are included in 12 technical and final reports, as well as in following impacted journal articles:

Selected references: 1, 4

6. X-ray computed tomography (X-ray CT) and analysis of the internal structure and composition of rocks and geomaterials

The use of the X-ray CT method for research of the state and behaviour of geomaterials and rocks has been developed intensively at the Department of Geomechanics and Mining Research since 2014. The internal structure and composition (e.g., pore size and distribution, occurrence of cracks, presence of chemically unstable mineral phases, etc.) of rocks have a fundamental influence on the behaviour and resistance of rocks to various external influences, such as mechanical loading, temperature changes or aqueous solutions. The study of the internal structure of rocks using X-ray was focused mainly on the factors influencing the durability of Godula sandstone in its outdoor use, especially on the characterization of its pore space. Roofing slates of various origins were also studied, paying particular attention to the size and spatial distribution of iron sulphide inclusions, the presence of which has a fundamental effect on the colour stability and weathering resistance of a particular slate. The method used 2D and 3D X-ray CT, which allows overall non-destructive analysis of the internal structure of rocks and geomaterials, in comparison with standard methods used for the analysis of internal structure and mineralogical composition of geomaterials (e.g., high-pressure mercury porosimetry, optical microscopy in transmitted and reflected light, X-ray powder diffraction, scanning electron microscopy with energy-dispersive X-ray spectroscopy, etc.). In the use of X-ray CT for the geomaterials study, the pore space of the granitic rocks (Fig. 8), the manner of concrete samples failure under thermal loading and, but not least, the investigation of the cracks propagation associated with the fracture toughness test, were studied too.

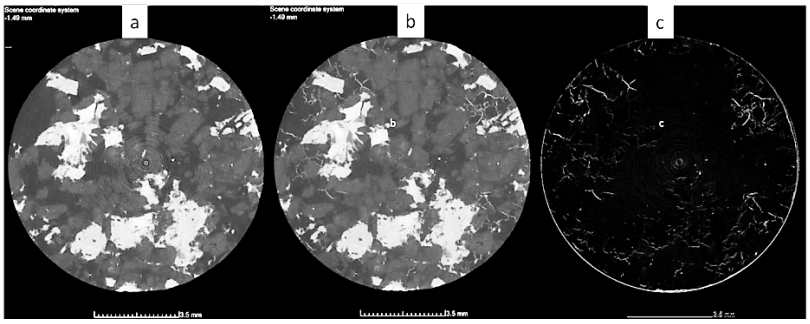

Fig. 8 Visualization of pore space of granitic rocks combining X-Ray CT and mercury intrusion porosimetry (MIP): a) CT slice before MIP application; b) CT slice after MIP application; c) visualization of crack distribution (subtraction image of CT slice before and after MIP)

The outputs of the research using X-Ray CT have been presented in 13 contributions in impacted journals and proceedings of specialized conferences. The main outputs can be documented by the following selected references: 12, 14, 16, 17, 19, 22

7. Study of the influence of local geology on the vibration effects on the surface

An evaluation of seismic hazard and seismic micro-zonation includes the study of subsurface geological patterns influencing the value of vibration effects on the surface. Determined seismic characteristics of subsurface sedimentary layers provide significant information, especially in inhabited regions where increasing of seismic loading has been expected. The discussed values are important for subsequent seismic loading evaluation of buildings in the given area, and for the analysis of the possible effects of soil-structure interactions. Our research concerning the determination of seismic characteristics of sedimentary layers, i.e., resonant frequencies and amplification factor, was realised in selected areas with complex geological patterns that are located in the surroundings of sources of technical vibrations and mining-induced seismicity (e.g., the edge of a sedimentary basin in the surroundings of a large open-pit mine, the undermined area affected by current underground exploitation). Records of seismic noise and/or records of mining-induced seismic events and quarry blasts were analysed using spectral ratio methods. This research confirmed the influence of local geological patterns on vibration effects on the surface in surveyed localities; moreover directional variation of maximum vibration effect has been documented at several localities, caused probably by the effects of surface topography or tectonic structure and stress conditions in the given area (Fig. 9). The results of the research were presented by 4 papers published in impact journals and 5 papers in conference proceedings.

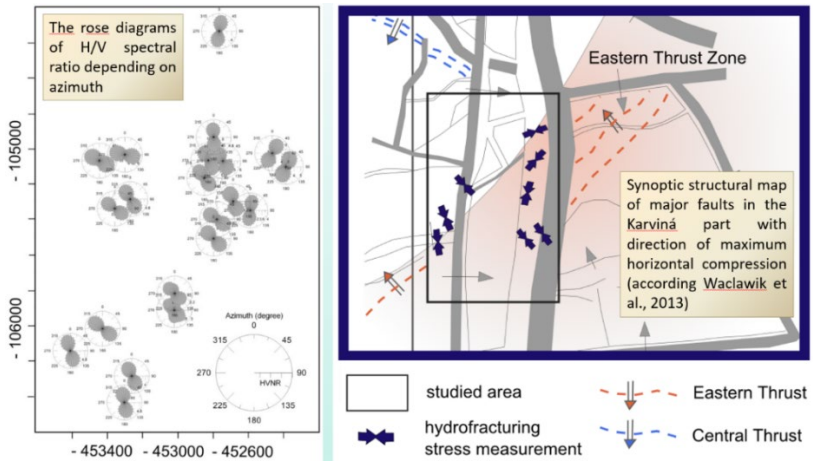

Fig. 9 Example of directional variation of H/V spectral ratio in studied area of undermined Karviná region

Selected references: 8, 9, 10.

8. Development of technical equipment and methodologies

Research continued in the field of methods for determining stress in the RM.

• The method of measuring the 3D stress tensor and its changes by conical probes (CCBO, CCBM), which we have been developing for a long time, was also implemented in monitoring systems such as the LASMO project in the Swiss Grimsel Test Site, or during the construction of the Bukov URF. A significant achievement was the completely new original development of CCBM probes and monitoring system tested and certified for use in gaseous coal mines throughout Europe (ATEX). Each probe allows work in two modes: (1) control of the experiment and data collection by a central control unit with the possibility of remote access via the Internet; (2) in autonomous mode, where each probe works completely independently, data are

stored in the probe memory until restored activities of the whole system. This allows the measurement of critical values even when, for safety reasons, the endangered site is often disconnected and closed.

• In close cooperation with colleagues of the Department of Applied Mathematics, a method for determining the 3D stress tensor from the measurement of convergences behind the advancing face was developed and tested.The basic principle of the methodology is the installation of measuring points located on the tunnel wall in two parallel profiles perpendicular to the longitudinal axis of the tunnel. The distances between the selected optimized pairs of measuring points are measured, and after a specified distance of the face progress, the distance between the same pairs is measured again. The difference of these distances is analysed by a mathematical model, which is part of the methodology, and the result of this analysis is the complete tensor of the original stress. This procedure was approved by the Mining Authority of the Czech Republic as a certified methodology.

References:

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1. Research activity and characterisation of the main scientific results

We will shortly describe research activities and their results in the period 2015-2019. The activities and results are presented in ten subsections, which more less follow the topics from the research plan for this period, see also Section 7. For the convenience of reading, each subsection provides its own list of the selected main outputs. A few papers from these lists were submitted in the evaluated period but published in 2020. The authors, who are members of the AMCS team, are marked by the boldface letters. This convention is also used in other places of this report. There are few papers that appear more than once as they concern more topics simultaneously. In such a case, the reference to the first appearance of the paper is reminded in all lists, which refer to such output.

