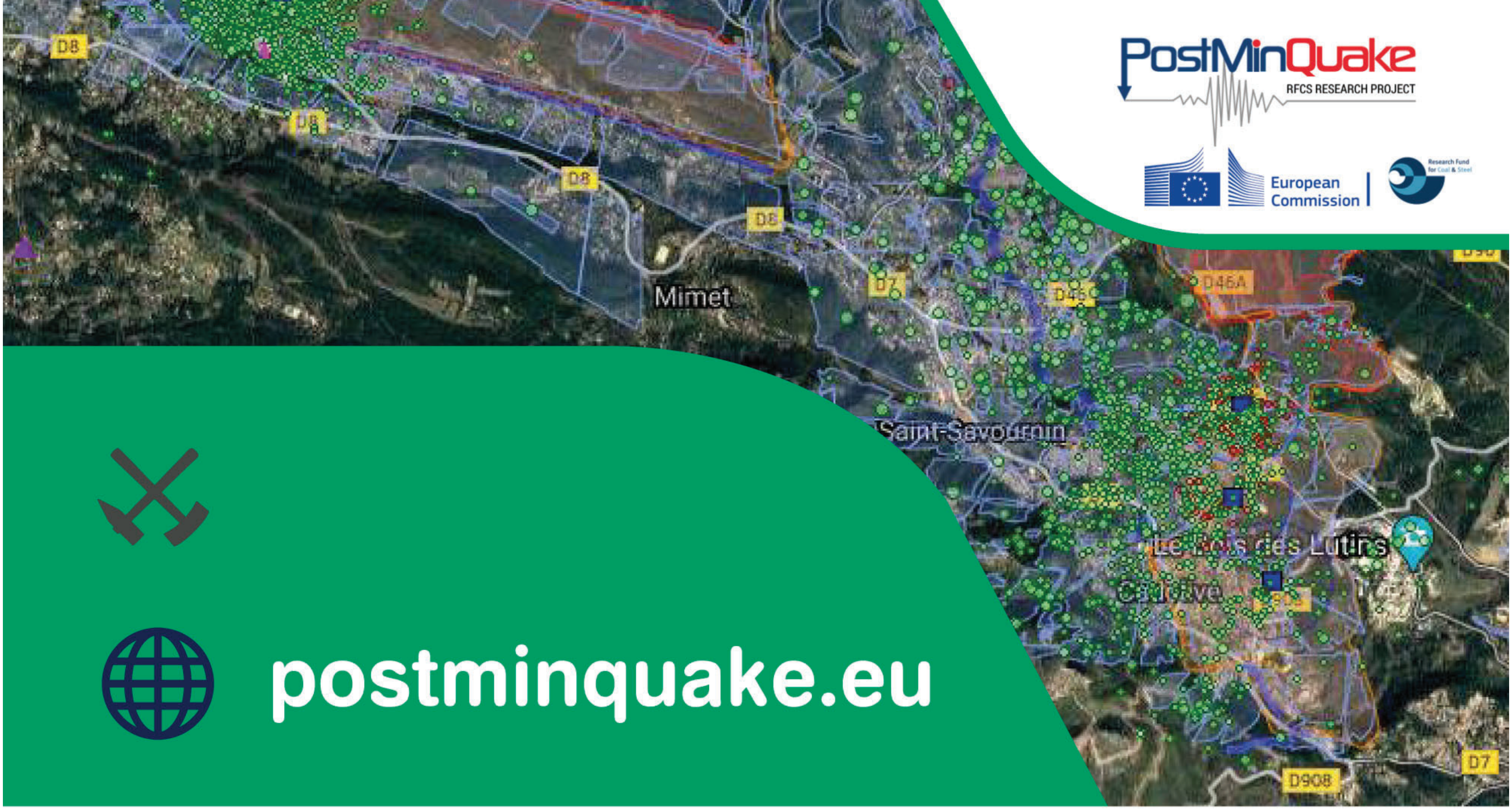

PostMinQuake
RFCS RESEARCH PROJECT

European Commission

Research Fund for Coal & Steel

postminquake.eu

METHODS ON ASSESSMENT AND MONITORING OF SEISMIC HAZARDS IN COAL POST-MINING AREAS

GUIDELINES

Collective work edited by
Violetta SOKOŁA-SZEWIOŁA
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PREFACE

The European Union (EU) is implementing climate change tasks, under which the EU is assumed to be climate neutral by the end of 2050. Member countries are taking steps to reduce greenhouse gas emissions, as part of which they have agreed, among other things, to close coal mines. Decommissioning a coalmine can create serious environmental, social, and economic problems related to surface stability, water pollution, gas emissions, etc. To date, several research projects have been carried out, the results of which have contributed significantly to the depth of knowledge concerning environmental problems that occur during and after coal mine operations. However, the characterization and mitigation of risks associated with seismic activity recorded after mining operation "induced seismicity" is not sufficiently addressed in public policy.

The characteristics of seismic events are known from active mining areas. Their origin is directly related to stress disturbances in the rock mass associated with mining activities. In post-mining regions, especially when mining operations are flooded or in the process of flooding, the estimation of seismic hazard is quite difficult and depends on many complex factors, such as the geometry and geological structure of the deposit, its long-term changes (modified by the presence of fluids), meteorological influences and climatic changes, and the presence of pre-existing fault structures or tectonic stresses. Induced seismicity in closed mines generally occurs at shallower depths than natural seismicity, which means that the impact on the surface can be greater. Seismic earthquakes induced during the sinking of mines are felt by people, can cause minor or major damage to buildings, and affect shallow mine workings. In the latter case, vibrations induced by seismic phenomena can cause reactivation of shallow mining workings in the form of sinkholes or other discontinuous deformations. These dangerous phenomena can threaten the safety of the population and the sustainable development of such regions after the closure of coal mines.

Research on induced seismicity and rock mass movements in post-mining areas was the subject of a European research project funded by the Research Fund for Coal and Steel, entitled **"Induced earthquake and rock mass movements in coal post mining areas: mechanisms, hazard and risk assessment"** (acronym: **PostMinQuake**, https://postminquake.eu/). The project was carried out from 2020 to 2023, under grant agreement No. 899192, and involved 10 partners. It was coordinated by Główny Instytut Górnictwa (GIG, Central Mining Institute-CMI) in Poland. The other partners were BRGM (Bureau de Recherches Géologiques et

Minières) and Ineris (Institut national de l'environnement Industriel et des risques) from France, THGA (Technische Hochschule Georg Agricola) and GFZ (Helmholtz Zentrum Potsdam-DeutschesGeoForschungsZentrum, German Research Centre for Geosciences) from Germany, IGN (Institute of Geonics of the Czech Academy of Science), DIAMO state enterprise as well as Green Gas DPB, Inc. from the Czech Republic, Politechnika Śląska (Silesian University of Technology-SUT) and SRK (Spółka Restrukturyzacji Kopalń) from Poland.

The findings obtained as a result of the project are of great importance for mining companies and authorities responsible for managing decommissioned coal mines in Europe. The results are applicable to numerous regions around the world where rock mass instability is observed in post-mining areas after and during the closure of coal mines.

The project focused on the geomechanical stability of the rock mass under conditions of natural flooding of the mine site, which can last for several years. During this period, the excavations are flooded with water from natural inflows, and the water table of the excavations rises gradually until hydrostatic equilibrium is reached with the aquifers present in the surrounding rock mass. In addition, once the hydrostatic equilibrium level is reached, there can be significant seasonal fluctuations in water level. Under such conditions, we can observe the occurrence of continuous and discontinuous deformations on the surface in the form of sinkholes and post-mining seismicity. Seismicity is one of the earliest indicators of rock mass instability.

One of the main objectives of the project was to study and select updated methods and plans for long-term monitoring of post-mining areas to mitigate the effects of seismic post-mining earthquakes and to mitigate seismic risk during and after mine closure.

The project was implemented through 7 work packages (WP), of which package one (WP1) involved project coordination and management. The other work packages included research leading to the realization of the project objectives. The research was conducted using data, on the project's test sites, i. e. in Poland, the Czech Republic, Germany and France.

The following was done as part of the implementation of the subsequent work packages:

– Data were collected on post-mining regions known to the project partners relevant to the realization of the project objectives. On this basis, the concept of the database, its structure and, and evidently parameters and indicators for the various ranges of data were developed, and then the reference database for the project (WP2) was compiled.

– Modelling of the mechanical and structural response of the rock mass to water loads during the flooding process was carried out. Hydro-mechanical simulations were performed in test regions to explain the phenomenon of seismicity triggering, and key parameters of the phenomenon were identified (WP3).
– A digital platform for integrated data was developed, including principles for unifying, integrating and storing data on flooded or being flooding post-mining areas. The platform includes data acquired at the test sites in the project (WP4).
– An analysis of post-mining seismicity observed in the EU countries was carried out, with particular emphasis on flooded coal basins. A seismological analysis was carried out to characterize the hazard of post-mining earthquakes. GMPE - ground motion prediction equations were adapted to induced seismicity in post-mining areas. The Seismic Intensity Scale was developed to take into account seismicity in post-mining areas. An early warning system was developed to mitigate and reduce the hazard and risk of post-mining induced seismicity (WP5).
– Strategies were developed for monitoring post-mining areas prone to seismicity, including the implementation of temporary near-surface geophysical surveys, continuous and periodic monitoring of the gravity field, monitoring of surface deformation using interferometric images from satellites as well as continuous GNSS (Global Navigation Satellite System) data, seismic monitoring, monitoring of the water table during mine flooding and monitoring of rainfall (WP6).

The last work package concerned the valorization and dissemination of project results (WP7). The results of the ongoing research were published in the form of peer-reviewed journal articles and conference materials. They have also presented at a number of national, European and international conferences. Information on the project was published in the form of news articles. Data on the dissemination of project results were included on the project website, (https://postminquake.eu/). The main results of the project were presented at a summary workshop held in Katowice, Poland, on August 24, 2023. The presented guidelines are an important final result of the implementation of this work package. They have been developed on the basis of the results of the research and are an implementation of the **Deliverable 7.2 entitled: "A comprehensive book (transnational guidelines) on a method on assessment and monitoring of seismic hazard in post mining areas."** Representatives of the following project partners participated in the development of the guidelines: **BRGM, DIAMO, GIG, GreenGas DPB, GFZ, IGN, INERIS, SUT, THGA**.

This book contains guidelines on the methods on assessment and monitoring of seismic hazard in the areas of decommissioned and flooded deep coal mines in Europe and in the world with the aim of ensuring public safety in post-mining areas. The successive chapters present methods and basic recommendations in the process of their implementation. The characteristics of the essential data relevant for the assessment and monitoring of seismic hazard were presented as well as the scope of numerical modelling and hydro-mechanical simulations, important during the period of mine flooding, issues regarding the harmfulness of the impact of ground vibrations caused by post-mining earthquakes on buildings and people, and in detail the scope and implementation method of comprehensive monitoring including continuous and periodic geophysical (seismology, gravimetry, hydrometry) and ground deformations measurements. The book also contains guidelines for the development of an automatic early warning system for rock mass movements caused by post-mining earthquakes and for reporting on the harmfulness of their impact on buildings. In each of the chapters describing the methodology for implementing the assessment and monitoring of seismic hazards, a brief theoretical introduction is included to allow a proper understanding of the content presented in the chapter with reference to studies where the interested party will find more information beyond what is necessary for these guidelines.

The guidelines are mainly addressed to mining consultants, potential investors and decision-making bodies in post-mining areas, including authorities responsible for managing closed mines, in particular the ones which are undergoing the flooding process.

1. CONTEXT, INTRODUCTION, AND OBJECTIVES OF THE GUIDELINES[1]

1.1. Induced seismicity in post-mining coal areas

Europe has entered the phase of stopping all coal and lignite mining to reduce the impact on the environment. Certain countries have even announced the cessation of coal-fired electricity generation. Several mining hazards can be potentially existed after the completion of mining activities. Such as among others ground deformation, induced seismicity and soil and water pollution. They present a risk in former mining regions, both in Europe and throughout the world. Nevertheless, these hazards should be assessed and monitored and mitigate.

The underground coal mine, hard coal, represents a significant proportion of the world's operating and abandoned mines. This is particularly the case for many coal and lignite mines in Europe (Czech Republic, France, Germany, Poland). The depth of the underground coal mines varies from tens of meters until more than thousands of meters. Gardanne coal mine reached 1450 m before the closure.

The mining operation is performed in dry conditions. Pumping is used to ensure the mine workings remain dry. After the mining operations have ceased, pumping is often stopped, and the water level continuously increases until reaching a natural or artificial equilibrium state. The increasing of the water level, the flooding of the mine, and the mine conditions can be the origin of the post-mining earthquakes. The characteristics (magnitude, duration, localization, etc.) of post-mining seismicity varies from mining site to another one.

The existence of such hazards in the coal post-mining regions requires development of methodology to manage it, mainly for ensuring the safety and the security of the population, the structures and infrastructures maybe can be damaged.

In order to unambiguously understand the content presented in the book, the following has been adopted:

- in the case of seismicity induced by the carried out mining operations, a seismic phenomenon (seismic event) is understood as a discharge of energy accumulated in the rock mass, manifested by rock mass vibrations and acoustic phenomena that do not impair the functionality of the workings or the safety of their use, while vibrations can

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[1] Authors: Marwan ALHEIB[1)]

[1)] Ineris, Institut national de l'environnement Industriel et des risques - Mines Nancy, France.

be felt on the surface, causing damage to facilities and technical infrastructure on the surface, and this is referred to as mining earthquake,

– in the case of induced seismicity, observed in the areas of liquidated and flooded underground coal mines, the seismic phenomenon (seismic event) is understood as a discharge of energy, manifested by rock mass vibrations, which may be felt on the surface, even causing damage to facilities and technical infrastructure on the surface, and this is referred to as post-mining earthquakes. The occurrence of such phenomena, as demonstrated by the research conducted as part of the PostMinQuake project, may be effected by rock collapse inside the rock mass, in particular in the areas of shallow mine workings, taking place after mine flooding, or by the reactivation of one or more faults by water migration towards the fault plane (Fig. 1.1),
– when reference in the text involves the field of global seismology, such phenomena are called natural earthquakes.

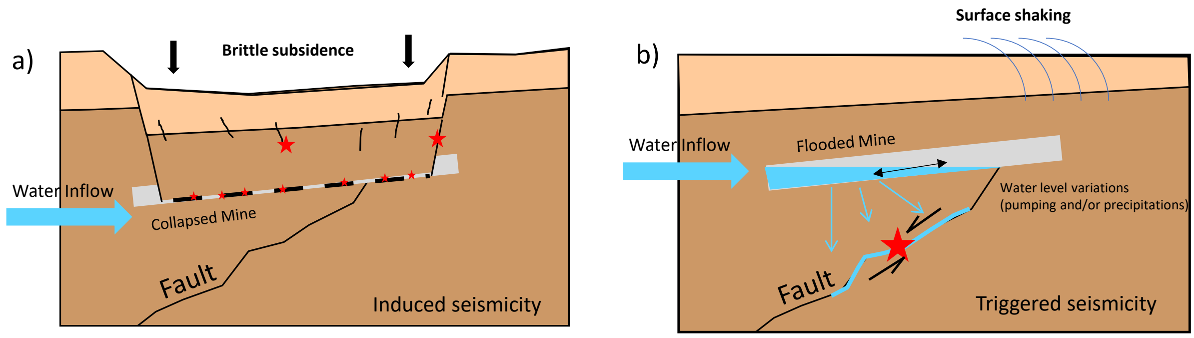

Fig. 1.1. Schematic view of the two geo-structural configurations creating seismicity in post-mining period: a) induced seismicity produced by the readjustment of mine workings reactivated collapses of mining workouts with possible effects on the surface), b) triggered seismicity, with fault reactivation by water migration towards the fault plane

1.2. PostMinQuake project

After mining activities come to an end and starting the flooding operation of the voids, there are two potential configurations: no potential post-mining hazards and existing potential hazards including the induced seismicity.

The goals of the PostMinQuake project were formulated to stimulate the monitoring and diagnosis of the threat caused by these ground movements and to manage this risk. The objectives related to diagnosing a threat are as follows:

– Development of a methodology for the collection and analysis of available mining, hydrogeological, geological and seismic and other geophysical data - development of reference database for European post-mining areas.

- Development of a methodology for the integration of monitoring data and the creation of an integrated digital data platform at European scale.
- Development of a website about post-mining areas in Europe prone to induce seismic activity.
- Understanding the mechanisms of seismic events and discontinuous deformation in post mining areas.

The objectives related to the management of vibration risk and discontinuous deformations were as follows:

- Elaboration of Ground Motion Prediction Equation (GMPE) for fluid-induced seismicity.
- Monitoring strategies and interpretation methods of areas with high seismic hazard.
- Risk and vulnerability assessment: Elaboration of the criteria of hazard rating.
- Development of vibration intensity maps (shake-maps) in selected areas to manage and mitigate the effects of vibrations.
- Recommendations to mitigate seismic (and discontinuous deformation) risk after coal mine closure.

The final result of the project is these guidelines in form of a comprehensive book which can be used by mining consultants, potential investors and decision-making bodies.

The guidelines are the realization of **Deliverable 7.2 titled "A comprehensive book (transnational guidelines) on a method on assessment and monitoring of seismic hazard in post mining areas".**

1.3. Objectives of the guidelines

The objective of the guidelines is the presentation of scientific and operational tools for assessing, characterizing and monitoring of potential induced seismicity during and after flooding of underground coal mines. The guidelines are intended to serve as a reference for future closures and flooded mines of European coal mines. The guidelines can also be used in other post-mining areas around the world.

The guideline is based on feedbacks and in-situ investigations from the main coal basins in Europe: Gardanne (France), Upper Silesian (Czech Republic and Poland) and Ruhr (Germany). The guidelines allow characterizing such seismicity and assessing potential damage risks to existing buildings based on their vulnerability and intensity of movement.

1.4. Structure and use of the guideline

The figure 1.2 presents the main steps and structure of the methodology developed for assessing and managing the risk related to the induced seismicity in the post-mining context.

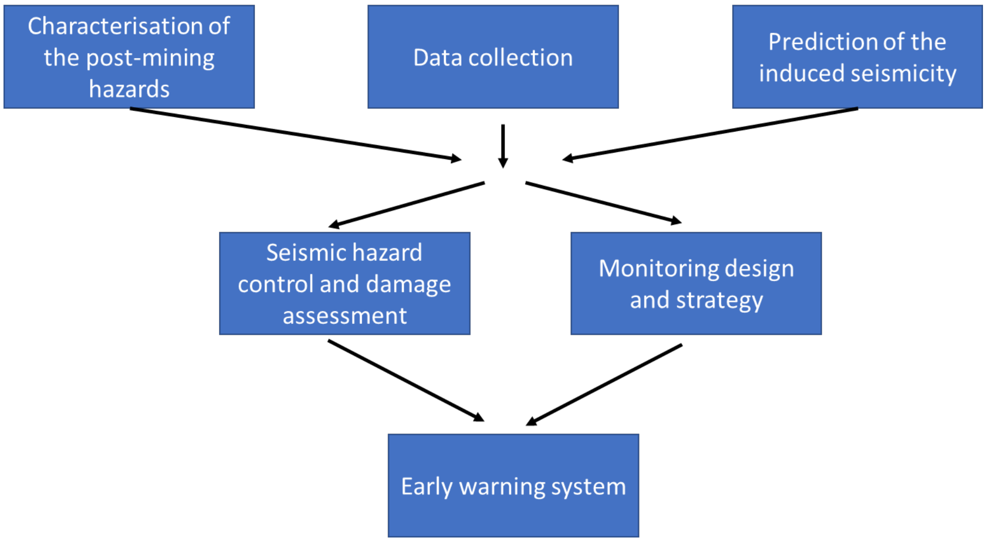

Fig. 1.2. Methodology for assessment and monitoring of seismic hazard in coal post-mining areas

The guideline is structured into 9 chapters. The structure of the methodology for assessment and monitoring of seismic hazard in coal post-mining areas follows the steps, described in following chapters:

- Chapter 2: The chapter presents the main post-mining hazards that may occur after mine closure of underground mines. The definition of each hazard was clearly presented. They can be adopted by the different actors of the post-mining and stakeholders.
- Chapter 3: The chapter summarizes the requirement data for preparing the folder for coal mine liquidation. The chapter presents the scope of geological and water level management data, mining and seismic monitoring data, and recommended database structure for data storage. The chapter also gives the importance and significance of collected data for assessing the rock mass, the mine conditions including the process of flooding and induced seismicity related to post-mining phase. The recommended structure of the database is presented in the section 3.3.
- Chapter 4: The chapter presents the usefulness of numerical modelling to predict the induced seismicity related to the post-mining and the flooding of the underground structures. The hydro-mechanical approach is strongly recommended for numerical prediction the potential post-mining earthquake due to the modification of the water pressure in the context of flooded coal mines. The chapter also gives useful information to carry out the predictive 3D numerical models**.** Recommendations in this regard are included in the section 4.2.

- Chapter 5: The chapter concerns particularly the seismic hazards associated with ground movements such as the collapse of mining structures and the sliding of the faults. It also presents the creation of shake maps, which are very useful for assessing potential damage of existing buildings that may be affected by seismic events. In this chapter, users of the guidelines can obtain information useful for monitoring induced seismicity. A scale developed in the project that can be used to assess the level of induced seismicity (MSIIS-22-Mining and Post-Mining Seismic Instrumental Intensity Scale) is presented and discussed. This scale takes into account the vulnerability of a structure, based on its capacity to resist against mining and post-mining earthquakes. Recommendations in this regard are included in the section 5.7.
- Chapter 6: Chapter 6 focuses the damage assessment of existing buildings due to the induced seismicity. The chapter presents the classical approach used for the natural seismicity (European Macroseismic Scale - EMS-98) and this developed for induced seismicity (MSIIS-22). The application of these approaches highlights that induced seismicity has very limited damage on structures and infrastructures due to the specific characterizations Peak Ground Velocity (PGV). The recommendations in this regard are included in the section 6.4.
- Chapter 7: The chapter concerns the monitoring methodology of the different physical information should be collected to follow the evolution over the time of the post-mining region. The chapter presents more precisely the monitoring of ground deformation, the water level variation, the seismicity. The chapter gives a very complete overview for using the large-scale ground movement using the Synthetic Aperture Radar Interferometry (InSAR) and Global Navigation Satellite System (GNNS). The chapter presents also the best operational recommendations for designing and using the monitoring in the post-mining context. The recommendations are given based on the feedback obtained thanks to the case studies investigated in the PostMinQuake project (Section 7.6).
- Chapter 8: The last chapter focuses on the designing of post-mining early warning system. The objective and the structure of the warning system are presented and discussed to givea complete description of how such a system should be prepared and used. The chapter also describes the technical data necessary: the main information can be obtained and communicated. The chapter presents in detail the different criteria related to the recording of the induced seismicity. At the end of this chapter, the data management and governance are presented based on the feedback of the seismic network installed in Gardanne Coal Basin (France). The recommendations are included in the section 8.3.

Chapter 9 contains the main conclusions and general suggestions for applying the recommendations made in the guidelines.

All abbreviations and symbols used in the study are included in the text.

1.5. Intended audience of the guidelines

These guidelines are intended primarily for authorities responsible for coal mine closure and decommissioning, environmental protection and post-mining land development, as well as mining consultants and potential investors in post-mining areas, in particular:

- mine management during the period of mine closure and decommissioning,
- state and local authorities responsible for environmental protection activities and the transformation of energy and coal mining companies,
- local governments responsible for planning and development in post-mining areas,
- specialists in closure and development of post-mining areas,
- authorities responsible for abandoned mines,
- environmental engineers,
- bodies responsible for surface water,
- researchers interested in further work in the area in question.

2. CHARACTERIZATION OF POST-MINING HAZARDS[2]

Mining is defined as the extraction of resources from the Earth, resulting in the extraction of great quantities of rock material. The exploitation method used is determined, amongst others, by the depth and shape of the deposit and the geology. In Europe, underground coal mines are generally used room and pillars for shallow seams and longwall for deep seams. During underground mining of coal, as well as for other resources, the rock mass equilibrium of the surrounding rock is modified, which can affect the surface, e. g. in form of subsidence or induced/triggered seismicity. Both subsidence and seismicity induce a risk for the people and surface infrastructure like buildings, streets, pipelines, cables and also vegetation and water resources. The closure of mining does not mean that the risks also cease, but that it is necessary to continue monitoring the site to prevent damage to people and infrastructure. When closing an underground mine, the pumping of water to prevent the mine workings from getting flooded stops, so the mine-/groundwater table starts rising again (Primo Doncel et al., 2023).

The main effects related to hard coal post-mining are listed on Table 2.1.

Table 2.1

Main hazards identified in the post-mining sites

	Name	Definition
Ground	Subsidence/Uplift	Continuous movement/ slow, smooth and flexible readjustment of surface. Subsidence = residual sorting of the rock-mass, uplift buoyancy effect of the water table rises.
	Sinkholes	Discontinuous movement – sudden appearance of a sinkhole deformation at surface, often related to near-surface mining, wild mining and/or former shaft openings.
	Induced seismicity	1. Residual ground motion: Mining causes a change on the balanced geomechanical forces that may result in the release of energy through the residual movement of the rocks surrounding the mine workings. 2. Mine water rebound. The rise of the mine water creates buoyancy, which influences the rocks surrounding the mine workings as well as the overburden rocks.
Water	Modification of outlet flow	Appearance of artificial springs, reactivation of springs or discharge of springs in sensitive areas.
	Appearance of humid zones or polder areas	Equilibrium of water table level close or above ground level.

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	Modification of river flows	Risk of floods or less water during low water periods.
Gas	Outflow of mine gas	Methane may escape to the surface through natural openings (i.e. faults, cracks) or artificial ones (i.e. shafts, adits).

Source: Based on (Didier et al., 2008).

According to Busch (Busch et al.,2012) another cause for ground movements would be the hydrogeological and hydrological changes that occur during water drainage (i.e. underground mining phase) and flooding (i.e. mine water rebound during the post-mining phase).
The effect of flooding-induced ground uplift has been widely studied in different hard coal basins. One of the studies even determined that the rebound velocity of the mine water had a direct effect on the upheaval motion (Pöttgens, 1985) caused by buoyancy that also affects the stress field of the rock mass, and the hydraulic pressure. This hydraulic pressure is also related to the post-mining seismicity, as was observed in several hard coal mining regions in Europe. The seismic activity in former hard coal regions is observed even after the mine closure (Didier et al., 2008, Melchers et al., 2019).

During the flooding phase of a mine, induced seismicity and surface instability are the most common events that occur. The cause is the modification of strength in the rock s' strength and stress distribution in the rock mass. The most critical time for induced seismicity in post-mining regions is during the flooding phase (Smith & Colls, 1996).

Monitoring systems aide to observe the ground movements. Depending on the movement to monitor, some systems work better than others. For instance, ground movements regarding subsidence or uplift use Satellite Radar Interferometry (Bamler et al., 2008), (Busch et al., 2012). The groundwater level is monitored by piezometers placed on former mines. Seismicity can be monitored by a seismic network. Nevertheless, the seismic networks active during mining operation usually shut-in once the mine closes, and monitoring relies on general seismic networks or of other near mines, which is not enough to detect the low magnitude of these seismic events (Primo Doncel et al., 2023).

The hazard can be defined a potential of undesirable event for causing an undesirable consequence (Canadian Standards Association, 1991), and it is defined by the probability of its occurrence and the possible magnitude of the event at a specific location.

In post-mining, the experts, based on the mining history and the potential mining hazards, evaluate and identify potential exposed areas that could affect people and infrastructure.

3. METHODOLOGY OF GEOLOGY AND MINING DATA COLLECTION[3]

Data collection is a crucial part of credible risk assessment of seismic and surface deformation hazards in post-mining areas, particularly during mine flooding. The chapter is organized into the following three parts, which summarize the content of collected data necessary for coal mine liquidation, subsequent flooding design, the flooding process, and the assessment of hazards (induced seismicity and surface deformation) associated with mine flooding: (i) geological data and water level management, (ii) mining data and seismic monitoring, and (iii) recommended database structure for data storage. The chapter is developed primarily on the basis of the results of the PostMinQuake project.

3.1. Geological data

This chapter presents the basic requirements for geological and mining data that are essential for subsequent analyzes and decisions about further monitoring.

3.1.1. Geological conditions

In the process of collecting information about the geological conditions of the studied area, it is necessary to focus especially on the following geological data:

1. Stratigraphy and lithology of the rock mass

This group of data includes, in particular, information on the petrographic composition and sedimentological characteristics of individual geological bodies, the spatial development of strata and their thickness, and on the relationships between individual sedimentary members within the entire geological formation. Special attention should be paid to the presence of thicker layers of competent rocks, consisting mainly of very strong conglomerates and quartz sandstones, where there is a risk of high and long-term stress concentration.

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2. Structural geology data

Basic structural data include data on the spatial orientation, i.e., dip direction and dip angle, of both primary structural elements (sedimentary layers) and secondary structural elements (faults). In the case of faults, it is also necessary to know their type, which is defined by the relative movement of rock blocks on either side of a fault plane. Fault types include normal faults, reverse faults, strike-slip faults, oblique-slip faults, and thrust faults.

3. Physical and mechanical properties of the individual rock types and the entire rock mass quality

The following properties should be collected: Bulk density, uniaxial compressive strength, Young's modulus, and Poisson's ratio can be considered as the basic material parameters of coal and associated rock that are important for the following analyses. The Rock Quality Designation (RQD) index (Deere et al., 1967), Rock Mass Rating (RMR) index (Bieniawski, 1969), Quality (Q) index (Barton et al., 1974), and/or Geological Strength Index GSI (Hoek et al., 2013) are examples of rock mass classification systems that can be used to describe rock mass quality.

4. Data on the cover layers in the overburden of the mined coal-bearing rock mass

If the rock mass of interest, in which mining has occurred and which is the subject of flooding, is covered by younger sedimentary rocks, the parameters of these overburden layers must also be known. This means having information about their thickness, petrography, and basic physical-mechanical properties.

The above-mentioned data characterizing the rock mass of interest can then be used to create geological, geomechanical, and/or hydrogeological models. How detailed and structured these models are then depends on the software used for modelling.

3.1.2. Surface conditions

Methods for measuring the ground surface movement include leveling, trigonometric height measurement, and remote sensing methods (which also provide position or spatial data) such as GNSS, and InSAR (Jiránková & Lazecký, 2016 and 2022, Nara et al., 2012, Ojo & Brook, 1990).

A diagram for assessing the impact of flooding on the ground surface is shown in Fig. 3.1. Ground surface change assessment methods based on ground displacement monitoring provide evidence of surface changes that either have already occurred or are occurring in real-time. The results are also used for parametric analyses, e.g., related to mine water level rise during mine flooding. Depending on the method chosen to measure surface displacements, data should be collected on elevation changes (vertical displacements) of the ground surface or also position changes in the horizontal plane (horizontal displacements) can be evaluated.

The data relating to the elevation measurements is a time series of the determined elevations above sea level of surface points. Elevation changes are then determined as elevation differences of the same surface point. The total altitude refers to the first altitude measurement of a surface point. The result of the position measurements in the horizontal plane is a time series of determined position coordinates of surface points in the reference coordinate system. The horizontal displacements, together with the vertical displacements, create data on the total motion vector of the surface point.

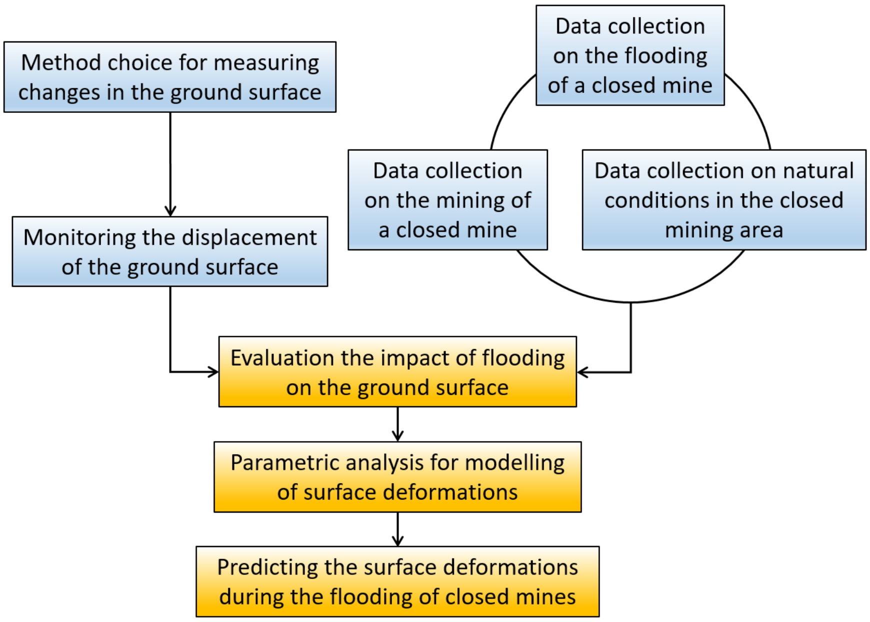

Fig. 3.1. Diagram of the effects of mine flooding on the ground surface

In connection with the European policy of suppression of coal mining and the frequent method of liquidation of mines by spontaneous flooding of closed spaces, due to the first experience with the manifestations of flooding of mines, uplifts of the ground surface are observed, and some authors begin to deal with their prediction. Possible in this regard is the acquisition of additional data obtained using numerical modelling of surface deformation (Dudek & Tajduś, 2021). The use of numerical models to predict surface uplift during mine flooding is also described by authors Zhao and Konietzky (Zhao & Konietzky, 2020). They used *in situ* measurements in the area of the abandoned Oelsnitz mine in Germany to calibrate the model.