2.1 Models and numerical methods for flow and thermo-hydro-mechanical problems in porous media.

This research field is essential due to many applications, including very important applications in the analysis of separated or coupled thermo-hydro-mechanical processes in the subsurface (see also Section 2.2). Our work started with the investigation of numerical methods for Darcy flow problems discretised by mixed finite element method (FEM). For the resulting saddle point systems, we analysed block type preconditioners in [1.1] including non-symmetric saddle point systems arising from a related transport problem. Investigation of saddle point problems is further continued in [1.2], where a more general framework can be found.

The focus on Darcy flow was enlarged to poroelasticity, which includes time evolution of the coupled hydro-mechanical processes. For these problems, we consider frequently used time discretisation by the backward Euler method and space discretisation by mixed FEM for flow (different treatment of pressure and velocity) and standard FEM for elasticity. A linear system with a double saddle point structure is then solved in each time step. For these systems, we investigated block preconditioners, primarily with the Schur complement of the block corresponding to pressure. Note that the pressure block is a diagonal matrix if the piecewise constant elements are used for the discretisation of pressure (velocity can be then discretised with the lowest order Raviart- Thomas elements). The arising Schur complement can be further simplified to block diagonal form, and, e.g. the Schwarz domain decomposition method can be efficiently used for the solution of velocity block of this Schur complement see [1.3].

We mentioned time discretisation by the backward Euler method, but it can be efficient to use also a higher-order time discretisation, as e.g. by the third-order Radau method. In this case, the systems which have to be solved in the time steps become larger (doubled in dimension) and non-symmetric. Nevertheless, a very efficient preconditioner for such systems was introduced in [1.4]. Its implementation consists in solving two block systems of the same type as those appearing in the backward Euler method. This preconditioner was further investigated in [1.5], where also a fully parallelised variant of the preconditioner was introduced.

In the paper [1.6], a similar type of block preconditioners was introduced and analysed for double porosity problems which can be used e.g. for the description of flow in porous matrix and fractures or damaged zones.

Finally, the focus on hydro-mechanical problems was enlarged to processes in porous media with explicitly defined fractures, see [1.7]. The fractures are considered as domains with reduced dimension, and the flow includes coupling between the

porous matrix and fractures. Mechanics involve opening and closing the fractures with the non-linear condition of non-penetration of fracture walls. The hydro-mechanical coupling includes the change of conductivity of fractures due to change of the aperture of fractures. All these aspects need a special treatment, but the crucial point is the suggestion of a suitable procedure for iterative coupling of hydro and mechanical parts. The solution procedure was implemented and tested also in connection with Bayesian inverse (see independent Section 2.4).

Selected publications: [1.1] O. Axelsson, R. Blaheta, P. Byczanski, J. Karátson, B. Ahmad. Preconditioners for regularised saddle point problems with an application for heterogeneous Darcy flow problems. Journal of Computational and Applied Mathematics, 2015, 280, 141-157 **[1.2] O. Axelsson,** Unified analysis of preconditioning methods for saddle point matrices. Numerical Linear Algebra with Applications. 2015, 22(2), 233-253. **[1.3] R. Blaheta, J. Kružík, T. Luber**, Schur complement-Schwarz DD preconditioners for non-stationary darcy flow problems. In: High-Performance Computing in Science and Engineering - HPCSE 2017, T. Kozubek et al. eds. Lecture Notes in Computer Science, 11087, Springer, 2018, pp. 59-72. **[1.4] O. Axelsson, R. Blaheta, R. Kohut,** Preconditioning methods for high-order strongly stable time integration methods with an application for a DAE problem. Numerical Linear Algebra with Applications. 2015, 22(6), 930-949 **[1.5] O. Axelsson, R. Blaheta, T. Luber,** Preconditioners for Mixed FEM Solution of Stationary and Nonstationary Porous Media Flow Problems. In: Large-Scale Scientific Computing, I. Lirkov et al. eds., LNCS 9374, Springer Berlin 2015, pp. 3-14. **[1.6] R. Blaheta, T. Luber**, Algebraic preconditioning for Biot-Barenblatt poroelastic systems. Applications of Mathematics, 2017, 62(6), 561-577 **[1.7] R. Blaheta, M. Béreš, S. Domesová, D. Horák**, Bayesian inversion for steady flow in fractured porous media with contact on fractures and hydro-mechanical coupling. Computational Geosciences (2020) 24:1911–1932 (submitted July 6, 2019).

2.2 Model formulation and solving thermo-hydro-mechanical problems related to underground deposition of the spent nuclear fuel

The hydro-mechanical (HM) and thermo-hydro-mechanical (THM) processes have to be analysed for a deeper understanding of the performance of technologies for Earth crust utilisation. As a partner in the international DECOVALEX (https://decovalex.org/) project, the AMCS team solved tasks concerning the behaviour analysis of bentonite-based barriers for geological deposition of the high-level radioactive waste. Two phases of DECOVALEX aimed at formulation, implementation and validation of models for the analysis of coupled HM and THM processes. The models and their implementation were validated by simulation of processes which were monitored in three large, long-term, in-situ experiments SEALEX, EB and FEBEX run in underground test sites Tournemire (France), Mont Terri (Switzerland) and Grimsel (Switzerland), respectively.

For the description of the bentonite barrier saturation, Richards type non-linear parabolic equation was used, including the water vapour diffusion in the case of non-isothermal FEBEX experiment. The flow was coupled with deformation, which was described as non-linear elasticity (plasticity without special treatment of unloading). The main hydro-mechanical coupling was the change of permeability and the retention function due to deformation and evolution of the elastic modulus due to saturation. The model developed by the team includes special ingredients like the construction of the retention functions and involving unique properties of the bentonites as swelling and

ability to saturate more water than corresponds to their bulk porous space (oversaturation). The FEBEX experiment also includes heaters simulating heat emitted by the canisters with the high-level radioactive waste. The model then includes heat conduction and significant influence of the saturation by the thermal vapour diffusion.

The developed complex HM and THM models were implemented by using COMSOL multiphysics software and solvers which are available in COMSOL, especially Newton-type solvers and so-called segregated solver for iterative coupling of the HM or THM processes. The code is then used for simulation of the processes from the described experiments, and the agreement of the computed outputs with observed experimental data and trends were considered as good. The publications [2.1]-[2.3] are connected to the DECOVALEX phase ending in 2015; the next phase ended in 2019, and the final results are described in the final report and journal papers [2.4] and [2.5].

Selected publications: [2.1] R. Blaheta, **Z. Michalec**, **M. Hasal,** Modelling of interaction of bentonite-based sealing element and host rock. In: Geomechanik Kolloquium Papers, TU Bergakademie, Freiberg 2016, pp. 205-219. **[2.2]** A. Millard, **R. Blaheta**, **Z. Michalec**, **M. Hasal** and others, Comparative modelling approaches of hydro-mechanical processes in sealing experiments at the Tournemire URL. *Environmental Earth Sciences*. **2017**, **[2.3]** 76: 78 (2017), 19 pp. A. Millard, **R. Blaheta**, **Z. Michalec**, **M. Hasal** and others, Comparative modelling of laboratory experiments for the hydro-mechanical behaviour of a compacted bentonite–sand mixture. *Environmental Earth Sciences*. **2016**, 75(20), 1311-1327. **[2.4]** A. Gens, **R. Blaheta**, **Z. Michalec**, **M. Hasal** and others, HM and THM interactions in bentonite engineered barriers for nuclear waste disposal. Int. J. of Rock Mechanics and Mining Sciences. Submitted 2020 **[2.5] Z. Michalec, R. Blaheta, M. Hasal, T. Ligurský**, Fully coupled thermo-hydro-mechanical model with oversaturation and its validation to experimental data from FEBEX experiment. Int. J. of Rock Mechanics and Mining Sciences, accepted for publication in 2020.