3.1.3. Rock mass properties

As a result of the rise of the mine water level during the flooding of the abandoned mine, the rock mass comes into direct and long-term contact with the mine water environment. This leads to the absorption of water into the pore space of sedimentary rock and the associated change in its material parameters. It is a well-known fact that upon wetting, rocks exhibit a reduction in their quality of mechanical properties, such as compressive strength. This phenomenon was already mentioned by Hirschwald (Hirschwald, 1908), who first introduced the so-called softening coefficient to describe the loss of strength of test specimens after storage in water. The degree of softening varies depending on the rock lithotype. For crystalline rocks such as granites, the strength reduction is very small, but porous sedimentary rocks such as sandstones are generally more sensitive to this effect.

Many papers have been published in the literature on the influence of moisture content on the decrease in compressive strength of sandstones, which are among the most common accompanying rocks of coal seams in coal-bearing formations (Dyke & Dobereiner, 1991; Hawkins & McConnell, 1992; Morales Demarco et al., 2007; Siedel, 2010). The most important factors determining the sensitivity of sedimentary rock strength to water content are, first, the distribution of pore radii and, second, the amount and mineralogy of the matrix as well as rock cement (Martinec, 2010). Therefore, the loss of compressive strength is higher in matrix-rich, clay-bearing sandstones than, for example, in quartz-rich sandstones with grain-supported texture (Guha et al., 2017; Seto et al., 2001). It is also important to note that the strength loss of sandstone can be remarkable even when the rock is not yet fully saturated with water (Martinec, 2010; Zhao & Konietzky, 2020), in some cases even when the moisture content is as low as 1% (Vásárhelyi & Ván, 2006).

The moisture contained in the rock also affects other material parameters such as tensile strength (Burshtein, 1969; Ojo & Brook, 1990; Ruedrich et al., 2011), Young's modulus (Guha et al., 2017; Hawkins & McConnell, 1992; Jimenez Gonzalez & Scherer, 2004; Vásárhelyi, 2003), or fracture toughness (Guha et al., 2017; Lau, 2016; Nara et al., 2012; Seto et al., 2001; Singh & Sun, 1990; Utagawa et al., 1998; Vavro & Souček, 2016).

It follows that the basic mechanical properties of rocks that should be monitored in the context of how mine water affects the rock mass are uniaxial compressive strength and splitting tensile strength. In the area of deformation properties, attention should be paid in particular to Young's modulus, and possibly also to Poisson's ratio. These properties should be determined according to the proposed test methods of the International Society for Rock Mechanics (ISRM, 1978, 1979). When soaking the specimens, care must be taken to wet the rock gradually and slowly so that the pore space is saturated with water as much as possible. A suitable procedure for the gradual saturation of the rock with water is described, for example, by Martinec or Vavro (Martinec et al, 2010, Vavro et al., 2016).

In most cases, the wetting of sediments also leads to an increase in the volume of the rock material. As stated, e.g., by Ruedrich (Ruedrich et al, 2011), mineralogical composition and pore size distribution play a crucial role in the intensity of moisture expansion. Rocks rich in clay minerals are particularly susceptible to volume increase. For this reason, the largest swelling values are expected in clay stones, while quartz sandstones and/or conglomerates are practically resistant to moisture-induced volume changes. It should be emphasized, however, that not all clay minerals have the same swelling ability. Kaolinite, for example, is representative of the non-swelling clay minerals. In contrast, smectite (montmorillonite), as a typical swelling clay, can increase its volume by up to 25 times upon contact with water compared to the dry state (Daneshfar et al., 2017).

Due to possible volume changes during water absorption in the pore space of the rock, it is therefore recommended to monitor also possible swelling. In particular, the values for longitudinal and transverse expansion values should be measured so that the volume change of the rock can subsequently be calculated. A caliper is a suitable enough laboratory aid for these measurements. In addition to monitoring the volume change, it is recommended to continuously determine the water absorption capacity.

3.1.4. Hydrogeological conditions

Hydrogeological conditions describe the flow, occurrence, and behaviour of water in the subsurface environment. It is a science intermediate between hydrology and geology, and both have a strong influence on understanding groundwater flow and solute transport. Hydrological processes are responsible, for example, for characterizing and understanding water supply from aquifer recharge. On the other hand, the physical properties and composition of geologic materials (rocks and sediments) provide the most important environment for groundwater flow and storage. The rocks and sediments also influence the quality of groundwater in terms of their chemical composition.

Hydrogeological data of the region associated with the mining period consist of the following: (i) identification and location of the main source of water inflow, (ii) identification of the main inflows to the mine(s) according to the regular reporting of water pumping during the mining period, and (iii) chemistry of water from each aquifer and surface water.

Before mine flooding, should be identified areas of the mines where we assume good hydraulic connectivity due to natural water connection corridors (aquifers and tectonic faults) as well as due to mining openings, and areas of goafs that represent potential zones for water flow in the rock mass. Removal of local barriers between classified ponds is strongly recommended for better hydraulic connectivity between ponds, e.g., installation of appropriately sized piping. If the connection between ponds is purely hydraulic, the creation of connecting corridors between ponds is highly recommended.

Concepts of "ponds" recommended by Younger (Younger et al., 2002) for post-mining flooding assessment and definition of hydraulic connections at pond boundaries are used. The definition of a pond is based on the concept that mining works within any one pond are largely interconnected (often at multiple levels if mining was undertaken on more than one horizon) so that water rising within any one pond shares a common level in that pond. At certain elevations, adjacent ponds may be connected by discrete decant features (Zang et al., 1996) . Typical decant features include (Zang et al., 1996): (i) roadways connecting areas of otherwise separate mining works, (ii) areas where two adjacent goafed panels coalesce, (iii) old exploration boreholes, and (iv) permeable geological features. All hydrogeological data necessary to define the above-mentioned ponds should be collected.

3.1.5. Water level management during mines flooding and water pumping

During mine closure planning, it is necessary to plan water level management for subsequent mine flooding and water pumping. After identifying the ponds, it is necessary to create sufficient number of monitoring points (points that evenly cover the entire area of the pond) where the water level in each pond is monitored. Monitoring the water level at one point in a particular pond is insufficient.

Water level management data includes the following: (i) location of water level monitoring points (coordinates in a local and global coordinate system), (ii) water level data in monitoring points and definition of altitude system used (date, time, and water level altitude), (iii) chemistry of water in selected monitoring points, preferably by zonal sampling. During the period of water pumping, the volume of water pumped from each pumping point should be recorded daily (volume per time). Hydro-chemical analysis of the water according to local hydrogeological conditions during water pumping is strongly recommended.

Before recording the water level at the monitoring points in the first part of the mine flooding, detailed data should be collected about flooding of the deeper parts of the mine if the mine is sequentially flooded and data can be collected from these parts.

3.2. Mining data

Mining data is the crucial part of data collection that is the basis for many following evaluations and monitoring. All accessible historical data should be collected. Special attention must be dedicated mainly to place where mining started in the region in the upper part of coal bearing rock mass and/or close to the surface because these parts are mostly mined by room and pillar method or due to method by parallel roadways and these parts are most prone to fracturing pillars left and unmined in rock mass. These re-fracturing processes are mainly responsible for induced seismicity and surface deformation hazard.

3.2.1. Mining history and mining conditions

Mining history data provide a detailed account of the history of mining in a particular region, covering all aspects of coal production. This encompasses a comprehensive description of mining activity in the region, including information on mining conditions, mining methods employed, the thickness of mining seams, and the extent of mining operations, among other pertinent details.

A critical component of information on mining history is data on mining conditions, which provides insights into the mining advancing to greater depths. This data includes the thickness of the mined coal seams, the unmined coal pillars remaining in the rock mass, the occurrence of seismicity in the region in question, and during the study period, among other relevant factors. Furthermore, it includes detailed information about the mining area, such as the character of the rock strata in the roofs and floors of the coal seams, as well as the properties of the strata, such as their thickness, volumetric weight, tensile and compressive strength.

Mining activity in many coalfields started several centuries ago, with intensive mining operations commencing in the mid-19th century and reaching their peak during the 20th century.

Summary publications by historians, mining specialists, geologists, geographers, and other experts are valuable sources of information on mining history and conditions. These publications offer comprehensive coverage of the mining history of a region from its beginnings to the present day and explore a range of topics such as technological development, mining legislation, the mining education system, the environmental impact of mining, and the cultural and social aspects of long-term mining. Apart from summary documents, there are various sources of information available on mining history and conditions. These include scientific and technical journals, a vast number of mining reports, historical maps, specially curated lists of mining attributes, and complex thematic internet portals also offer valuable information.

3.2.2. Mining methods

Mining methods have evolved over centuries of mining production due to technical advancements and deeper mining operations. The selection of a particular mining method for mineral extraction depends primarily on deposit conditions and the technology available at the time.

Part of the mining methods description involves providing a detailed characterization of the methods employed in the region. For example, longwall mining can be carried out with or without backfilling and using different materials and methods. Along with the mining method, it is beneficial to include details about the extent of the mining.

3.2.3. Mining panels and mining thickness

Maps of mined panel contours, along with other relevant spatial information, are typically used to represent mining panel data. This includes historical, recent, and current mining maps, as well as vertical cross-sections and other sources of spatial data, which can be used for modelling the mining areas.

Supplementary input data, such as regional maps of mineral resources, maps of mining claims, maps of mining shafts, maps of boreholes, or schematic mining panel contours, are also valuable. Description attributes should be provided for all of these features.

In addition to maps, mining panel data also comprise various mining parameters, such as the width of the mining face, the length of continuous advancement, the positional coordinates of the mining face, the mining depth, and spatial information regarding the unmined pillars.

A crucial aspect of the mining panel information is the data regarding the thickness of mining, which is presented in the form of a list of coal seams extracted in the relevant area along with their thicknesses (including both the range and the average thickness). This information should be structured appropriately, including the name and number of the coal seam, as well as the minimum, maximum, and average thickness of the mined seam.

For most reports and overview tables, a basic text or spreadsheet format is recommended since it can be easily imported into various processing software. To facilitate further work, it would also be beneficial to have a model of the thickness of the seams or, ideally, a comprehensive model of the mineral deposit.

3.2.4. Seismic monitoring network data and monitoring protocol during and after closing of mining operations

Data on natural and induced seismic activity during and after coal mining must be collected continuously to analyse seismicity during mine flooding and water pumping, especially in locations where the rock mass has been classified as a hazard zone for mine earthquakes and rock bursts. The data provided by such monitoring is a necessary input for evaluating the structural deformation of surface buildings. Natural seismicity is represented by earthquakes recorded before, during, and after the closure of the mining area and its surroundings. If induced seismicity was recorded during coal mining, all data must be collected. Seismicity includes the following data: (i) location and specification of seismic stations used for seismic monitoring (coordinates in local and global coordinate system, specification of seismic stations, description of seismic network), (ii) database of registered seismic events (date, time, 3D location of seismic events in local and global coordinate system, information about underground damages - rock bursts or surface incidents - vibrations, Peak Particle Velocity in the horizontal or total velocity vector - PPV), and (iii) detailed records of the registered seismic events from all seismic stations used for monitoring in an open seismological format, or ASCII allow detailed interpretation of the seismic events (frequency analysis, seismic moment inversion analysis, etc.).

3.3. Database structure

When you start collecting a package of different data types, it is necessary to define a suitable structure for logical categorization so that it is easily searchable and usable. Possible descriptions of predefined categories and subcategories in the mining data domain are as follows: (i) Basemap, contains available appropriate referenced map sources in raster or vector format, temporally corresponding aerial photographs, links to web services that provide relevant map layers and other data, another appropriate map sources, (ii) Mining history data is represented by a description of mining history in the evaluated region, (iii) Mining conditions data is represented by a description of mining depth, coal seam thickness, unmined coal pillars left in the rock mass, rock burst occurrence in the evaluated region, etc., (iv) Mining methods is represented by a list of mining methods used in the evaluated region with a brief characterization, (v) Mining panels is represented by maps of mined panels' contours (enclosed polygons of the panels in 2D/3D location in space in the evaluated region), (vi) Mining thickness data is represented by a list of mined coal seams with thickness (range of thickness and average of thickness) in the evaluated region in an appropriate data structure.

The database structure recommended for practical application is shown in Fig. 3.2. The structure was applied to the PostMinQuake project.

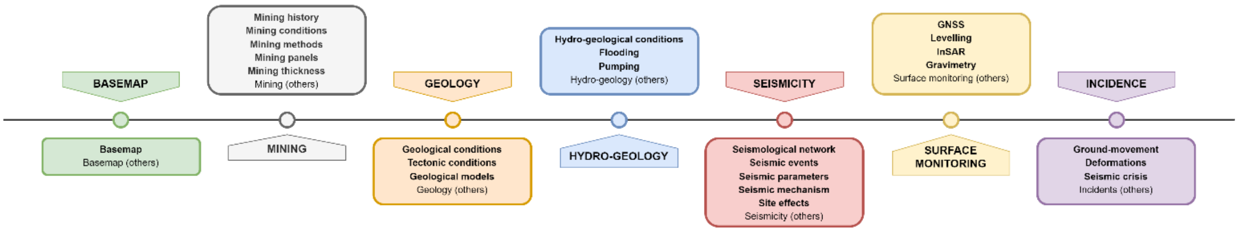

Fig. 3.2. Example of database structure

4. HYDRO-MECHANICAL MODELLING AS A TOOL FOR SEISMICITY PREDICTION IN FLOODED COAL MINES[4]

The impact of hydro-mechanical perturbation within the rocks and the potential link with the triggering of seismicity has been studied since few decades. The hydro-mechanical (HM) perturbation can be correlated to anthropic activities due to fluid injection/pumping such as geological reservoirs exploitation of heat, hydrocarbons, water resources or CO_2 storage (Elsworth, 2013; Lee, 2019; Rutqvist, 2013; VanWees, 2014; Jeanne, 2017 and Pang, 2020). Recently the evidence of seismicity in link with natural meteoritic recharge of specific geological contexts such as karstic rocks (Bragato, 2021) or crystalline rocks (Maystrenko, 2020) has been studied. In both causes (anthropic and natural), the triggering of seismicity is mainly linked to the stress perturbation acting on existing tectonics structures (fault zones, faults, fractures). The stress perturbation on faults can be due to pore pressure changes within the faults and/or by changes of their loading conditions (Fig. 4.1).

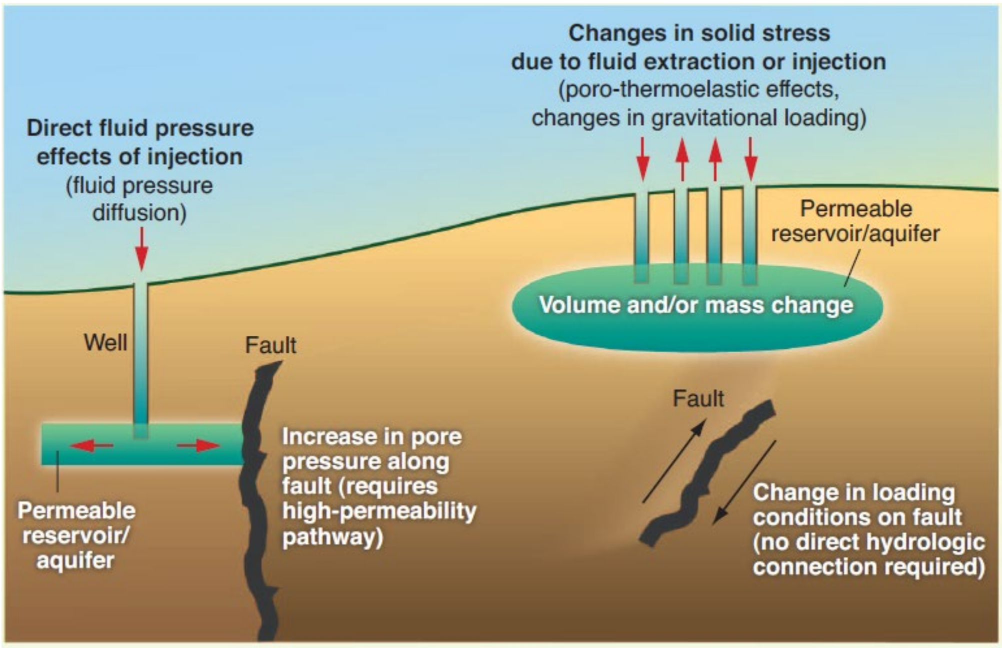

Fig. 4.1. Schematic stress perturbation on faults because of fluids recharge/discharge (issued from Ellsworth, 2013)

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In the case of abandoned coal mines, the stop of water pumping leads to the flooding of abandoned mines depending on the hydrogeologic context. The water level, without any control and active management, will then fluctuate depending on the water venues from meteoritic conditions. Due to the flooding of mines and water table fluctuations, the rocks around the mines are submitted to a change of their mechanical equilibrium. Two kinds of hazards can be related to a water effect:

- Due to ageing process accelerated by the water contact (Luo, 2021), the rock matrix can be weakened leading to a rupture of mine structures (such as pillars). This can lead to recorded events (at the depth and above mines) and deformations such as surface subsidence depending on the depth of mines and mechanical competence of the rock layers above the mines.
- Due to change of pore pressure and volumetric changes (as in Fig. 4.1), the existing geological discontinuities, such as faults and fractures, can be reactivated and shear as mentioned above. This shear phenomena can be associated to recorded seismic events at depth correlated with the water level.