2.3 Efficient and reliable numerical methods in elasto-plasticity and related limit load analysis

Numerical analysis and solution of elasto-plastic problems is a traditional and long-time activity of the Team. This activity is motivated by the assessment of geotechnical stability, including stability of slopes, foundations or tunnels. We have focused on advanced numerical analysis, innovative numerical methods, development of in-house codes and on the geotechnical applications. In the period 2015-2019, we published 11 journal papers on this activity, see [3.1-3.11]. Selected topics are briefly recapitulated below.

a) *Reliable computation of limit load*. The presence of limit (safe) load is one of the main features in perfect plasticity and some other elasto-plastic models. Beyond the limit load, no solution exists. Determination of the limit load is important for engineering practice because it enables us to find safety factors of structures and find failure zones. We have proposed several reliable estimates of the limit load factor using a priori and a posteriori error analysis of discretisation errors, see [3.1, 3.4, 3.7-3.10]. For perfectly plastic models with cone-shaped yield criteria (used in geotechnical practice), we have suggested the so-called inf-sup condition on convex cones to complete missing mathematical theory. We have also used local mesh adaptivity in 2D to improve the estimates and detect failure zones more accurately.

b) *Continuation and Newton-like methods*. Our current solution concept in elasto-plasticity is based on the finite element method, continuation techniques and the semismooth Newton method [3.1-3.12]. The computation is challenging mainly in the vicinity of the limit load where a small change of the load factor can cause a large response on the output. We have developed the so-called indirect method of incremental limit analysis, which enables to control loading process by the auxiliary parameter representing the compliance, see [3.9, 3.10]. Later, we showed that this method is meaningful even for infinite-dimensional problems [3.8] and that it can be interpreted as a penalisation method for solving the so-called limit analysis problem [3.1, 3.4, 3.7]. Convergence analysis of the used continuation and Newton-like methods was studied in [3.8-3.11]. Continuation and semismooth Newton methods were used by the team not only in elasto-plasticity but also in contact mechanics, see e.g. paper [3.13].

c) *Sub-differential approach for solving constitutive problems*. Elasto-plastic constitutive operators are in implicit form for complicated models from engineering practice. It can cause rounding errors leading to loss of quadratic convergence of the semismooth Newton method, especially if the yield surface is nonsmooth. We have proposed to use a sub-differential variant of the Karush-Kuhn-Tucker conditions to solve the constitutive problems [3.5, 3.6]. This approach simplifies the construction of the constitutive operators and their derivatives. It also enables to prove that the operators are semismooth.

d) *Development of in-house MATLAB codes*. Our own codes have been systematically developed in 2D and 3D since 2014 to illustrate theoretical results and efficiency of suggested solution schemes [3.1-3.8, 3.11]. They include various elastoplastic models, several types of finite elements and advanced computation of the limit load. In [3.2], we introduced a fully vectorised implementation of elastoplastic problems. The vectorisation in MATLAB significantly saves computational time. Our codes to papers [3.2, 3.5, 3.6] are publicly available for download, see e.g. [3.12].

Within this activity, we cooperated with S. Repin (Jyvaskyla, St. Petersburg), J. Valdman (UTIA Prague), J. Kruis, J. Zeman (all CTU Prague) and others in 2015-2019.

Selected publications: [3.1] J. Haslinger, S. Repin, **S. Sysala**: Inf-sup conditions on convex cones and applications to limit load analysis. Mathematics and Mechanics of Solids 24 (2019) 3331-3353. **[3.2]** M. Čermák, **S. Sysala**, J. Valdman: Efficient and flexible MATLAB implementation of 2D and 3D elastoplastic problems. Applied Mathematics and Computation 355 (2019) 595-614. **[3.3] S. Sysala, R. Blaheta, A. Kolcun**, J. Ščučka, K. Souček, P. Pan: Computation of composite strength by limit analysis. Key Engineering Materials 810 (2019) 137-142. **[3.4]** S. Repin, **S. Sysala, J. Haslinger**: Computable majorants of the limit load in Hencky's plasticity problems. Computer & Mathematics with Applications 75 (2018) 199-217. **[3.5] S. Sysala**, M. Čermák, **T. Ligurský**: Subdifferential-based implicit return-mapping operators in Mohr-Coulomb plasticity. ZAMM - Z. Angew. Math. Mech. 97 (2017) 1502-1523. **[3.6] S. Sysala**, M. Cermak, T. Koudelka, J. Kruis, J. Zeman, **R. Blaheta**: Subdifferential-based implicit return-mapping operators in computational plasticity. ZAMM - Z. Angew. Math. Mech. 96 (2016) 1318-1338. **[3.7] J. Haslinger**, S. Repin, **S. Sysala**: Guaranteed and computable bounds of the limit load for variational problems with linear growth energy functionals. Applications of Mathematics 61 (2016) 527-564. **[3.8] J. Haslinger**, S. Repin, **S. Sysala**: A reliable incremental method of computing the limit load in deformation plasticity

based on compliance: Continuous and discrete setting. Journal of Computational and Applied Mathematics 303 (2016) 156-170. **[3.9]** M. Cermak, **J. Haslinger**, T. Kozubek, **S. Sysala**: Discretisation and numerical realisation of contact problems for elastic-perfectly plastic bodies. PART II - numerical realisation, limit analysis. ZAMM 95 (2015) 1348-371. **[3.10] S. Sysala, J. Haslinger**, I. Hlaváček, M. Cermak: Discretisation and numerical realisation of contact problems for elastic-perfectly plastic bodies. PART I - discretisation, limit analysis. ZAMM 95 (2015) 333-353. **[3.11] O. Axelsson, S. Sysala**: Continuation Newton methods. Computers & Mathematics with Applications 70 (2015) 2621-2637. **[3.12]** M. Čermák, **S. Sysala**, J. Valdman. Matlab FEM package for elastoplasticity, 2018. https://github.com/matlabfem/matlab_fem_elastoplasticity, **[3.13] T. Ligurský**, Y. Renard, A method of piecewise-smooth numerical branching. ZAMM - Z. Angew. Math. Mech., 97(2017), 815–827.

2.4 Deterministic and Bayesian inverse problems

In a number of applications in geotechnics and other fields, the solution of inverse problems is important or even necessary for obtaining (realistic) material parameters or information about the sources, loads, boundary and initial conditions for the use of mathematical models. Our interest in inverse methods is motivated by two main types of applications.

The first one is to determine the initial stress in rock mass from measurements of deformation in response to load changes (e.g. given by progress in excavation). The measurements involve distances of selected points on tunnel walls (convergence) and the use of different types of extensometers. In this application, the identified values (initial stress components) contributes to the right-hand side of the system arising from finite element analysis. For linear elastic behaviour of the rock mass, it leads to linear least squares, but still, there is a space for optimisation of the strain measurement sites localisation etc. Some details of this technique were described earlier; the results of practical applications can be found in reports published by the team of Department of geomechanics, another research team of the Institute of Geonics.