This chapter addresses only the scope of the second category of hazards, those linked to hydro-mechanical perturbations on faults/fractures because of fluid flows and water table variations within the geological vicinity of mines.

4.1. Hydro-mechanical simulations

The chapter presents the issue of conducting an assessment of the impact of the flooding process and water table fluctuations on the triggering of seismic activity in abandoned coal mines. It includes a description of the modelling methods that can be used and the range of data needed to carry them out. It also presents the practical application of the proposed methods on the testing sites of the PostMinQuake project.

4.1.1. Methodology

In order to evaluate the impact of the flooding process and water table fluctuations on the triggering of seismic activity in abandoned coal mines, it is advantageous to carry out predictive numerical simulations. Provided that sufficient data is available to build the numerical models, this methodology should be transposable to any mining site. We proposed to apply this numerical approach to two mining sites: one at Kazimierz Juliusz site (Poland) and the other at Gardanne Fuveau (France) site as part of the PostMinQuake project. For both sites, the numerical models have been built with the existing data and knowledge in term of structural model of sites and water level information. Simulation results should be confronted with existing recorded seismic data. At this stage, tests on the influence of parameters such as the flooding process and in situ stress state should be conducted to highlight key parameters.

4.1.2. Modelling method

Simulations in the case of the occurrence of faults in the post-mining region mainly focus on the loading state of this existing/assumed faults (Fig. 4.2) and its variation due to hydraulic changes because of flooding and water level fluctuations. Starting with a fault zone naturally locked under the local stress state (Fig. 4.2a), the circulating fluid can force opening of fault and trigger shearing because of the associated shear resistance reduction (Fig. 4.2b). After shearing, irreversible deformation can appear because of fault shape mismatch resulting in incomplete closing and fluid pathway (Fig. 4.2c).

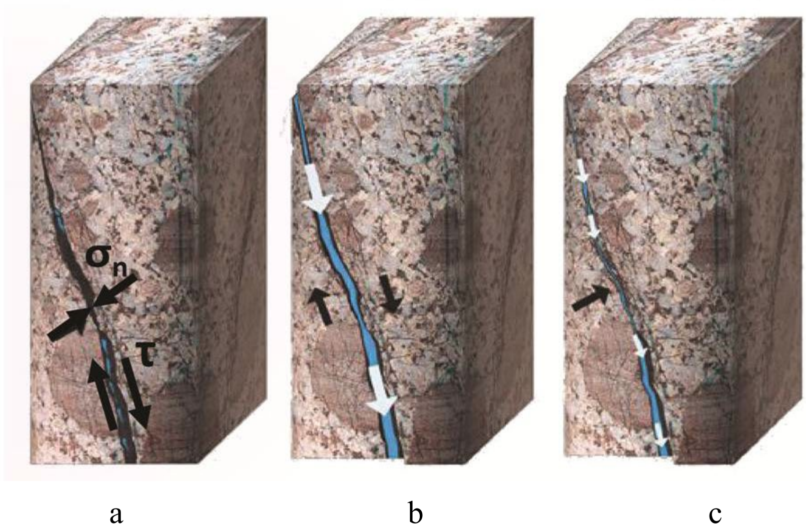


Fig. 4.2. Schematic loading state of a permeable fault with fluid flow: a - natural state with the normal stress locking the shear stress, b - shearing due to normal stress reduction when fluid opens the fault, and c - irreversible opening when fault closes once the fluid flew away

The codes used are able to simulate the mechanical behaviour of both rock matrix and faults and their mechanical response due to the imposed hydraulic solicitation representing the flooding and the water level fluctuations. Considering that the seismic events are linked to the shearing of faults, a key aspect is to account for irreversible processes in the mechanical behaviour. Such processes are conditioned by a threshold beyond which irreversibility occurs. In our case, a Mohr Coulomb yield criteria (4.1) is analysed during the whole simulations in order to assess the triggering of this shearing (Fig. 4.2):

$$f_s^{MC} = \tau_s - \tau_s'^{yield} = \tau_s - (c - (\sigma_n + p_l) \times \tan(\phi)) \quad (4.1)$$

Where τ_s and σ_n stresses are the shear and normal stress acting on the faults, p_l $[Pa]$ the pore pressure in the permeable faults, $\tau_s^{\prime yield}$ $[Pa]$ is the effective yield stress, ϕ $[rad]$ the friction angle and c $[Pa]$ the cohesion. f_s^{MC} is commonly noted CFF for Coulomb Friction Failure. The hydraulic solicitation imposed impacts the pore pressure in faults and the total stress on faults (τ_s and σ_n) through the change of the rock density above the fault if presence of fluid in rock matrix is considered. To highlight the effects of stress perturbation on the fault stability, CFF is commonly derived in a change of CFF denoted ΔCFF (4.2):

$$\Delta CFF = \Delta\tau_s + (\Delta\sigma_n + \Delta p_l) \times \tan(\phi) \quad (4.2)$$

Interestingly, (4.2) highlights that all following phenomena will favour shearing (ΔCFF>0):

- Increasing shear stresses $\Delta\tau_s > 0$,
- Decreasing normal stress $\Delta\sigma_n > 0$,
- Increasing fluid pressure $\Delta p_l > 0$.

With the computed shear displacements, once the CFF is reached in faults, seismic moments M_0 can be estimated using (Aki, 1966):

$$M_0 = \oiint_S G u_s dS \quad (4.3)$$

where: u_s [m] is the shear displacement and G [Pa] the shear modulus of the rock mass.

To have a comparison with *in situ* behaviour, we can compute the seismic moments from the local magnitudes of the recorded events.

4.1.3. Data

The corner stone of the simulations are the existing data linking the evolution of water level and the recorded seismic events during the same period. The evolution of water level is the imposed solicitation of the simulations: this can be a recorded data (as for example in the Fuveau Gardanne site: green curve in Fig. 4.3.) or can be a forecast evolution (as in Kazimierz Juliusz site Fig. 4.4A). The evolution of the number of seismic events recorded within the same period will allow to confront the results of simulation in order to validate the models (blue line in Fig. 4.3. and Fig. 4.4B).

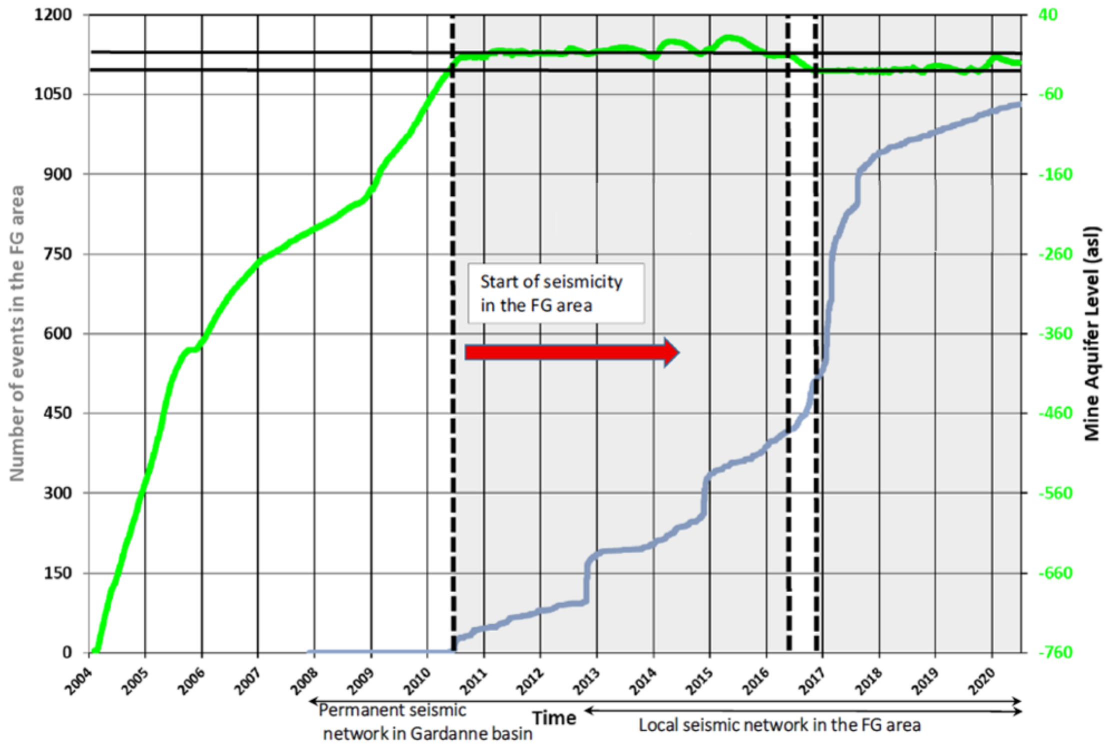


Fig. 4.3. Events count (blue line) and mine aquifer level (green, asl- above sea level [m]) recorded at the Gardanne site (from Dominique et al 2022)

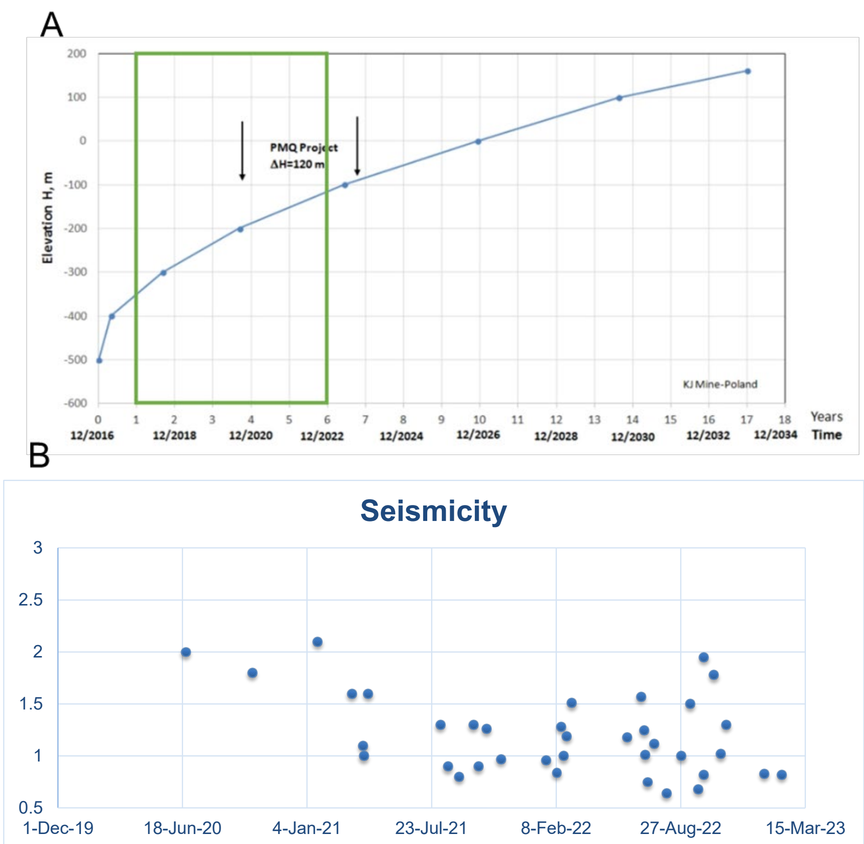


Fig. 4.4. A - Flooding plan in the Kazimierz-Juliusz site, and B - Seismic activity recorded (vertical axis - M L- local magnitude)

The localisation of the seismic events around the mine (Fig. 4.5 as for example in the Fuveau Gardanne site) is also an important information to confront the spatiality evolution of the shear phenomena simulated.

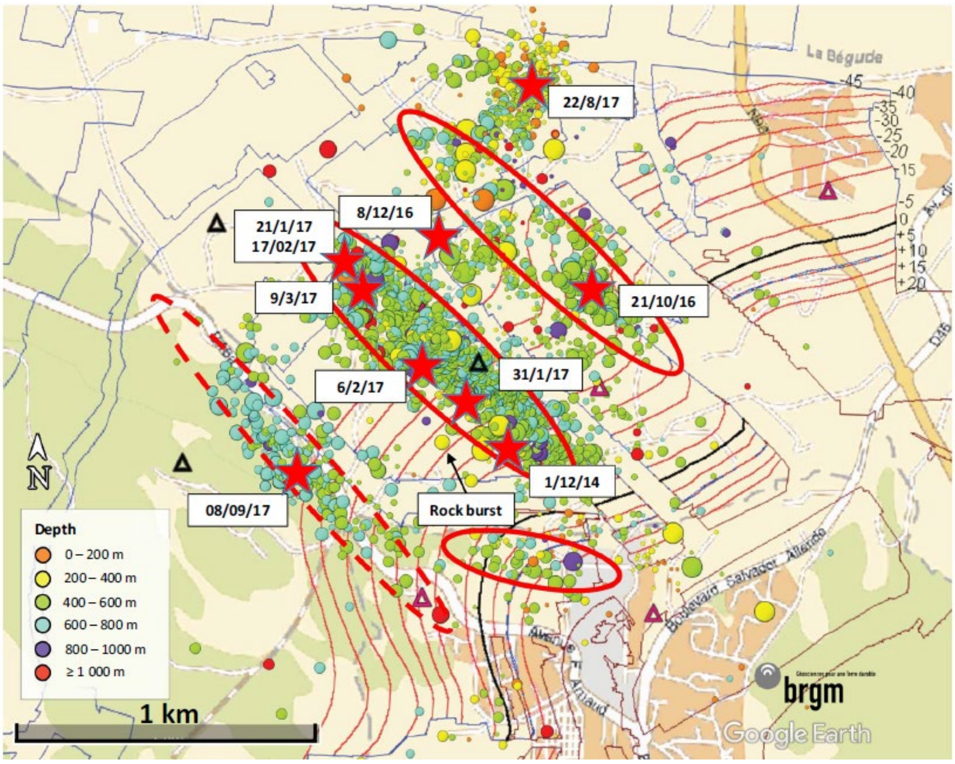


Fig. 4.5. Cloud of seismicity at Fuveau during the period 2013-2017 (from Dominique et al., 2022)

4.1.4. Practical application

Carried out as part of the PostMinQuake project for the Fuveau Gardanne site, the simulations focused on the period from mid-2010 to 2020. Indeed, the recorded seismicity (Fig. 4.3) arises after the flooding of the mine (mid 2010) and looks to be correlated to water level fluctuations. The results show a clear impact of the increase of the pore pressure in faults in the triggering of seismic events: by applying directly the hydrostatic pore pressures variations because of water table fluctuations shear displacements occurred in the faults (see the final state of simulation in Fig. 4.6). Based on that mechanical response in faults, a sequence of computed triggered seismic events is observed and can be confronted to the recorded events (Fig. 4.7).

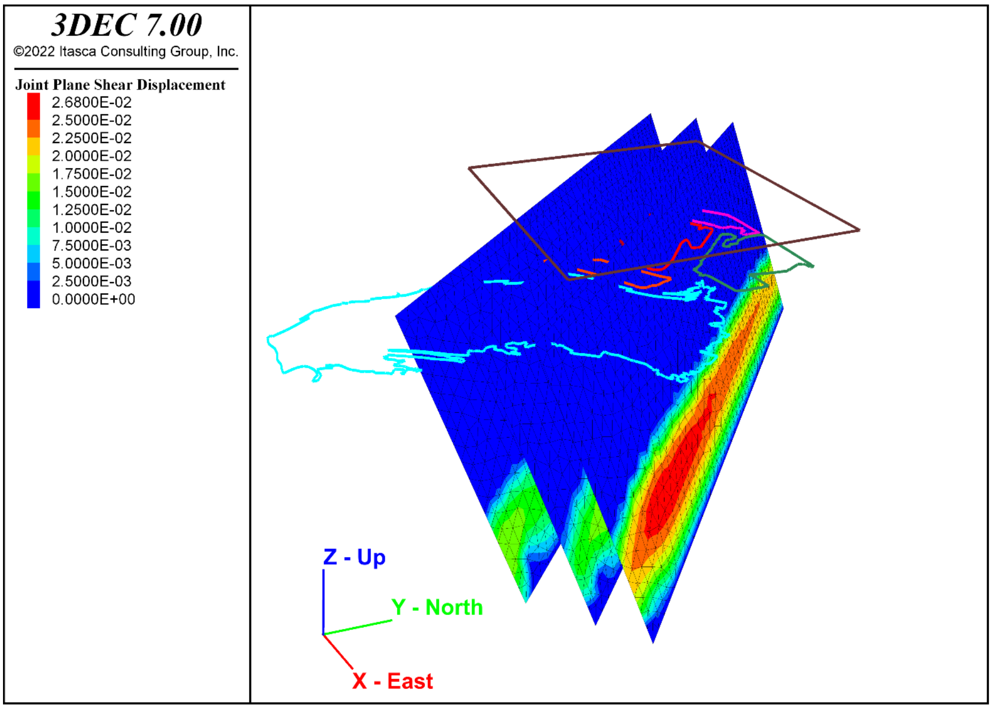
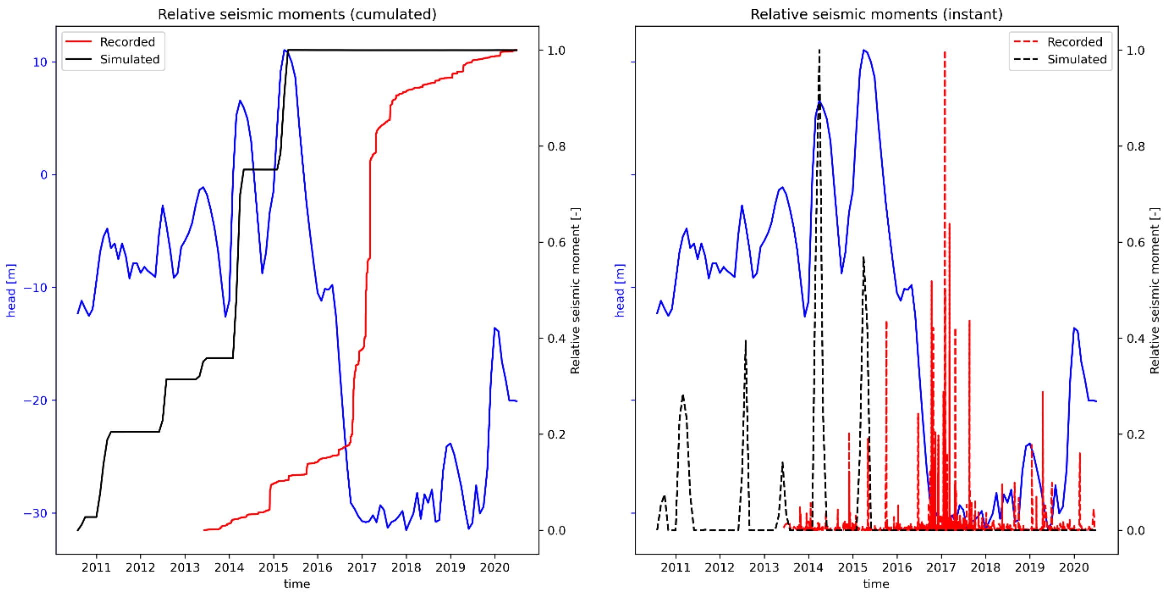


Fig. 4.6. Modelled shear displacements in the faults at the final state (July 2020) for the Fuveau Gardanne case



a b

Fig. 4.7. Computed and data-inferred relative seismic moments for Fuveau Gardanne case (with water head level in blue): a - cumulated and b - instant seismic moments

For the Kazimierz Juliusz site, simulations have been focused on the flooding phase of the mine (increase of the water level in the mining sites). For this site also, the numerical model integrates the faults identified around mines (Fig. 4.8).

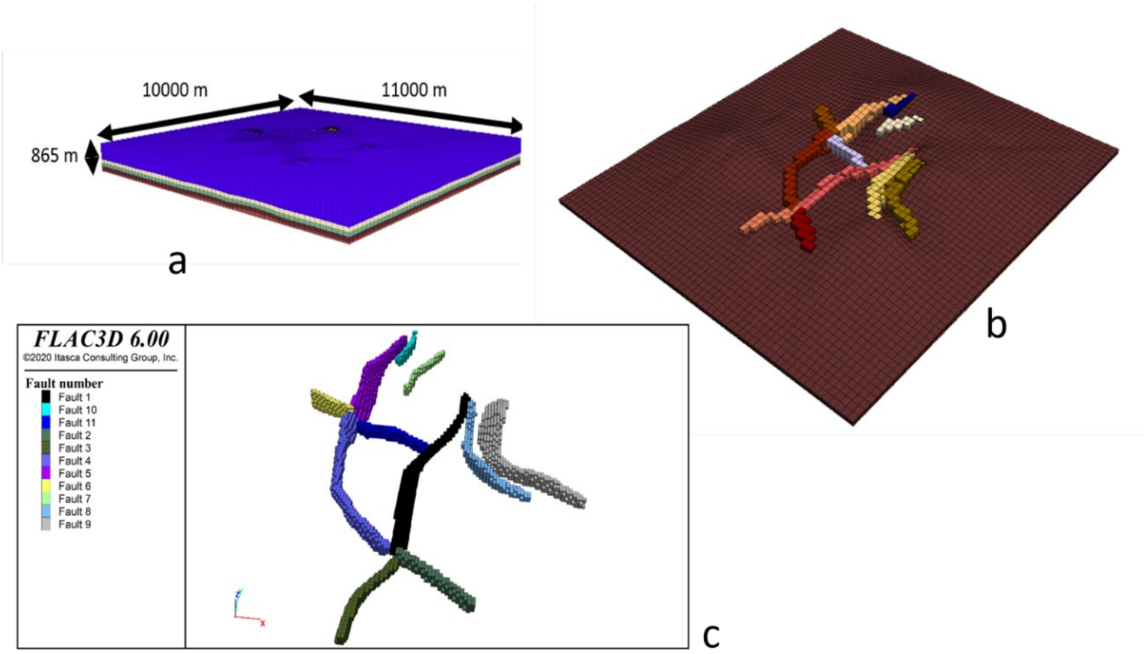


Fig. 4.8. Kazimierz-Juliusz geometry in FLAC3D: a - geological layers, b - faults as assemblies of mesh cells and c - fault labeling

From the simulations, it appears (see Fig. 4.9. and Fig. 4.10) that the major characteristics and parameters acting on the triggering of seismicity are the mechanical loading state of faults (depending on their orientation and the local stress state), the permeability of faults and the pore pressure impact due to water level increase. However, the period of availability of seismic data is limited and further data is necessary to validate the model.

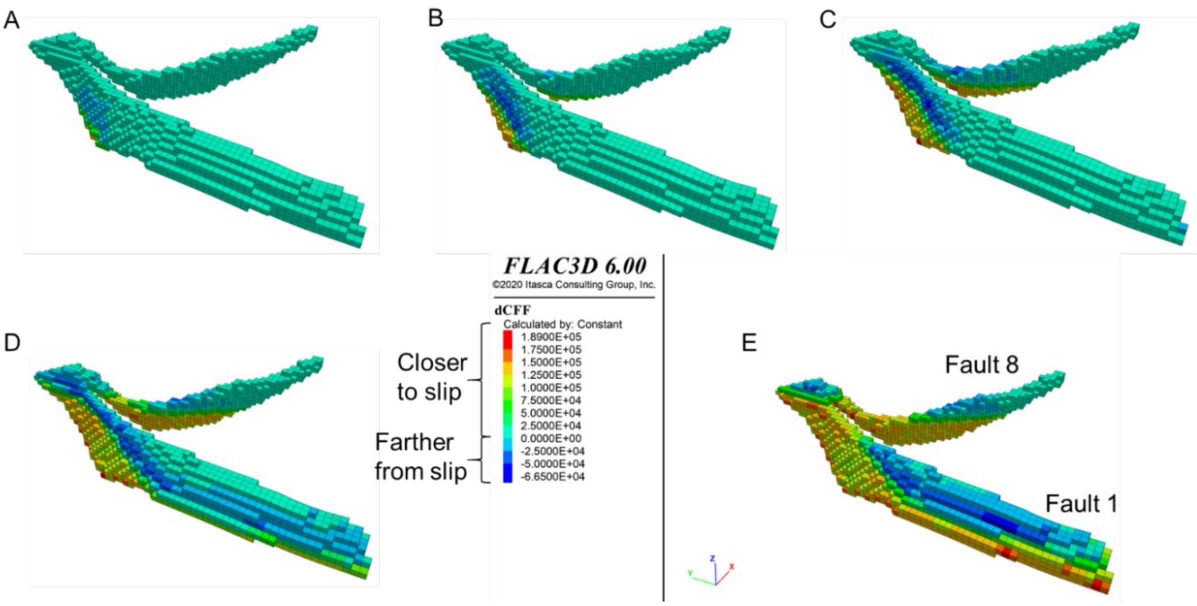


Fig. 4.9. Coulomb friction failure increments at Kazimierz-Juliusz site on fault 1 and 8: when water table is raised: A - From -500 m to -400 m ASL, B - From -400 m to -300 m, C - From -300 m to -200 m, D - From -200 m to -100 m, and E - From -100 m to 0 m - Refer to Fig. 4.8 for localization of faults 1 and 8

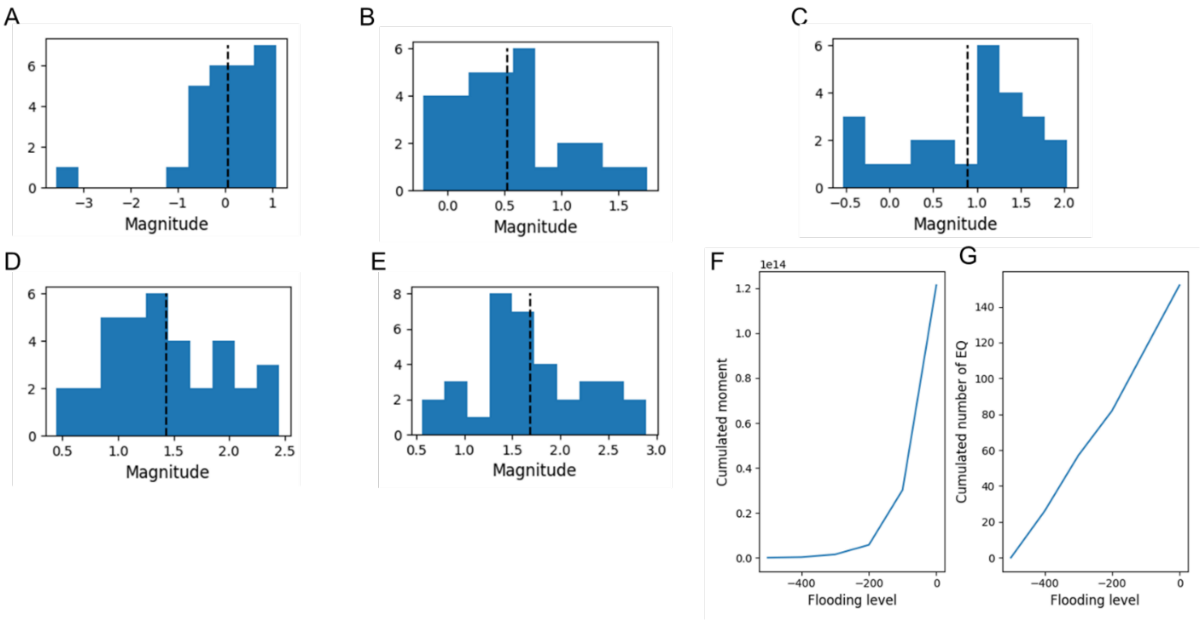


Fig. 4.10. Histogram of magnitude for post-mining earthquakes generated when water table is raised: A - From -500 m to -400 m ASL, B - From -400 m to -300 m, C - From -300 m to -200 m, D - From -200 m to -100 m, E - From -100 m to 0 m (vertical axes– number of events) and cumulated moment in Nm (F) and cumulated number of these events (G) in function of level of water table in m. Dashed line indicates the mean magnitude

From both sites studies, the simulations highlight major parameters and characteristics that can explain the triggering of seismicity during the flooding of abandoned mines (Kazimierz Juliusz) or during water table fluctuations in a flooded mine (Gardanne Fuveau). The key process, with respect to the assumptions and limits of the numerical models, looks to be the increase of the pore pressure within the faults, these faults being in a specific mechanical loading state (with respect to their orientation and the local stress state).

The model shows a limit in its ability to reproduce the recorded chronology of seismic events with water table fluctuations after the mine flooding. More specifically, the model, in Gardanne Fuveau case, failed to reproduce recorded seismic events when the water table goes down (see Fig. 4.7). The effect of discharge of the total stress on faults below mining chambers because of the overweight variations depending on the mining voids filling (with water) has been studied: this effect looks to be insufficient to trigger seismicity and is several order of magnitude lower compared to the pore pressure effect. An assumption to explain the delay of the seismic events occurrence between recorded and simulated ones could be that the effect of the lowering of the water table is delayed, the pore pressure variations in faults does not occur immediately. In that case, a real improvement of the numerical model could be to impose pore pressure distributions given by a 3D hydraulic model of the mining site able to reproduce heterogeneous diffusivity of the rocks and transient hydraulic evolutions. This 3D complexity is likely based on the geological observation of the site that highlights the presence of karsts.

4.2. Recommendations

The results of the numerical models for Gardanne Fuveau and Kazimierz Juliusz highlight the importance of realising a numerical simulation before the mine closure to anticipate the potential effects of this closure on seismicity. These simulations must be focused on modelling the main phenomena that may create seismicity. In Gardanne Fuveau for example, it was established that what must be considered is the loading state of existing/assumed faults near mines and its variation due to hydraulic changes because of flooding and water level fluctuations. Nevertheless, some other mechanism can exist and cause seismic events such as pillar collapse related to mine flooding.

In light of the hydro-mechanical simulation results, some generic recommendations can be established (Fig. 4.11) to better predict seismicity related to loading state of existing/assumed faults near mines and its variation due to hydraulic changes because of flooding and water level fluctuations. These recommendations shall be considered in light of the hypotheses, limits and needed improvements of the numerical models. So, it is also recommended that the hydro-mechanical models should be updated if new information becomes available, related to the monitoring of seismicity for example. In practice, HM models should be realised before mine closure based on seismicity information acquired during the exploitation period. Key parameters must be extracted at this step and a monitoring protocol established, as well as recommendations on characterization and further modelling.

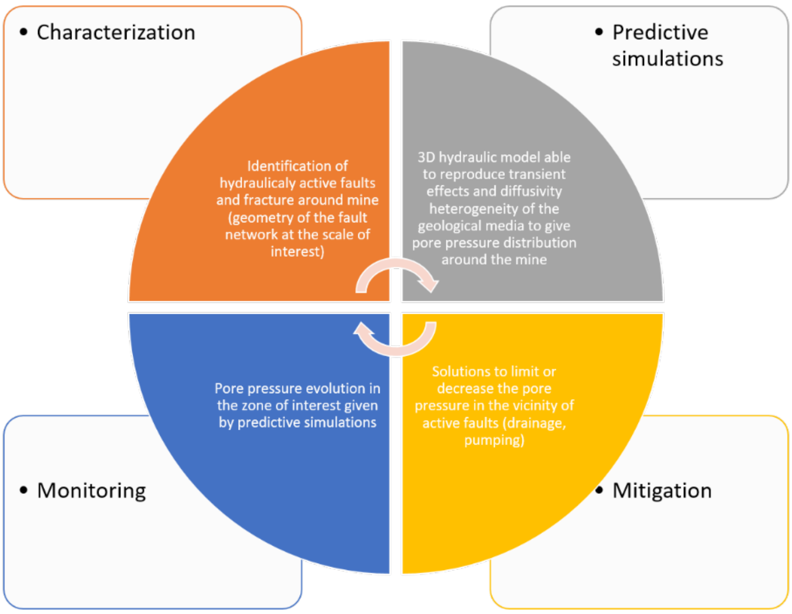


Fig. 4.11. Proposed recommendations derived from hydro-mechanical simulations of water level variation impact on post-mining seismicity associated with fault zones surrounding mine galleries. Recommendations are based on two models from two mining sites, Fuveau Gardanne (France) and Juliusz-Kazimierz (Poland)

5. SEISMIC HAZARD CONTROL AND PREDICTION OF SURFACE ADVERSE EFFECTS[5]

Ground vibration caused by mining and post-mining earthquakes can affect surface infrastructure reactions, feeling earthquakes by people, and disturb everyday life and can cause disruption of the normal use of buildings. To determine the level and effects of post-mining earthquakes, it is necessary to know the ground motion parameters in the assessed site. For this purpose, seismic monitoring, the ground motion prediction equation (GMPE) and spatial variation of ground motions (GM shake- maps) should be developed for the studied areas. The intensity of vibrations caused by earthquakes and blast vibrations is quantitatively described by numerous empirical scales, but mining-induced seismicity is different from natural earthquake (depth, frequency, duration time, PGA (Peak Ground Acceleration)/PGV (Peak Ground Velocity) value (Mutke& Dubiński, 2016). To mining and post-mining earthquakes the Mining and Post Mining Seismic Instrumental Intensity Scale, MSIIS-22 was developed under PostMinQuake and former COMEX projects (Mutke et al., 2015, Deliverable report 5.3 of the PostMinQuake project 2022). To use the MSIIS-22 scale, the ground-shaking maps must be calculated for the distribution of the peak horizontal velocity PGV_H and the seismic intensity shake-maps of seismic intensity according to the MSIIS-22 scale. Knowing the distribution of instrumental intensity degrees, I_{MSIIS}, the seismic hazard and the dynamic resistivity of infrastructures can be evaluated for different typologies of buildings.