Another kind of applications consists of the identification of material parameters, i.e. coefficients (parameters) in the corresponding mathematical models. One of the first of our applications was the identification of the elastic parameters for coal in coal-resin composite [4.1], a present application is the identification of permeability of the excavation damaged zone around underground openings. These problems can be formulated as non-linear least-squares minimisation, which requires the use of different optimisation methods and searching for their efficient variants and implementation. We particularly investigated properties of a specific class of the identification problems, when the computational domain can be split to a priori known subdomains and the searched parameters are constant in these subdomains. Under such assumption, we provided a proof of the existence of the solution of the identification problem (with continuous PDE model) and show that this solution is obtainable as a limit of optimal solutions of identification problems which use discretised PDE models [4.2].

As already noted in [4.2], the solution of identification problem become difficult if some noise in the measurement is present (the noise may also involve inaccuracy of model and its discretisation). With the presence of noise, the identification requires suitable regularisation, which can be difficult to adjust. For us, it was one motivation for the interest in stochastic Bayesian inverse, see [4.3] for comparison and discussion of the deterministic and stochastic approaches. The realisation of Bayesian inverse was further improved by use delayed Metropolis-Hastings and surrogate model for the generation of the posterior distribution of identified parameters. This approach is

described in [4.4], where the identification concerns permeabilities for the hydro-mechanical problem of flow in deformed porous media with fractures (see Section 2.1). The paper shows that the Bayesian inverse is applicable to a complicated multiphysics problem with relatively expensive realisation through finite element computations. Nevertheless, it is crucial to use a cheap surrogate model which is still able to provide an acceptable approximation. In [4.4], stochastic collocation is used for the construction of a surrogate model for the hydro-mechanical problem. Our results in material parameter identification were so far mostly tested on artificial benchmark problems, but the application for solving real engineering problems is planned.

Selected publications: [4.1] R. Blaheta, R. Kohut, A. Kolcun, K. Souček, L. Staš, L. Vavro. Digital image based numerical micromechanics of geocomposites with application to chemical grouting. International Journal of Rock Mechanics and Mining Sciences. 77(2015), pp. 77-88 **[4.2] J. Haslinger, R. Blaheta, R. Hrtus**. Identification problems with given material interfaces. Journal of Computational and Applied Mathematics. 2017, 310, 129-142 **[4.3] R. Blaheta, M. Béreš, S. Domesová**, P. Pan. A comparison of deterministic and Bayesian inverse with application in micromechanics. Applications of Mathematics. 2018, 63(6), 665-686 **[4.4]** see [1.7] **R. Blaheta, M. Béreš, S. Domesová, D. Horák,** Computational Geosciences (2020)

2.5 Uncertainty

Mathematical models with uncertain input data are very common in geotechnical engineering. It introduces a specific problem, which is an analysis of how this uncertainty propagates through mathematical models described by partial differential equations or their discretisation. Our work in this fields starts with the implementation of multilevel Monte Carlo method and application of this method for analysis of porous media flow problem with permeability described by a Gaussian field, see [5.1]. The work continued with the investigation of the use of stochastic expansions [5.2] and the stochastic Galerkin method, which represents a different approach to the uncertainty quantification. Discretisation in both the physical and the stochastic space results in large coupled linear systems which have to be solved by iterative solvers. There are two contributions in this respect. The paper [5.3] investigates the use of a reduced basis (RB) solver, which looks for a low-rank representation of the solution. The construction of the RB is usually done iteratively and consists of multiple solutions of systems of equations. The paper examines the reduced rational Krylov subspace method and Monte Carlo sampling approach. Moreover, the deflated conjugate gradients (DCG) is used. In the paper [5.4], a preconditioner was proposed, which was obtained by modifying the stochastic part of the differential equation. This paper also includes a general approach for obtaining bounds to the spectrum of the preconditioned matrices. The bounds are obtained from the spectral information of certain small matrices, from which the large stochastic Galerkin matrix is constructed and require only point-wise or local dominance of the deterministic part of the expansion of the parameter-dependent function diffusion coefficient, while the standard bounds are typically based on the absolute global dominance. The obtained bounds are sharper than the classical ones and also applicable to problems where global dominance is not achieved.

Selected publications: [5.1] R. Blaheta, M. Béreš, S. Domesová A study of stochastic FEM method for porous media flow problem. In: Applied Mathematics in Engineering and Reliability, R. Bris, P. Dao eds., 2016, pp. 281-289 **[5.2] M. Béreš**, Karhunen-Loéve Decomposition of Isotropic Gaussian Random Fields Using a Tensor Approximation of Autocovariance Kernel.

In: High Performance Computing in Science and Engineering. T. Kozubek et al. eds, Lecture Notes in Computer Science, Volume 11087 Springer, 2018, pp. 188-202. **[5.3] M. Béreš**: A comparison of approaches for the construction of reduced basis for stochastic Galerkin matrix equations. Applications of Mathematics, vol. 65, no. 2, 2020, pp. 191-225 **[5.4] M. Kubínová**, I. Pultarová: Block preconditioning of stochastic Galerkin problems: New two-sided guaranteed spectral bounds, SIAM/ASA J. Uncertainty Quantification, 8(2020), 88–113

2.6 Homogenisation and micromechanics

Computational homogenisation technique was examined for assessment of the influence of microstructure on the macro-scale properties of composite materials. The homogenisation is based on numerical testing and applied to general heterogeneous materials with non-periodic microstructure. In the range of linear material behaviour the homogenisation was tested in connection with the use of CT images for getting information about the microstructure, see [5.1]. The use of the above techniques for the computationally demanding application of the analysis of fibre reinforced concrete is described in [5.2]. The analysis of material behaviour beyond the range of linear behaviour is done in [5.3] with the use of elasto-plasticity and limit analysis for the components of heterogeneous geocomposite, see also Section 2.3. A collaboration with other teams from the Institute is visible from lists of authors in [5.1] and [5.3].

Selected publications: [5.1] R. Blaheta, R. Kohut, A. Kolcun, K. Souček, L. Staš, L. Vavro. Digital image based numerical micromechanics of geocomposites with application to chemical grouting. International Journal of Rock Mechanics and Mining Sciences. 77(2015), pp. 77-88 **[5.2] R. Blaheta**, I. Georgiev, K. Georgiev, **O. Jakl, R. Kohut**, S. Margenov, **J. Starý**, High Performance Computing in Micromechanics with an Application. Cybernetics and Information Technologies, 17(2017), pp. 5-16. **[5.3] S.Sysala, R. Blaheta, A. Kolcun,** J. Ščučka, K. Souček, P. Pan, Computation of Composite Strengths by Limit Analysis. Key Engineering Materials. 2019 (810), pp. 137-142.

2.7 Parallel algorithms and software

The Team is for a long-period interested in algorithms which can be used for the construction of efficient and parallelisable solvers. This interest is also supported by participation in the supercomputing project IT4Innovation. Two algorithms (preconditioners) suitable for solving hydro-mechanical problems were already mentioned in Section 2.1. It was parallel preconditioner for time step systems arising from second-order Radau time discretisation [7.1] and Schwarz domain decomposition method for velocity block (Hdiv system) within a Schur complement preconditioner for systems arising from backward Euler time discretisation [7.2].

Some variants of the Schwarz domain decomposition method for symmetric positive definite systems were investigated and can be used for the solution of elasticity block of Schur complement preconditioner mentioned above. In [7.3], a special Schwarz alternating iteration method coupled with a coarse or a coarse-fine mesh stabilisation was suggested. This technique was firstly applied with long layer subdomains usually corresponding to layers of different materials which frequently appear in geophysical applications. The domain decomposition method makes use of two strongly overlapping sets of subdomains. The longer-ranged modes of the solution are approximated by a coarse or coarse-fine mesh which stabilises the Schwarz alternating iteration method. Standard domain decomposition with stabilisation by problem created by a straightforward aggregation was analysed in [7.4]. Different types

of coarse spaces created by aggregation and wavelet technique and combined with deflation were suggested and tested. For deflation preconditioning, the PCDeflation software [7.5] was designed and after careful testing included in the worldwide used PETSc library, developed under the coordination of Argonne National Laboratory USA.