The present chapter of guidelines aims at topics related to seismic hazard and damage assessment, providing recommendations for the specific context of post-mining earthquakes. Sections focus on seismic hazard control, seismic monitoring, ground motion prediction equation (GMPE), earthquake maps, seismic scenario, and MSIIS-22 instrumental intensity scale adapted to post-mining earthquakes.

The elaborated equations and MSIIS-22 scale were verified on the results of post-mining seismic monitoring at PostMinQuake testing sites (Primo Doncel et al., 2023). Basic seismic data on each testing site are as follows.

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Gardanne testing site: 3 200 post-mining earthquakes in magnitude range from -3 to 3 and highest recorded on the BULL station PGV=4.9 mm/s and PGA=550 mm/s^2 for an event and frequency range of the main phase of GM (Ground Motion) from 1 to 20 Hz.

Kazimierz Juliusz testing site: 48 post-mining earthquakes in magnitude range from 0.7 to 2.1 and highest recorded PGV=0.96 mm/s (PGA=65 mm/s^2) and frequency range of the main phase of the Ground Motion from 1 to 20 Hz.

Upper Silesia Coal Basin (USCB) - Ostrava-Petrvald testing site: 147 post-mining earthquakes in magnitude range from 0.1 to 3.15 and highest recorded PGV=1.2 mm/s and frequency range of the main phase of GM from 1 to 20 Hz.

Main symbols and definitions are presented in the table 5.1.

Table 5.1

The main symbols and definitions

f_o	First harmonic frequency of free vibrations of buildings.
R_e	Epicentral distance (distance from the epicenter of the mining induced and post-mining earthquake).
R	Hypocentral distance (distance from the hypocenter of the mining induced and post-mining earthquake).
t_H	Duration of vibration of the horizontal components of the velocity of the ground *v*, determined between the times when the intensity $I_V(t_k) = \int_0^{t_k} (v_X{}^2(t) + v_Y^2(t))dt$ reaches 5% and 95% of its maximum value.
M_L, M_0	Local magnitude, moment magnitude.
E_s	Seismic energy of the mining induced and post-mining earthquake.
PGV_H	Peak Ground Velocity of horizontal vibrations, determined as the maximum length of the horizontal ground vibrations vector.
V_s	Propagation velocity of seismic shear waves.
W_f	Vibration amplification (a factor defining amplification or damping of vibrations by geological deposit for the characteristic frequency range).
Intensity of vibrations (I MSIIS)	Categorization and description of the effects of mining and post-mining seismic events based on instrumental seismic parameters and macroseismic observations in buildings, as well as assessment of the perceptibility of vibrations by people (degree of harmfulness S) and the level of the nuisance of using buildings. The intensity of the vibrations is expressed in 8 degrees on the MSIIS-22 scale.
S	Degrees of harmfulness *S* corresponding to degrees of instrumental intensity I_{MSIIS} and depending on the type of building structure and its technical condition.
Structural elements of a building	**Elements of the load-bearing structure of a building** – elements of the structure bearing mainly vertical loads of the building. **Elements of the stiffening structure of a building** – elements of the structure bearing mainly horizontal loads of the building.

Non-structural elements of a building	**Filling elements of a building** – building elements for spatial planning of the building, that is non-structural external walls (curtain walls) and non-structural internal walls (partition walls) of the building. **Decorative elements of a building** – building elements for improving the appearance and comfort of using the building, such as facade claddings, plasters, wall and ceiling coatings, paint coats, wall, ceiling and floor linings made of ceramic tiles, coverings and other linings, suspended ceilings, window and door woodwork as well as roof. **Fitting elements of the building** – devices and technical installations fitted in the building, including the lifting installations, installations of particular media and elements enabling and supporting the use of those media.
Nuisance	Nuisance of using buildings affected by the mining and post-mining earthquake area.
Seismic scenario	The assessment of the probability of exceeding the magnitude of seismic mining and post-mining earthquakes, and the average recurrence period.
Dynamic resistance of building	The dynamic resistance of a building is defined by factoring in the potential damage it can sustain as a result of ground vibration, where each successive level entails a lower resistance of the building to PGV_H according to the MSIIS-22 scale.

5.1. Seismic hazard monitoring and control

The post-mining seismic events can be induced by the collapse of post-mining voids, the burst of the old pillars or by activation of tectonic stresses on faults mainly during the flooding of closed mines.

Ground vibrations caused by mining and post-mining induced earthquake can affect the reactions of surface infrastructure, can be felt by people, and can cause nuisance in the normal use of buildings. To determine the level and impact of coal mining and post-mining seismicity, the dedicated Mining and Post-Mining Seismic Instrumental Intensity Scale (MSIIS-22) can be used.

In the case of shallow seismic events, discontinuous surface deformations (sinkholes, fissures) in the future can be expected. In such cases, seismic monitoring allows us to study the development of the movement of post-mining seismic events and locate coal pillars in which the process of cracking and destruction of pillars takes place. Seismicity induced by changes in water level changes and the destruction of shallow coal safety pillars, which can result in the formation of a sinkhole.

Seismic monitoring is the basis for determining the seismic activity, location of seismic events, magnitude and/or seismic energy, seismograms/accelerograms, engineering parameters of vibrations, and afterwards for development and implementation of indirect methods of assessing seismic effects, based on the GMPE empirical relationships.

To ensure a high quality of seismic recording and to ensure the possibility of applying specialized procedures for processing and interpretation of the results, the number of recorded vibrations samples should not be less than 100 samples/ second (100 Hz).

In post-mining areas, we distinguish regional and local seismic monitoring (Rische et al., 2023).

Regional post-mining seismic monitoring

Regional seismic monitoring is conducted to determine the location of the post-mining earthquake foci (or epicenter), magnitude/energy, engineering vibration parameters (PGV, PGA), duration time of the main phase of vibrations and mechanism. Seismic monitoring in post-mining areas should allow us to create a database including the epicentre location (if possible hypocentral location) with errors less than 250 meters and a magnitude from M 0.5 or even lower. The measuring sensor should be three-component receivers aligned in mutually perpendicular directions (two horizontally and one vertically). The sensor requires installation directly in the ground or in small buildings, for which the function of vibration transmission, from the soil to the foundation of the object, is close to one in the frequency band from 0.5 Hz to 10 Hz.

Seismic stations should be deployed near strategic infrastructures and allowed to reach the best distributed engineering ground motion data in the study area. It is recommended to install several sensors in the boreholes to improve the location of the vertical component of the post-mining earthquake foci.

At each seismic station, the V_{S30} shear wave velocity should be recognized and the amplification factor should be calculated (Schnabel, 1972). The A, B, C, and D ground type according to Eurocode 8 is recommended to designate under each station.

A map of the thickness of Quaternary deposits (grid map) is recommended to elaborate on the study area. Using such a map, it is possible to calculate the analytical amplification effects expected in the post-mining study area. The experience from the Upper Silesia Coal Basin (USCB) indicates, that the high amplification effect for post-mining and mining induced earthquakes is related mainly to quaternary overburden. This is due to the main frequency of induced earthquakes (generally ranging between 1 Hz and 10 Hz) and the low shear wave velocity in the quaternary deposits. The first resonant frequency of low-velocity Q layers is $f_{res1} = Vs/4H$, and very often is very similar to the frequency of the main phase of post-mining earthquakes, in the range of 1-10 Hz.

Seismic monitoring of post-mining induced earthquakes should provide nonclipped data in the range:

- velocity amplitudes of vibrations (PGV) up to 0.2 m/s,
- acceleration amplitudes of vibrations (PGA) up to 5 m/s^2,

and ensure

- the sampling frequency of 100 Hz or more,
- time duration of seismic events not shorter than 10 seconds in case of triggered data.

Digital recordings of mining and post-mining earthquakes should be stored in a database with information including:

- location of the measuring station,
- date and time of the seismic event,
- location of the epicenter (hypocenter) of the seismic events,
- seismic magnitude (seismic energy),
- V_{S30} and the amplification effect and/or ground type according to Eurocode 8 under each station.

Engineering parameters of ground motion, such as:

- PGV_H, PGV_Z - velocity amplitudes,
- duration of the horizontal ground motion velocity, $t_{H,}$
- PGA_{H10}; PGA_Z after filtering out the signal in the frequency range from 0.5 Hz to 10 Hz,
- f_D - main frequency band of the main phase of vibration, reads from spectral analysis,
- other engineering parameters such as response spectra, Arias intensity, PGA/PGV and others are strongly recommended.

Seismic monitoring carried out for a sufficiently long time allows the development of a ground vibration database, which is also used to develop an empirical ground motion prediction equation (GMPE).

Local post-mining seismic monitoring

Local seismic monitoring is carried out to track the development of seismicity in the area of the old shallow exploitation. The analysis of the location of the post-mining shallow earthquakes foci indicates the places where the pillars have cracked and the roof rocks collapsed in the underground rooms and galleries. Thus, we obtain information about a specific zone of hazard of a sinkhole or other discontinuous deformation (Kotyrba & Mutke, 2015).

In this case, the accuracy of the location of the post-mining earthquake foci should be below 20 m, and the magnitude level of M 0 or even smaller. Such a micro-seismological network should consist of surface and underground stations located in boreholes.

5.2. Ground motion prediction equation (GMPE)

To determine the level and effects of post-mining earthquakes, it is necessary to know the vibration parameters at the assessed site. For this purpose, a ground motion prediction equation (GMPE) and spatial variation of ground motions should be developed for sites. These equations relate ground motion parameters, to sets of independent variables connected with the characteristic of the source, path, and site (Douglas et al., 2022, Atkinson, 2015).

Local site effect conditions can increase Peak Ground Motion Parameters (PGMP) values and thus increase the damage risk to infrastructures. In case of the high variability of the overburden of weak quaternary layers in analyzed seismic station locations, the GMPE equations and resulting shake-maps must take into account the amplification effect. To use the intensity scale MSIIS-22, the horizontal Peak Ground Velocity (PGV_H) should be calculated.

An extended GMPE form is proposed to use in post-mining seismicity sites, based on the initial equation of Joyner and Boore, including site amplification terms (Joyner & Boore, 1981, 1993):

$$log\left(PGV_H\right) = c_1 \log E + c_2 (\log E)^2 + c_3 log\left(R\right) - R + \sum_{i=1}^{n} c_{4i} S_i + \varepsilon \quad (5.1)$$

where: PGV_H - Horizontal Peak Ground Velocity measured in a horizontal plane, log E - seismic energy (or seismic magnitude, M), R - effective point-source distance, n - number of surface seismic stations, q_i - coefficients related to amplification determined with multiple regression analyses, S_i - set of binary parameters, 1 for soil sites and 0 for rock sites, ε - residual error described by Gaussian distribution with zero mean and nonzero variance, $c_1 \div c_4$ - coefficients estimated using multiple regression analysis. $R = \sqrt{Rh^2 + h^2}$ is an effective point-source distance that includes near-source distance saturation effects using effective depth parameter h that minimizes the sum of squares of residuals, where R_h - epicentral distance.

The second approach, used in post-mining areas in France, is the Bayesian regression introduced by Kuehn & Abrahamson (Kuehn & Abrahamson, 2018), which estimates the posterior distribution of the predictor variables, as well as the values of the standard deviations τ, σSS, and σS2S, and the values of the event terms and station terms for each event and station. It allows us to take into account measurement uncertainty in predictor variables, such as magnitude, in the development of a GMPE.

5.3. Shake-Maps

When an earthquake is detected (along with its characteristics, such as magnitude, epicenter location, and depth), the application of a GMPE provides estimates of the distribution of ground-motion parameters around the epicenter (shake-map of PGV). Then, observations recorded during the induced earthquake (i.e., ground-motion measurements and macroseismic intensities) are collected. The latter result is called a shake-map (Wald et al., 1999), which is an estimate of the ground motion usually in the form of intensity measures.

Depending on geological site characteristics, the number of seismic stations in the observed area and the number of post-mining earthquakes, two approaches are recommended to develop shake-maps.

1) Using the GMPE model on firm ground type A (Eurocode, EC8), the peak horizontal ground motion velocity, and shake- map of PGV_{H}, can be estimated using the following formula (Mutke 2019):

$$PGV_{H} = PGV_{Hrock} \cdot W_{f(f1\text{-}fn)} \tag{5.2}$$

where: $W_{f(f1\text{-}fn)}$ - amplification factor in the time domain for dominant frequency bandwidth (generally 1-10 Hz, but should be studied on site) - calculated as average values for the frequency range (Mutke & Dworak,1992; Dubiński et al., 2020), PGV_{Hrock} - peak horizontal ground motion velocity on firm rock (soils class *"A"* according to EC8). This model was used at the Kazimierz Juliusz testing site in the PostMinQuake project. This model is suitable in case of not too many seismic stations and of high variability of the Q overburden, as is the case in Polish and Czech testing sites (Mutke. & Holecko, 2012, Dubiński et al., 2020).

2) Applying the Bayesian shake-map approach introduced by Gehl et al. (Gehl et al., 2017), which is based on the updating of spatially correlated Gaussian fields. In this case, information about PGV_{H} or PGA_{H10} recorded at large number of seismic stations is required.

An example of the PGV_{H} and intensity I_{MSIIS} shake-maps elaborated based on the Mining Seismicity Instrumental Intensity Scale (MSIIS-22) in the Kazimierz Juliusz post-mining area of the Polish testing site, is presented in Fig. 5.1 (Deliverable report 5.3 of the PostMinQuake project, 2022).

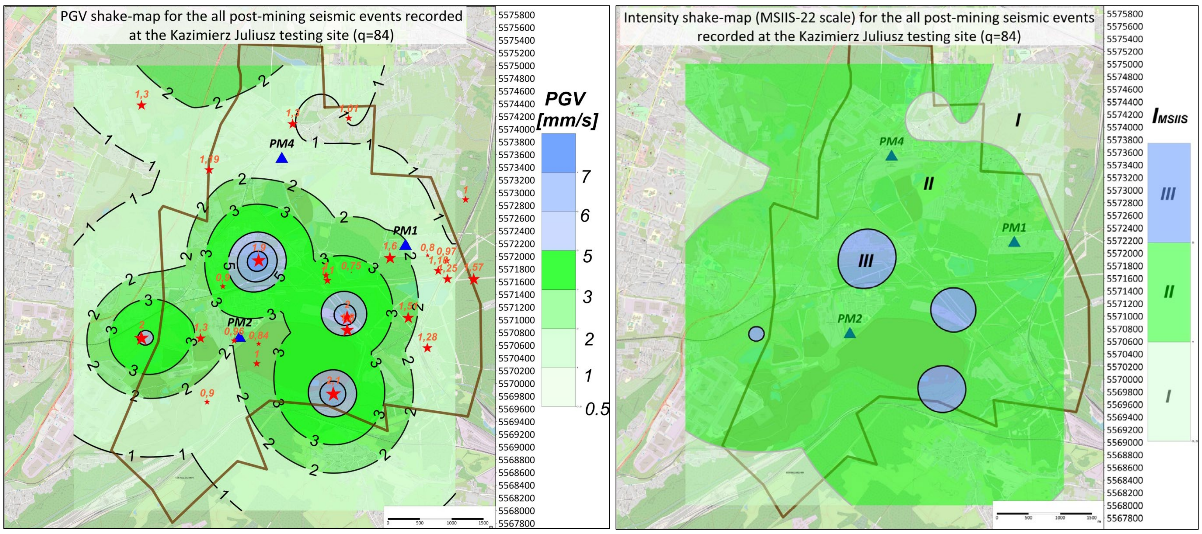

Fig. 5.1. PGV_{H} shake-map for all post-mining seismic events recorded at the Kazimierz Juliusz (KJ-Poland) testing site from January 2018 to July 2022, using the GMPE equation developed for hard soils (class A according to Eurocode 8) and the distribution of the amplification factor in the KJ testing site. The case was calculated for the 84th percentile - (on the left site). Intensity shake-map for all post-mining seismic events recorded at the KJ testing site from January 2018 to July 2022, using the PGV_{H} predicted for the 84th percentiles (on the right site)

An example of the PGV_H and intensity I_{MSIIS} shake- maps elaborated based on the Mining Seismicity Instrumental Intensity Scale (MSIIS-22) in the Gardanne post-mining area of the France testing site, is presented in Fig. 5.2.

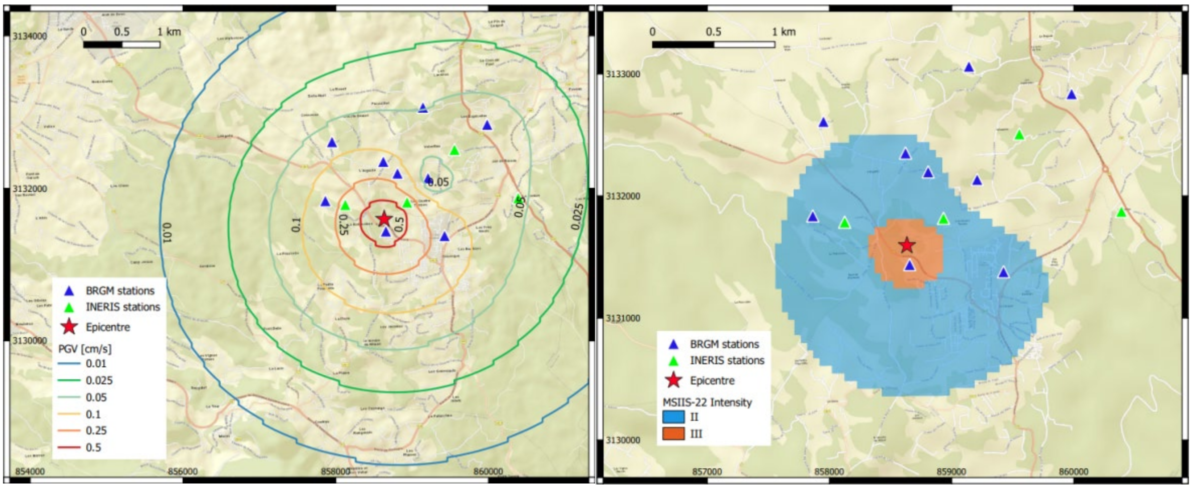

Fig. 5.2. PGV_H shake- map for the post-mining earthquake of April 19th 2019, using observations from 13 stations. Projection system EPSG:27573(left). Intensity shake-map (MSIIS-22 scale) for the post-mining earthquake–of April 19th 2019, using observations from 11 stations. Projection system EPSG:27573 (right)

5.4. Seismic scenario

The assessment of the probability of exceeding the magnitude of seismic mining and post-mining earthquake, and the average recurrence period, is determined based on statistical distributions of extreme values (e.g., Gumbel III distribution). The most important parameter characterizing the seismic risk, assuming knowledge of the distribution function $G(x) = P\{X < x\}$, is the so-called seismic hazard $R(x)$, determining the probability of mining and post-mining earthquake with a seismic magnitude x or higher, during time intervals D, expressed by the formula (Kijko, 1982, 1983) (5.3):

$$R_D(x) = 1 - G^D(x) \tag{5.3}$$

and predicted the average recurrence period T of the induced earthquake for the third Gumbels distribution with magnitude x (5.4):

$$T(x) = 1 / (1 - G(x)) \tag{5.4}$$

The probabilistic seismic scenario can be determined in a specific area, when the seismic database used for calculations meets the condition of similarity of geological, tectonic, geotechnical, and hydrogeological conditions, inducing seismicity in the area of research.

5.5. Seismic hazard assessment using the Mining and Post-Mining Seismic Instrumental Intensity Scale (MSIIS-22)

The Mining and Post-Mining Seismic Instrumental Intensity Scale (Deliverable report 5.3 of the PostMinQuake project, 2022)), was elaborated, based on the MSIIS-15 scale developed under the project COMEX (Deliverable report 1.4 of COMEX project, 2015) and GSIS-2017 scale developed in Central Mining Institute (Mutke 2019), and is applied to assess the impact of vibrations caused by mining and post-mining earthquakes on buildings, the perceptibility of vibrations by people, the nuisance level of using buildings and empirical dynamic resistance criterion for buildings.

The application of the instrumental intensity I_{MSIIS} requires determining appropriate parameters of velocity ground motion and duration of vibration:

- the maximum amplitude of horizontal vibrations velocity $PGV_{H\max}$, designated as the resultant of the horizontal maximum of vector length,
- duration of the horizontal ground motion velocity, t_H: The duration of the horizontal ground motion velocity is calculated from the integral of the sum of the squares of horizontal velocities in the x and y directions.

Those parameters can be determined based on:

- the direct instrumental seismic record of vibrations,
- the forecast values for the designed exploitation, determined based on the local empirical formula (GMPE).

The short form of the MSIIS-22 scale is intended to give a very generalized view of the scale and is presented in Table 5.2 and Table 5.3.

Table 5.2

Short form of the Mining and Post-Mining Instrumental Intensity Scale MSIIS-22 (more details in Deliverable 5.3 of the PostMinQuake project, 2022)

MSIIS-22 Degrees of seismic instrumental intensity I_{MSIIS}	Vibration velocity (mm/s)		Perceived shaking	The potential damage to buildings	Degrees of the harmfulness of vibrations in buildings S
	short time duration impact (t≤1.5 s)	long-time duration impact (t>1.5s)			
I	<1	<1	Not felt or very weak felt	none	S_1
II	1-5	1-5	weakly felt or felt indoors	none	S_2
III	5 - 20	5 - 10	Felt indoors by many people, and outdoors by few. The dishes rattle, and the hanging objects begin to swing.	none	S_3
IV	20 - 40	10 - 25	Felt strongly indoors by many people. Weak shaking of the entire building. Open windows and doors may close.	Intensification of existing damages	S_4
V	40 - 60	25 - 40	Felt strongly by most people. Many people are frightened and run outdoors. The furniture may be moved. The rocking of the whole building.	Damage to decorative elements. Fall of plaster pieces. Hair-line cracks in walls. Failure of partitions or gable walls	S_5
VI	60 - 90	40 - 60	Felt very strongly by most people. Most people are frightened and try to run outdoors. A few people lose balance. Objects fall from shelves in large numbers.	Slight single structural damage. Chimney fracture at the roof line. Large cracks in most walls, Failure of gable walls	S_6

VII	90 - 160	60 - 100	Most people have a problem with balance. Fear and panic. In single cases, heavy objects, such as television sets and furniture, can fall. Objects fall from shelves in a large number	Vibrations can damage the structural elements of buildings. The collapse of the chimney. Seismic event significantly reduces their dynamic resistance, when the low-frequency range of the main phase of horizontal vibrations, f <5 Hz take place. The stability of buildings is not threatened.	S_7
VIII	> 160	>100	The whole building sways and creaks, and furniture can move, sway, and overturn. People are very scared and run outside, most of them lose their balance. There is a danger to people outside the building - falling tiles, cornices, bricks from chimneys, and gable walls. Nuisance is unacceptable for buildings tenants.	Damage to structural elements threatening the stability of the structure. Ground motion can cause very large damage to the most severely stressed elements of building structures. Vibrations are particularly dangerous in the low-frequency range of the main phase of horizontal vibrations, f <5 Hz.	S_8

The following classes and sub-classes of buildings were distinguished from the observations:

Masonry buildings **(I)**

– simple stone masonry **(I-A)**
– unreinforced brick masonry **(I-B)**
– unreinforced brick masonry with RC floor **(I-C)**
– reinforced masonry **(I-D)**

Reinforced concrete wall structures buildings **(II)**

Reinforced concrete frame buildings **(III)**

The effects of vibration harmfulness expressed with the degree of harmfulness S, assigned to the instrumental measurement levels of the I_{MSIIS} seismic intensity, are different for different building structures and their technical conditions (Table 5.3).

Table 5.3

Relation of the degrees of the instrumental measurement intensity I_{MSIIS} with the degrees of harmfulness ***S*** depending on the type of building structure and its technical conditions

<table>
<tr><th rowspan="2">MSIIS-22 Degrees of seismic instrumental Intensity I_{MSIIS}</th><th>Masonry buildings (I): Simple stone masonry (I-A) Unreinforced brick masonry (I-B) Unreinforced brick masonry with RC floor (I-C)</th><th>Reinforced concrete wall structures buildings (II) and Reinforced masonry (I-D)</th><th>Reinforced concrete frame buildings (III)</th><th>Buildings in poor technical conditions</th></tr>
<tr><td colspan="3">Buildings in good technical condition</td><td></td></tr>
<tr><td colspan="5">Degrees of harmfulness S corresponding to degrees of instrumental intensity I_{MSIIS}</td></tr>
<tr><td>I</td><td>S_1</td><td>S_1</td><td>S_1</td><td>S_1</td></tr>
<tr><td>II</td><td>S_2</td><td rowspan="2">S_2</td><td>S_2</td><td>S_2-S_3</td></tr>
<tr><td>III</td><td>S_3</td><td>S_3</td><td>S_4</td></tr>
<tr><td>IV</td><td>S_4</td><td>S_3</td><td>S_4</td><td>S_5</td></tr>
<tr><td>V</td><td>S_5</td><td>S_4</td><td>S_5</td><td>S_6</td></tr>
<tr><td>VI</td><td>S_6</td><td>S_5</td><td>S_6</td><td>S_7</td></tr>
<tr><td>VII</td><td>S_7</td><td>S_6</td><td>S_7</td><td>S_8</td></tr>
<tr><td>VIII</td><td>S_8</td><td>S_7</td><td>S_8</td><td>Strong S_8</td></tr>
</table>

It is assumed that if the $I_{MSIIS-22}$ intensity meets the conditions of conditions of IMSIIS-22 **<I – III>** the resistance of buildings in good technical conditions is sufficient to transfer the impact of post-mining earthquake, without any visible structural element and finishing element damage.

The assessment of the levels of nuisance for buildings used by people, affected by post-mining earthquakes can be carried out according to the criteria presented in Table 5.4.

Table 5.4

Levels of nuisance for used buildings

Inconvenience	*Disruption of normal use*	*Perceiving the mining earthquake by people*	*$I_{MSIIS-22}$ intensity*
Imperceptible	Practically does not occur	Negligible	I - II
Small	Insignificant	Noticeable	III
Medium	Hinder the usage	Rising adverse reactions	IV - V
High	Interruptions in use may occur	Annoying and fear	VI-VIII

5.6. Empirical dynamic resistance criterion for buildings per the MSIIS -22 scale

The dynamic resistance of a building is defined by factoring in the potential damage it may sustain as a result of ground vibration. The MSIIS – 22 scale includes descriptions of building damage assigned to the individual vibration intensity degrees; dynamic resistance levels can therefore be determined in close connection with this scale.

Definitions of dynamic resistance for buildings

Five levels of dynamic resistance are defined within the MSIIS-22 scale, determined according to the possible mining and post-mining earthquake effects that may occur as described in the scale, where each successive level entails a lower building resistance to earthquakes:

Full dynamic resistance – entails the ability to assume additional forces generated in the building as a result of mining and post-mining induced earthquakes without the occurrence of visible structural element and finishing element damage.

Partial – high dynamic resistance – entails the ability to assume additional forces generated in the building as a result of mining and post-mining earthquake effects with acceptable non-structural and finishing element damage.

Partial – acceptable dynamic resistance – entails the ability to assume additional forces generated in the building as a result of mining and post-mining earthquake effects without building stability loss and without structural element load capacity and rigidity loss. Non-structural and finishing element damage may occur (including major damage) as well as single structural element damage.

Partial–conditional dynamic resistance – entails a state where additional forces generated in the building as a result of mining and post-mining earthquakes provoke structural element damage, which influences the safety of the building structure. The upper limit of this state is determined by the critical load capacity of the weakest structural element.

Unacceptable dynamic resistance – very poor data set up till now.

The dynamic resistance of buildings depends on their geometric and structural-material properties and technical condition. The dynamic resistance levels, referenced to the MSIIS-22 intensity for buildings with various structures and in good technical condition, are presented in graphically in Table 5.5.

Table 5.5

The levels and thresholds of the empirical dynamic resistance according to the MSIIS-22 scale for buildings in the good technical condition

	Buildings in good technical condition			
Degree of measured seismic intensity (MSIIS-22)	Masonry buildings (I): **Simple stone masonry (I-A)** Unreinforced brick masonry (I-B) Unreinforced brick masonry with RC floor (I-C)	Reinforced concrete wall structures buildings (II) and reinforced masonry (I-D)	Reinforced concrete frame buildings (III)	
	Dynamic resistance levels			
I	**full**	**full**	**full**	
II	**full**	**full**	**full**	
III	**full**	**full**	**full**	**Harmless vibration threshold**
IV	**high**	**full**	**high**	
V	**acceptable**	**high**	**acceptable**	
VI	**conditional**	**acceptable**	**conditional**	
VII	**conditional**	**conditional**	**conditional**	**Structural safety threshold**
VIII	**unacceptable**	**unacceptable**	**unacceptable**	

Dynamic resistance levels, referenced to the MSIIS-22 intensity for buildings in a poor technical conditions, are presented in graphic form in Table 5.6.

Table 5.6

The levels and thresholds of the empirical dynamic resistance according to the MSIIS-22 scale for buildings in poor technical condition

	Buildings in bad technical conditions			
Degree of measured seismic intensity (MSIIS-22)	Masonry buildings (I): Simple stone masonry (I-A) Unreinforced brick masonry (I-B) Unreinforced brick masonry with RC floor (I-C)	Reinforced concrete wall structures buildings (II) and reinforced masonry (I-D)	Reinforced concrete frame buildings (III)	
	Dynamic resistance levels			
I	**full**	**full**	**full**	
II	**full**	**full**	**full**	**Harmless vibration threshold**
III	**high**	**full**	**high**	

IV	**acceptable**	**high**	**acceptable**	
V	**conditional**	**acceptable**	**conditional**	
VI	**conditional**	**conditional**	**conditional**	**Structural safety threshold**
VII				
VIII	**unacceptable**	**unacceptable**	**unacceptable**	

Five levels of dynamic resistance defined within the MSIIS-22 scale, are determined according to the possible mining and post-mining earthquake effects that may occur as described in the scale, where each successive level entails a lower building resistance to aforementioned earthquakes. Checking the dynamic resistance of the building consists in demonstrating that the value of the building resistance measure determined as a criterion according to the MSIIS-22 scale is not lower than the maximum *d* horizontal vibration velocity PGV_H in the building foundation.

5.7. Recommendations and conclusions

The assessment of seismic hazards in post-mining areas is inextricably linked to the appropriate monitoring of induced seismicity. The proposed rules for conducting seismic observations on a regional scale to assess seismicity and engineering parameters of surface vibrations, and on a local scale to assess the locations of potential sinkhole zones.

To determine the level and effects of post-mining earthquakes, it is necessary to know the vibration parameters at the assessed site. For this purpose, ground motion prediction equations (GMPE) and spatial variation of ground motions for sites were recommended. These equations relate ground motion parameters, to sets of independent variables connected with the characteristic of the source, path and site.

Depending on the characteristics of the geological site, the number of seismic stations in the observed area and the number of post-mining earthquakes, two approaches can be recommended (see Section 5.3) to develop PGV_H shake- maps and MSIIS-22 intensity shake-maps.

To assess the intensity of mining and post-mining earthquakes, the MSIIS-22 instrumental intensity scale was developed in the PostMinQuake project, using the parameter of Horizontal Ground Motion Velocity PGV_H, vibration duration, and vibration frequency.

The effects of vibration harmfulness expressed with the degree of harmfulness S, assigned to the instrumental measurement levels of the I_{MSIIS} seismic intensity, are different for different building structures and their technical condition.

The assessment of the levels of nuisance for used buildings by people, affected by post-mining earthquakes was elaborated in the MSIIS-22 scale as well.