Another domain decomposition method used for the solution of linear systems arising from the discretisation of PDE is the Finite Element Tearing and Interconnecting (FETI) method. It enables parallel computing with perfect parallelisation of all subproblems with the exception of the projector onto the natural coarse space. A novel approach provided in [7.6] consists of using a precomputed explicit inverse and dense matrix-vector products for the realisation of the projector. The paper shows numerical experiments and advantages of the new method. The FETI method fits well with the solution of contact problems and therefore, was applied for the hydro-mechanical problems in porous media with fractures, see [7.7].

Selected publications: [7.1] see [1.5] O. Axelsson, R. Blaheta, T. Luber, In: Large-Scale Scientific Computing (2015), **[7.2] see [1.3] R. Blaheta, J. Kružík, T. Luber**, in: High-Performance Computing in Science and Engineering - HPCSE 2017, **[7.3] O. Axelsson**, I. Gustafsson. A coarse-fine mesh stabilisation for an alternating Schwarz domain decomposition method. Numerical Linear Algebra with Applications. 2019, 26(3), 1-19. **[7.4] R. Kohut**, Parallel Solution of Elasticity Problems using Overlapping Aggregations. Applications of Mathematics. 2018, 63(6), 603-628 **[7.5] J. Kružík**, PCDeflation sw procedure in PETSC https://www.mcs.anl.gov/petsc/petsc-current/docs/ manualpages/PC/PCDEFLATION.html, 2019 **[7.6] J. Kružík, D. Horák,** V. Hapla, M. Čermák, Comparison of selected FETI coarse space projector implementation strategies, Parallel Computing 93(2020), 102608, https://doi.org/10.1016/j.parco.2020.102608 **[7.7] see [1.7] R. Blaheta, M. Béreš, S. Domesová, D. Horák**, Computational Geosciences (2020)

2.8 Optimal control problems

A general framework for the efficient solution of optimal control problems was provided, both to achieve an accurate solution and to provide a robust and fast convergent iterative solution method. The optimal control problems aim at finding a solution close to a given target solution on the whole or on parts of the given domain and are regularised by the use of a control cost term with a small regularisation parameter. The given differential equation is imposed as a constraint with the use of a Lagrange multiplier in the form of an adjoint variable to the state solution. Different types of applications were considered. The basic solution method is based on two-by-two block matrices with square matrix blocks, possibly with complex-valued off-diagonal blocks, such as arises in time-harmonic problem, see [8.1]- [8.4]. For acceleration of the solution process with Krylov subspace problems, see [8.5], [8.6], and with Chebyshev iteration, see [8.7]. For various aspects of modifying the preconditioning with a parameter, see [8.8] and [8.9]. For an application with bound constraints on the solution, see [8.10].

Selected publications: [8.1] O. Axelsson, D. Lukáš. Preconditioning methods for eddy current optimally controlled time-harmonic electromagnetic problems. Journal of Numerical Mathematics. 2019, 27(1), 1-21. **[8.2] O. Axelsson**, Z.Z. Liang. A note on preconditioning methods for time-periodic eddy current optimal control problems. Journal of Computational and Applied Mathematics JCAM 2019, 352, 262-277 **[8.3] O. Axelsson**, S. Farouq, M. Neytcheva. A preconditioner for optimal control problems, constrained by Stokes equation with a time-harmonic control. JCAM 2017, 310, 5-18 **[8.4]** Z.Z. Liang, **O. Axelsson**, M. Neytcheva. A robust structured preconditioner for the time-harmonic parabolic optimal control problem.

Numerical Algorithms. 2018, 79(2), 575-596. **[8.5] O. Axelsson**, S. Farouq, M. Neytcheva. Comparison of preconditioned Krylov subspace iteration methods for PDE-constrained optimisation problems - Poisson and convection-diffusion control. Numerical Algorithms. 2016, 73(3), 631-633. **[8.6] O. Axelsson**, S. Farouq, M. Neytcheva. Comparison of preconditioned Krylov subspace iteration methods for PDE-constrained optimisation problems. Numerical Algorithms. 2017, 74(1), 19-37 **[8.7] O. Axelsson**, Z.Z. Liang. Parameter modified versions of preconditioning and iterative inner product free refinement methods for two-by-two block matrices. Linear Algebra and Its Applications. 2019, 582, 403-429 **[8.8] O. Axelsson**. Preconditioning of two-by-two block matrix systems with square matrix blocks, with applications. Applications of Mathematics. 2017, 62(6), 537-559 **[8.9] O. Axelsson**, D.K. Salkuyeh. A new version of a preconditioning method for certain two-by-two block matrices with square blocks. BIT Numerical Mathematics. 2019, 59(2), 321-342 **[8.10] O. Axelsson**, M. Neytcheva, A. Ström. An efficient preconditioning method for state box-constrained optimal control problems. Journal of Numerical Mathematics. 2018, 26(4), 185-207

2.9 Iterative solution methods and preconditioners

A number of techniques were investigated by the team members. A lot of them were connected with a specific type of problems and applications, and therefore they were already mentioned in the previous subsections. Here, only some more results are described.

In order to get a more robust solution method for ill-posed problems, various techniques can be applied. One possibility is the use of low-rank improvements of the inverse of the Schur complement; such idea was tested for two-level preconditioning in [9.1]. To derive discretisation methods in the maximum norm, one can use a splitting of the matrix, which involves a monotone preconditioning part, see [9.2].

In the case of exact arithmetic, the rate of convergence of Krylov subspace methods shows typically three phases of convergence, an initial phase, a linear rate of convergence phase which is followed by a superlinear convergence phase arising when outlier eigenvalue components have been more or less eliminated. The superlinear rate of convergence is h-independent. For a general discussion of this topic, see [9.3], and for treatment of complex Helmholtz equations, see [9.4].

Block Krylov subspace methods are iterative methods for solving systems of linear equations with multiple right-hand sides. From the theoretical point of view, they are considerably less studied and understood than their single right-hand-side counterparts. By reframing the problem as a single linear system over a ring of square matrices, new convergence results for the block generalised minimum residual (GMRES) method were developed, see [9.5]. They explicitly formulate conditions on the admissible convergence behaviour of the residuals of block GMRES using an appropriate block generalisation of the norm. In particular, the paper shows what convergence behaviour is admissible for block GMRES and how the matrices and right-hand sides producing any admissible behaviour can be constructed.

Selected publications [9.1] O. Axelsson, R. Blaheta, Low-rank improvements of two-level grid preconditioned matrices. Journal of Computational and Applied Mathematics. 2018, 340(1), 432-442 **[9.2] O. Axelsson**, J. Karátson. Discretisation error estimates in maximum norm for convergent splittings of matrices with a monotone preconditioning part. Journal of Computational and Applied Mathematics. 2017, 210, 155-164 **[9.3] O. Axelsson**, J. Karátson. Superlinear Convergence of the GMRES for PDE-Constrained Optimisation Problems. Numerical Functional Analysis and Optimisation. 2018, 39(9), 921-936 **[9.4] O. Axelsson**, J. Karátson, F. Magoulès. Superlinear convergence using block preconditioners for the real system formulation of complex Helmholtz equations. Journal of Computational and Applied Mathematics. 2018, 340, 424-431 **[9.5] M. Kubínová**, K. Soodhalter: Admissible and

attainable convergence behavior of block Arnoldi and GMRES, SIAM J. Matrix Anal. Appl., 41(2), 464–486

2.10 Miscellaneous topics - suspension bridges and fluid mechanics

[10.1] J. Malík. Spectral analysis connected with suspension bridge systems. IMA Journal of Applied Mathematics. 2016, 81(1), 42-75 **[10.2] J. Haslinger**, R. Kučera, V. Šátek, T. Sassi. Stokes system with solution-dependent threshold slip boundary conditions: Analysis, approximation and implementation. *Mathematics and Mechanics of Solids*. 2018, 23(3), 294-307

Besides the institutional support, the research was supported by the projects

1. IT4Innovations Centre of Excellence
   a) EUCF CZ.1.05/1.1.00/02.0070 IT4Innovations Centre of Excellence, 2011 - 2015
   b) MEYS LQ 1602 IT4Innovations excellence in science (Sustainability) 2016–2020
2. DECOVALEX
   a) SURAO-RAWRA - Development of Coupled Models and their Validation Against Experiments - DECOVALEX 2015, Task SEALEX, 2012 - 2015
   b) INR/SURAO-RAWRA - THMC modelling within the international project DECOVALEX 2019, Task D, 2016 – 2019
3. GA CR 13-18652S Numerical modelling of damage and transport processes in quasi-brittle materials 2013 – 2015
4. GA CR 19-11441S Efficient and reliable computational techniques for limit analysis and incremental methods in geotechnical stability 2019 – 2021
5. TA CR TK02010118 Prediction of EDZ properties with an impact on the safety and reliability of a deep geological radioactive waste repository 2019 - 2022
6. COST
   a) Network for Sustainable Ultrascale Computing (NESUS), COST Action IC1305
   b) MEYS LD15105 Ultrascale computing in geo-sciences 2015 – 2017
7. CAS, IRSM Wuhan, China Z016001 CT and computational micromechanics of rocks 2017 – 2018
8. EURAD H2020 847593/ WP DONUT Development and Improvement Of Numerical methods and Tools for modelling coupled processes 2019 – 2024

EUCF – EU Cohesion Funds; SURAO-RAWRA Radioactive Waste Authority CR

Research activity and characterisation of the main scientific results

The research activities of the EG-Team have been concentrated around four broad areas of concern, which have involved partial sub-thematic topics tied to specific international and national grant projects, international bilateral and multilateral scientific cooperation agreements, or specific expert studies, as well as relating to recent theoretical and empirical developments in the discipline as a whole. Such specific research foci of the Team reflect some of the major current global environmental challenges (such as energy sustainability and security, urban sprawl, environmental restoration and the regeneration of brownfields, climate-forced drought, food security, etc.), as well as regional, socially relevant issues (e.g., energy poverty, traffic accessibility and transportation planning, regional and rural development, etc.). In many of these areas, the EG-Team carries out cutting-edge research -- not only in the context of the Czech Republic, but also on the international stage, where it has achieved some very well regarded results.
The **four broad areas of concern**, with respect to the discipline and topical concentration from the EG-Team, are as follows:

- Urban Geographies**: 2.1 Transformation and recycling of urban spaces;**
- Energy Geographies: **2.2 Renewable energy development and related land use and social conflicts;**
- Agricultural and Food Geographies: **2.3 Restructuring and diversification of agriculture and food production;** and
- the 'Physical Geography - Natural Hazards' nexus: **2.4 Diversity of natural and cultural landscapes: development, risks, contexts.**

1 Transformation and recycling of urban spaces

Research activities in this thematic area focus on the continuing changes in the socio-spatial aspects and positive and negative impacts of the transformation of urban spaces in regions of different types, including the phenomena of re-urbanization, urban space recycling and brownfields regeneration, the new patterns of space-time behaviours, spatial mobility, and accessibility problems.

The EG-Team, as one of the few existing research collectives of its kind world-wide, has applied a rigorous spatial (geographical) approach to the analysis and assessment of urban renewal and brownfields regeneration processes. We have defined and elaborated an 'area-wide' approach to the study of brownfields regeneration (Frantál et al., 2015), which takes into account the wider geographic areas generated by brownfields. Such a unique perspective can be regarded as an alternative to the more common 'site-based approach', which is usually applied in the more technical sciences and environmental management.

Three members of the EG-Team (Martinát, Klusáček, Frantál) have been included among the Top Five most productive and influential authors in the field of brownfields research in a global survey (see Lin, H., et al. (2019): A scientometric analysis and visualization of global research on brownfields*. Environmental Science & Pollution Research,* 26:17). In addition to providing original field-based empirical evidence on existing spatial patterns, drivers of and barriers to post-socialist urban redevelopment, Team members have contributed key elements to the creation of the innovative "*TIMBRE Brownfield Prioritization Tool*" (FP7 project) (Bartke et al., 2016; Limasset et al., 2018). In addition, they have developed a novel interpretation of micro-perspectives

on ‘framings’ and the roles of actors in regeneration processes (Alexandrescu et al., 2016; Klusáček et al., 2018).

These results in the field of brownfields research, which were achieved in collaboration with researchers from other European countries and the USA, as well as experts from practice, can be considered as examples of ‘Applied Geography’, representing both a significant contribution to the theoretical understanding of urban transformation processes and their implications for urban planning and practice.

Finally, it should be noted that three members of the EG-Team collaborated as National Contact Persons on the H2020 project preparing *“The Europeans’ Strategic Research Agenda for Integrated Spatial Planning, Land Use and Soil-Sediment-Water Management”* (for more information see Part 12: Participation in large collaborations).

It should be noted that Team members have been collaborating on joint projects and have co-authored important papers with leading world experts in the field of brownfields regeneration research: for example, Dr. Annette Gatchet (*US Environmental Protection Agency, Washington, D.C., US*); Dr. Stephan Bartke and Professor Matthias Gross (*UFZ-Helmholz Centre for Environmental Research, Leipzig, DE*); Professor Andrea Critto and Dr. Lisa Pizzol (*Università Ca' Foscari, Venice, IT*); Professor Paul Nathanail (*University of Nottingham, UK*), and many others.

Relevant research projects:

- “Geography of Recycling Urban Space” (The Czech Science Foundation, Grant no. 17-26934S, duration: 2017-2019);
- “Integrated Spatial Planning, Land Use and Soil Management Research Action (INSPIRATION)”, (Horizon 2020, Grant No. 681256, duration: 2014–2018); and
- “New Methods for Improving Brownfields Regeneration to Optimize Decision-Making Processes” (Technological Agency of the Czech Republic, no. TD020259, duration: 2014-2015).

Key publications (Team members in **bold**):

- Limasset, E., Pizzol, L., Merly, C., Gatchett, A. M., Le Guern, C., **Martinát., S**., **Klusáček, P.,** Bartke, S. (2018). Points of Attention in Designing Tools for Regional Brownfield Prioritisation. *Science of the Total Environment*, 622–623, 1, 997-1008. (IF_{2018}= 5.589, Q1 in Environmental Sciences in 2018);
- **Klusáček, P.,** Alexandrescu, F., **Osman, R.**, **Malý, J., Kunc, J., Dvořák, P., Frantál, B.,** Havlíček, M., **Krejčí, T., Martinát, S**., Skokanová, H., **Trojan, J.** (2018). Good governance as a strategic choice in brownfield regeneration: Regional dynamics from the Czech Republic. *Land Use Policy*, 73 (April), 29–39. (IF_{2018} = 3.573; Q1 in Environmental Studies);
- Alexandrescu, F., **Klusáček, P**., Bartke, S., **Osman, R., Frantál, B., Martinát, S.,…** & Critto, A. (2017). Actor networks and the construction of applicable knowledge: The case of the Timbre Brownfield Prioritization Tool. *Clean Technologies and Environmental Policy*, 19(5), 1323–1334. (IF_{2016} = 3.331; Q2 in Environmental Sciences);
- Bartke, S., **Martinát, S., Klusáček, P.**, Pizzol, L., Alexandrescu, F., **Frantál, B.,** Critto, A., Zabeo, A. (2016). Targeted selection of brownfields from portfolios for sustainable regeneration: User experiences from five cases testing the Timbre Brownfield Prioritization Tool. *Journal of Environmental Management*, 184, 94-107. (IF_{2016} = 4.010; Q1 in Environmental Sciences); and
- **Frantál, B**., Greer-Wootten, B., **Klusáček, P., Krejčí, T., Kunc, J., Martinát, S.** (2015). Exploring Spatial Patterns of Urban Brownfields Regeneration: The Case of Brno, Czech Republic. *Cities*, 44, 9-18. (IF_{2015} = 2.051; Q1 in Urban Studies).

2 Renewable energy development and related land use and social conflicts

Research activities in this thematic field focus on the socio-spatial aspects and the environmental, economic and socio-cultural impacts of the on-going 'low-carbon' energy transition. We explore the space-time diffusion and social acceptance of renewable energy innovations (wind turbines, solar farms, biogas plants, geothermal energy, etc.), and land use conflicts associated with the implementation of new technologies and traditional forms of energy developments (coal mining, nuclear energy, nuclear waste disposal, etc.).

The research outputs of the EG-Team have contributed significantly to the emerging sub-discipline of Energy Geographies at a global scale. Our world-leading research on the compatibility of renewable energy production facilities and their landscapes has contributed to current levels of knowledge, by means of a novel classification of the generic criteria of 'best practice' of siting renewable energy facilities in a given landscape, introducing the new concept of 'smart practice'. This work provided a completely new typology, based on a multi-criteria analysis of more than fifty projects from 20 EU countries, and resulted in the proposals of different types of spatial targeting and synergies (Frantál et al., 2018). In another project, we have provided the first cross-sectoral analysis of employment benefits of investments in renewable energy developments in the EU context (Dvořák, et al., 2017). Besides a comparative analysis of employment trends and turnover data, the results included measures of employment benefits and economic efficiency (new jobs per installed capacity; generated energy per employee) for each sub-sector. Finally, we should note that our research on the assessment of the socioeconomic contexts and the environmental risks of the potential upgrading of nuclear power plants, expanded theoretical and empirical knowledge on the socio-spatial dynamics of the impacts of nuclear power plants in their host regions (Frantál, Malý 2017).

Most of these results have clear implications for policy and practice, and they can be used for setting principles for energy landscape planning, the spatial targetting of proposed facilities, as well as new project designs and consent via cross-national learning and fertilization.

The Team members have been collaborating on joint projects and have co-authored significant papers with the leading world experts in the field of Energy Geographies, e.g., Dr. Dan van der Horst (*University of Edinburgh, UK*), Professor Richard Cowell (*Cardiff University, UK*), Professor Matthias Buchecker (*Swiss Federal Institute for Forest, Snow and Landscape Research, WSL, CH*), Professor Michael Roth (*Nuertingen-Geislingen University, DE*), among others.

Relevant research projects:

- "Adaptation to sustainable energy transition in Europe: Environmental, socio-economic and cultural aspects (ADAPTAS)" (Ministry of Economy, Industry, and Competitiveness of Spain, State Research Agency of Spain, and European Regional Development Fund, Project no. CSO2017-86975-R, duration: 2018-2021);
- "Renewable Energy and Landscape Quality (RELY)" (COST Action TU1401, Horizon 2020, duration: 2014-2018); and
- "Exploring social-spatial diffusion of renewable energy projects in the Czech Republic: lessons for adaptive governance of energy transition" (Czech Science Foundation, Grant No. 16-04483S, duration: 2016-2018).

Key publications (Team members in **bold**):

- **Frantál, B**., Van der Horst, D., **Martinát, S.,** Schmitz, S., Teschner, N., Silva, L., Golobic, M., Roth, M. (2018). Spatial targeting, synergies and scale: Exploring the criteria of smart practices for siting renewable energy projects. *Energy Policy*, 120, 85-93. (IF_{2018} = 4.880; Q1 in Environmental Sciences);
- Suškevičs, M., Eiter, S., **Martinát, S.,** Stober, D., Vollmer, E., de Boer, C. L., Buchecker, M. (2019). Regional variation in public acceptance of wind energy development in Europe: What are the roles of planning procedures and participation? *Land Use Policy*, 81, 311-323. (IF_{2018} = 3.194; Q1 in Environmental Studies);
- **Frantál, B., Malý, J.** (2017): Close or renew? Factors affecting local community support for rebuilding nuclear power plants in the Czech Republic. *Energy Policy*, 104 (May), 134–143. (IF_{2016} = 4.140; Q1 in Environmental Sciences);
- **Dvořák, P., Martinát, S.,** Van der Horst, D., **Frantál, B.,** Turečková, K. (2017). Renewable energy investment and job creation; a cross-sectoral assessment for the Czech Republic with reference to EU benchmarks. *Renewable and Sustainable Energy Reviews*, 69 (March), 360–368. (IF_{2016} = 8.080; Q1 in Energy & Fuels); and
- **Martinát, S.,** Navrátil, J., **Dvořák, P.** Van der Horst, D., **Klusáček, P., Kunc, J., Frantál, B**. (2016). Where AD plants wildly grow: The spatio-temporal diffusion of agricultural biogas production in the Czech Republic. *Renewable Energy*, 95, 85-97. (IF IF_{2016} = 4.357; Q1 in Energy & Fuels).

3 Restructuring and diversification of agriculture and food production

Research activities in this thematic area focus on the geographies of agriculture and food, reflecting the current changes in farming and food production sectors. We investigate the spatial and societal contexts of food production in urban, suburban and rural areas. We map the emerging forms of agriculture (urban agriculture, food self-sufficiency) in different geographic and socio-cultural conditions, and we attempt to develop cooperation with various local actors (farmers, gardeners, non-governmental organizations (NGOs), local action groups (LAGs), etc.).

The research of the EG-Team has contributed significantly to the evolving interdisciplinary field of 'Food Geographies', connecting geographical, societal, agrarian and environmental aspects of food systems. Our research priorities focus on exploring relevant research themes such as urban agriculture, its conceptualization, classification and relevance on a European level via international cooperation in the COST Action Urban Agriculture project. Team members contributed chapters to the book '*Urban Agriculture Europe'* (Lohrberg et al., 2016), which has received great acclaim by both academic and professional audiences. Another example of productive international co-operation is a book chapter on urban metabolism and the re-use of organic waste, published by Springer (Simon-Rojo and Duží, 2017). Furthermore, the EG-Team members edited and contributed to a Special Issue on 'New trends and challenges of urban agriculture in the context of Europe' in the *Moravian Geographical Reports* (WOS- indexed journal, Vol. 25, No. 3, 2017). This initiative has brought together a large group of food geography researchers, with a set of theoretical as well as empirical studies on urban and peri-urban agriculture across Europe (Duží, Frantál and Simon-Rojo, 2018). Finally, the Team also deals with specific aspects of food production, particularly 'food self-provisioning' (Vávra et al., 2018), and the related problem of the transformation and changing functions of urban allotment gardens (a critical review of this phenomenon in post-socialist countries is presented in Tóth et al., 2018).

In summary, the EG-Team's research efforts in this field have contributed in important ways to an elaboration of the platforms of Food Geographies in both conceptual and

theoretical senses, and we note that most of the results also have some directly relevant implications for policy and practice, especially in urban planning for green spaces.

The Team members have been collaborating on common projects and have published papers together with some of the leading experts in the field of Food Geographies, such as Dr. Daniel Craig (*James Hutton Institute, UK*), Professor Frank Lohrberg (*RWTH Aachen University, DE*), Dr. Sebastian Eiter (*Norwegian Institute of Bioeconomy, NO*), and Professor David Fanfani (*University of Florence, IT*), among others.

Relevant research projects:

- "Between de-agrization and perforated development of rural space: The search for development patterns of post-communist agricultural properties" (The Czech Science Foundation, Grant no. 19-23870S, duration: 2019–2021);
- "New challenges for food security and cultural landscape protection" (Academy of Sciences of the Czech Republic: Programme for research and mobility support of starting researchers, MSM100861801, 2018-2019); and
- "Citizen Science to promote creativity, scientific literacy, and innovation throughout Europe" (COST Action CA15212, H2020, duration: 2016–2019).

Key publications (Team members in **bold**):

- Vávra, J., Megyesi, B., **Duží, B.,** Craig, T., Klufová, R., Lapka, M., Cudlínová, E. (2018). Food Self-provisioning in Europe: An Exploration of Socio-demographic Factors in Five Regions. *Rural Sociology*, 83 (2): 431-461. (IF_{2016}: 1.718; Q1 in Sociology);
- Tóth, A., **Duží, B**., Vávra, J., Supuka, J., Bihuňová, M., Halajová, D., **Martinát, S., Nováková, E.** (2018). Changing patterns of allotment gardening in the Czech Republic and Slovakia. *Nature and Culture*, 13(1), 162-188. (IF_{2018}: 0.724, Q4 in Environmental Studies in 2018);
- **Duží, B., Frantál, B.**, Simon-Rojo, M. (2017). The geography of urban agriculture: New trends and challenges. *Moravian Geographical Reports*, 25(3): 130–138. (IF_{2017} = 1.435; Q3 in Geography);
- Simon-Rojo, M., **Duží, B.** (2017). Connecting Local Food and Organic Waste Management Systems: Closing Nutrient Loops in the City of Madrid. In: Fraňková, E., et al. (eds.): *Socio-Metabolic Perspective on the Sustainability of Local Food Systems. Insight for Science, Policy and Practice* (pp. 351-376). Dordrecht, Springer; and
- Simon-Rojo, M., Recasens, X., Callau, C., **Duží, B.,** Eiter, S., … and Vejre, H. (2015). From Urban Food Gardening to Urban Farming. In: Lohrberg, F. et al. (eds.): *Urban Agriculture Europe* (pp. 24-31). Berlin, Jovis.

4 Diversity of natural and cultural landscapes: development, risks, contexts

The EG-Team research in this area focuses on the diversity of living organisms in space, as well as processes and objects of an inanimate nature. We focus on mapping the current state, changes and development of natural and cultural landscapes, including bio-monitoring, mapping and assessing natural hazards and geo-hazards, as well as their impacts and risk management, and the 3-D documentation of natural and cultural objects. In addition, the possibilities of integrating the public into decision-making processes and the geographic aspects of citizen science fall into the ambit of this thematic area.

Some significant results have been achieved in research on the geo-diversity of the abiotic parts of landscapes and the possibilities of geo-diversity evaluation. Given current global research trends, a methodology for assessing geomorphological localities was developed for the first time in the Czech Republic. This methodology was applied in the assessment of geomorphosites in selected areas (Rypl et al., 2019;

Kubalíková and Kirchner, 2016). The results of these projects were used to formulate the concept of geomorphological heritage and the possibilities of its utilization in relation to landscape protection and geo-tourism (Kubalíková, 2016, 2018). Recently, the concept of secondary geo-diversity has been developed, with respect to anthropogenic relief transformation while maintaining sustainable landscape development (Kubalíková et al., 2019). The concept of secondary geo-diversity has been used in the evaluation of geo-cultural localities, considering the potential development of urban geo-tourism.

Another area of research in this cluster concerns the inventory of pre-industrial segments of the landscape in Moravia, which has significantly contributed to our understanding of the development of historical and cultural landscapes at the European level (Project NAKI II -DG16P02B042). Based on the study of historical maps, field research and aerial photographs of current land use, as well as GIS tools, segments illustrating the state of the landscape before the Industrial Revolution in the Czech lands, were defined. Such localized segments are a suitable basis for the national authorities dealing with the protection of nature, landscape and cultural heritage.

Relevant research projects:

- "Geodiversity within urban areas: perception, function, potential" (Technological Agency of the Czech Republic, Grant no. TL02000219, duration: 2019-2021);
- "Inventory of pre-industrial landscape in Moravia and publics information ensuring about it as cultural heritage" (Ministry of Culture, NAKI II - DG16P02B042, duration: 2016-2020); and
- "Natural Hazards" (Academy of Sciences of the Czech Republic, Strategy AV21: Natural Hazards, Theme: Man and landscape transformation, 2016-2020).

Key publications (Team members in **bold**):

- Rypl, J., **Kirchner, K.** Ryplová, R. (2019): Contribution to the assessment of geomorphosites in the Czech Republic (A Case Study of the North-eastern Part of the Novohradské Mountains). *Geoheritage*, 11(2), 427-439 (IF_{2018} = 2.597; Q2 in Geosciences, Multidisciplinary);
- **Kubalikova, L., Kirchner, K., Kuda, F.,** Machar, I. (2019): The role of anthropogenic landforms in sustainable landscape management. *Sustainability* 11(16), 4331. (IF_{2018} = 2.592; Q2 in Environmental Sciences);
- **Kubalíková, L.** (2018): Czech Republic: The planning and management of geotourism's hidden resources. In: Dowling R.K., Newsome, D. (Eds.): *Handbook of Geotourism* (pp. 417-432). Edward Elgar Publishing Limited, Cheltenham, UK.;
- **Kubalíková, L., Kirchner, K.** (2016) Geosite and Geomorphosite Assessment as a Tool for Geoconservation and Geotourism Purposes: A Case Study from Vizovická vrchovina Highland (Eastern Part of the Czech Republic). *Geoheritage* 8(1), 5–14. (IF_{2016} = 1.472; Q3 in Geosciences, Multidisciplinary); and
- **Kubalíková, L**. (2016): Geomorphological heritage and geoconservation in the Czech Republic. In: Pánek, T., Hradecký, J. (Eds.): *Landscapes and Landforms of the Czech Republic* (pp. 387-398). Dordrecht, Springer.

In addition to the basic research foci and results noted above, the EG-Team members have also focused attention on applied research, the practical utilization of results in the field of public administration, landscape planning and regional development, and for innovations in teaching in Geographic study subjects (including the active participation of PhD and MSc students from co-operating universities in field research activities, project-based learning, new subjects informing current trends in international geographical research, supervision of student theses, etc.). The pedagogical and

popularization activities of Team members are summarized and described in detail in Sections 10 and 13 of this report, below.