The MSIIS-22 intensity scale allows for an empirical assessment of the resistance of buildings to mining and post-mining earthquakes. Comparison of the dynamic resistance of buildings, taking into account the type of building and its technical condition, with the I_{MSIIS} forecast of instrumental intensity levels from post-mining earthquakes, allows for the assessment of the safety of transferring dynamic impact through buildings.

The observations on testing sites in Gardanne, Kazimierz Juliusz, and Ostrava-Petrvald positively verify the operation of the MSIIS-22 scale, according to which the vibrations were at maximum intensity level of degree III. The seismicity forecast made in the PostMinQuake project for the Kazimierz Juliusz testing site indicates the possibility of an increase in seismic hazard as the water table is further reconstructed.

6. DAMAGE ASSESSMENT OF POST-MINING EARTHQUAKES ON BUILDINGS AND INFRASTRUCTURE[6]

As a result, a growing body of literature has started to look into the damaging potential of induced earthquakes and the specificities of associated ground-motion records. However, most of the relevant studies in the literature are related to on-going exploitation processes that trigger seismic events, such as shake gas exploitation by hydraulic fracturing (Edwards et al., 2021; Cremen & Werner, 2020), hydraulic stimulation of geothermal wells (Broccardo et al., 2020), geological carbon storage (Templeton et al., 2021) or natural gas production (Crowley et al., 2019). Risk analyses related to mining induced seismicity are much scarcer. Camelbeek et al., 2022 have reviewed the damaging potential of past mining earthquakes in the Hainaut coal basin (Belgium), through the analysis of macroseismic intensities in the EMS-98. An analysis of more recent damage due to mining earthquakes in Upper Silesia Coal Basin (Poland) has been performed by Pilecka et al. (2021): the authors have identified multiple damaged buildings in the epicentral zone of a M_L (local magnitude) 3.6 mining induced event, examining the severity of the damages in light of the Mining Seismic Instrumental Intensity Scale (MSIIS-15 – Mutke et al., 2015).

While the differences between natural and induced ground motions in terms of structural response are not systematically evidenced (e.g., Whyte & Stojadinovic, 2014; Bal et al., 2018), specific tools (i.e., vulnerability models, damage scales) should still be carefully considered, in order to account for recurring low-magnitude, low-depth seismic events. Therefore, the present chapter aims at exploring the state-of-the-art approaches for vulnerability and damage assessment, while providing recommendations for the specific context of post-mining earthquakes. The section 6.1 focuses on the main vulnerability assessment approaches that have been developed for natural earthquakes. Then, in the section 6.2, a macroseismic scale adapted to mining earthquakes is introduced and discussed. These approaches are then applied to illustrative damage scenarios in the section 6.3, before final conclusions and recommendations in the section 6.4.

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6.1. Application of seismic fragility models

The damage assessment of a given structure is usually performed thanks to a fragility model, which represents the probability to reach or to exceed a given damage state, for a given level of ground shaking. Usually, damage states are defined by a consistent damage scale that describes a gradation in the severity of the sustained damages, e.g. from no damage to complete destruction. In the case of natural earthquakes, a reference scale is the European Macroseismic Scale EMS-98 (Grünthal, 1998), which contains six discrete states: DS0 – no damage, DS1 – negligible to slight damage, DS2 – moderate damage, DS3 – substantial to heavy damage, DS4 – very heavy damage, DS5 – destruction. In general, the evaluation of the functional form of the fragility model (i.e., the relationship between the ground shaking level and the probability of damage) is done by exploiting results of numerical simulations (i.e., structural models subjected to external loadings) or empirical data (i.e., damage datasets from past mining earthquakes).

Alternatively, the Risk-UE Level 1 method, a semi-empirical vulnerability approach based on the EMS-98 framework, has been developed by Lagomarsino & Giovinazzi (2006) as an outcome of the Risk-UE project (Milutinovic & Trendafiloski, 2003). This method relates intensity, vulnerability and average damage level μ_D using the equation below. It is based on several concepts:

1) The macroseismic intensity $I_{EMS\text{-}98}$, which is used as an intensity measure.
2) Vulnerability classes and semi-empirical mean vulnerability functions based on Damage Probability Matrices (DPM).
3) A damage distribution (beta distribution), relating the mean damage μ_D to probabilities of being in each of the EMS-98 damage states.

The association of a building with a specific vulnerability class is defined by a vulnerability index. The index values are arbitrary as they only represent a score that quantifies the seismic behaviour of a building. The vulnerability index ranges from 0 to 1. Values near 1 represent the most vulnerable buildings. Values close to 0 are buildings with a high level of seismic design. The average damage level μ_D is then defined as follows (6.1):

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25\,V_I - 13.1}{2.3}\right)\right] \tag{6.1}$$

Recently, a large research effort has been dedicated to the hazard, risk and loss analysis of the Groningen area (Netherlands), due to seismicity induced by natural gas exploitation. As a result, a set of fragility models have been specifically developed for the building typologies present in the area. While this type of induced seismicity is not directly comparable to the seismicity due to post-mining (neither in terms of magnitude ranges nor in terms of trigger mechanisms), it remains interesting to identify related fragility models and the way they have been assembled. In Crowley & Pinho (2020), based on experimental tests for the calibration of structural properties of the Groningen building stock, numerical models have been developed and subjected to non-linear dynamic analyses. As a result, fragility models are available for 35 building typologies or vulnerability classes (i.e., unreinforced masonry buildings, cast-in-place concrete and prefab buildings, timber and steel frame buildings). The selected intensity measure is the average of spectral accelerations over a range of periods (between 0.01 and 1.0 s). Several damage states are covered by the fragility models:

- damages states DS2 (minor structural damage) and DS3 (significant structural damage), which are comparable to the EMS-98 damage scale,
- collapse states CS1, CS2 and CS3 (from partial collapse to global collapse).

Other versions of analytical fragility functions for unreinforced masonry and reinforced concrete buildings in Groningen (7 vulnerability classes) have been proposed by Crowley et al. (2019). Regarding non-structural damage (damage state DS1 according to EMS-98), (Crowley et al., 2019) have applied an empirical approach, by using observed damage data from past events in the Groningen area, for 3 typologies, namely farmhouses, low-rise unreinforced masonry housing pre-1940, and low-rise unreinforced masonry housing post-1940. Finally, another study by Crowley et al. (2018) has dwelt on the threat posed by falling chimneys. Therefore, the authors have recommended applying chimney fragility functions that have been empirically derived by Taig & Pickup (2016) for the Groningen area. These functions take the form of probability bands of chimney failure, for various ranges of Peak Ground Acceleration (PGA).

From this brief review of existing methods and models, it appears that conventional models may be applicable to the case of induced earthquakes, theoretically. However, several points may require additional care and improvement:

- The studied areas may not coincide with areas usually exposed to natural seismicity, with different typology distributions (e.g., presence of highly vulnerable structures or non-seismically designed buildings).
- There is a need to focus on lower damage grades, related to non-structural elements.
- Due to the reduced area of the earthquake impacts and the relatively short history of induced seismicity, the lack of empirical data prevents an extensive calibration of existing fragility models.

6.2. A macroseismic scale adapted to mining and post-mining earthquakes

Alternatively, the latest version of the Mining Seismic Instrumental Intensity Scale (MSIIS-22- refer to the chapter 5), which is based on MSIIS-15 (Mutke et al., 2015) and on damage data collected in Upper Silesia Coal Basin (Poland) during mining earthquakes, follows a similar framework as EMS-98, in terms of:

1) Definition of a macroseismic intensity $I_{MSIIS\text{-}22}$ (eight discrete levels from I to VIII), which is estimated from a direct relationship to Peak Ground Velocity (PGV).
2) Definition of six building vulnerability classes:
   - Masonry buildings (I): Unreinforced brick masonry (I-B) and Unreinforced brick masonry with RC floor (I-C).
   - RC wall structures buildings (II) and reinforced masonry (I-D).
   - Reinforced concrete frame buildings (III).
   - The three classes above are further divided into buildings in "good " or "poor" technical condition, amounting to six classes in total.
3) A qualitative damage scale, relating $I_{MSIIS\text{-}22}$ to damage severity for the various vulnerability classes.

Compared to EMS-98, the MSIIS-22 scale only contains eight intensity degrees and it does not reach complete structural damage (i.e., the highest damage grade is described as 'damage to structural elements threatening the stability of the structure'). Instead, the lowest grades focus on the expansion of pre-existing damages such as the extension of hairline cracks. This observation is in line with the need to use vulnerability and damage models that are consistent by low magnitude of mining earthquakes.

Another difference between the two macroseismic scales lies in the determination of macroseismic intensity. In MSIIS-22, the intensity degrees are directly defined by PGV intervals (i.e., similar to instrumental intensity), while the link between PGV and $I_{EMS\text{-}98}$ is usually ensured by empirical ground-motion intensity conversion equations (GMICE). A brief comparison between the PGV levels that would lead to corresponding macroseismic intensity degrees shows that, for lower intensity degrees, there is almost one degree of discrepancy between $I_{EMS\text{-}98}$ and $I_{MSIIS\text{-}22}$ (with $I_{MSIIS\text{-}22}$ corresponding to higher PGV values): this difference should be further investigated.

6.3. Application to damage scenarios

In order to illustrate the use of the aforementioned models, damage scenarios are performed on the Gardanne Coal Basin (France). To this end, the post-mining induced earthquake of April 19th 2019, (moment magnitude M_w 1.7) is considered, for which a shake-map in terms of

PGV is estimated. Based on this event's data and on the building exposure dataset in the surrounding municipalities (i.e., distribution of building typologies at the level of IRIS (Incorporated Research Institutions for Seismology) zones, which are statistical spatial units below the municipal level), three damage assessment methods are applied, as shown in Fig. 6.1:

1) Method A: use of macroseismic intensity I_{EMS-98} and of the Risk-UE Level 1 method to get distributions of EMS-98 damage grades (D1: negligible to slight damage; D2: moderate damage).
2) Method B: direct application of the definition of the $I_{MSIIS-22}$ scale, which introduces levels of remaining structural dynamic resistance (from 'Full' to 'Unacceptable') for the different intensity degrees and building types. In particular, the level 'High dynamic resistance' (as opposed to 'Full') is relevant in the induced seismicity context, because it implies that the structure has started to get solicited by the ground-motion loading, but without leaving the elastic state.
3) Method C: use of macroseismic intensity $I_{MSIIS-22}$ and adaptation of the Risk-UE Level 1 method to empirical damage data from Upper Silesia coal basin (Poland) to fit mean vulnerability functions based on Damage Probability Matrices. Distributions in terms of MSIIS-22 damage grades (S4: intensification of existing damages; S5: damage to decorative elements) are obtained.

As the impacts of the scenarios are very low, it is more relevant to spatially represent a qualitative gradation of the represented indicators. Thus, a distinction is made within the IRIS zones regarding a lower (pale color) or higher (dark color) sensitivity to these damage levels. As the intensities (both EMS-98 and MSIIS-22) estimated are very low, the resulting level of damage is negligible as well. Almost all of the residential buildings present no damage. The rest of the buildings (a non-significant percentage) is mainly associated with non-significant damage. These findings are in line with the actual impact of this earthquake, since no damages have been reported across the area, making it difficult to spot any significant difference between the damage scales for this range of intensities.

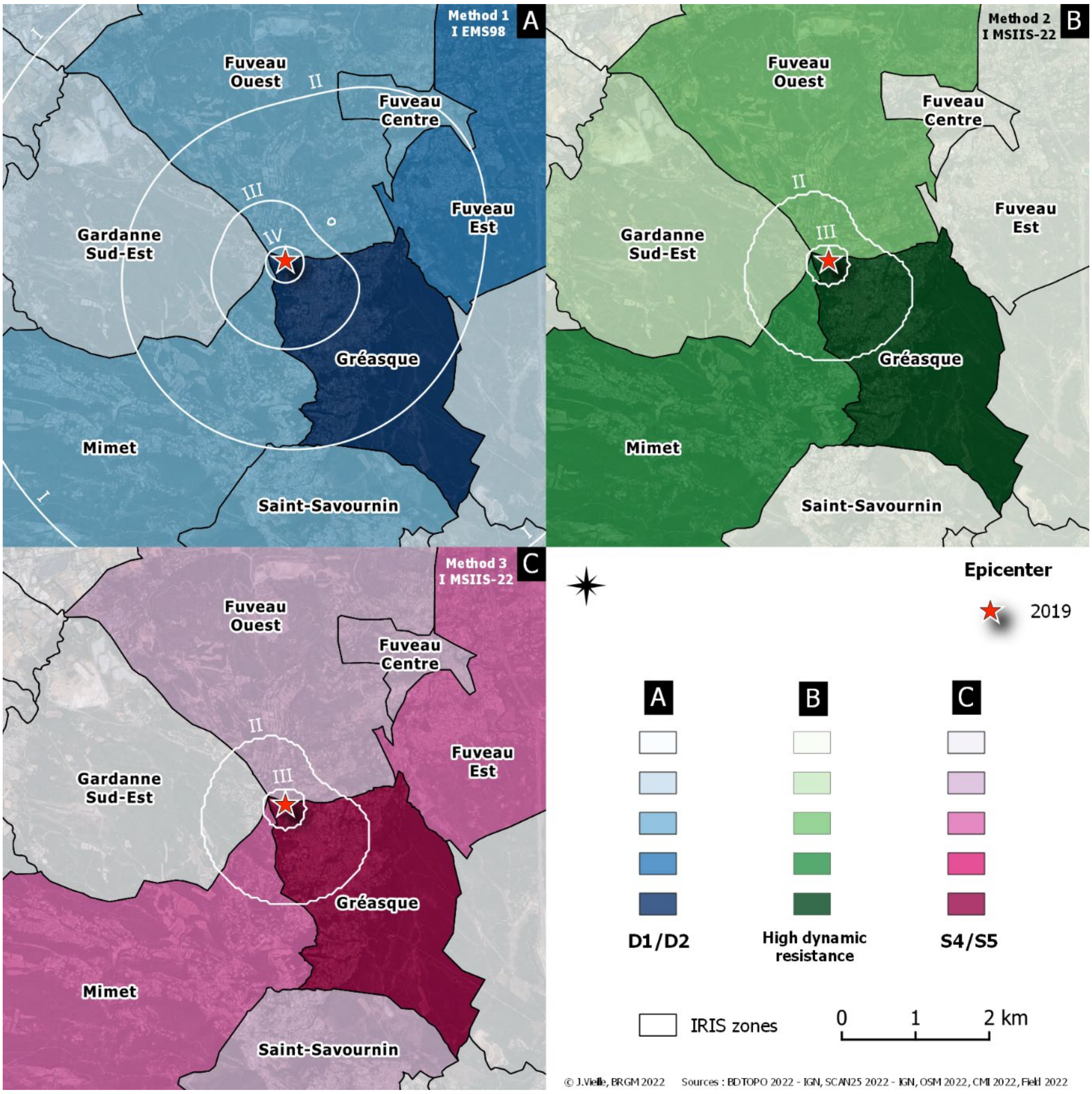

Fig. 6.1. Damage scenario results of the April 19th 2019, post-mining earthquake (M_W 1,7) using method A (based on EMS-98 intensity), methods B and C (based on MSIIS-22 intensity). The ”gradation of damage” shown in the figure is statistically meaningless (variations of very small fractions of percentages), and it is just shown here to illustrate the ability to rank the various exposed built areas. Map A represents the gradation of buildings where the risk of damage ranges from negligible to slight, map B represents the risk of damage gradation for buildings with high dynamic resistance, map C represents gradation of zones where can occur intensification of existing damage or can occur new damage to decorative elements

6.4. Recommendations and conclusions

According to the available literature, there is no strong evidence of differences in terms of destructive potential or damage mechanisms between natural and induced ground motions. Conventional vulnerability and damage assessment methods based on the well-established EMS-98 framework have been applied to several risk analyses in induced seismicity contexts, without any major challenge. The main issue, however, pertains to the consideration of very low damages, such as the intensification of existing damages or the damage to decorative elements, which are frequent in the case of recurring low-magnitude induced earthquakes. The newly developed MSIIS-22 scale constitutes a promising alternative regarding this matter: yet, further calibration with more empirical damage data, preferably from additional coal basin areas, would be required before a consistent application of this framework.

Finally, whatever the fragility or the vulnerability approach chosen, the main steps needed to perform a damage scenario remain mostly the same:

- Estimation of the ground shaking field around the earthquake epicenter (e.g., distribution of ground-motion parameters via a shake-map).
- If needed, conversion of ground-motion parameters (e.g., PGV) into macroseismic intensity (I_{EMS-98} or $I_{MSIIS-22}$).
- Inventory of building typology distributions, for some predefined spatial zones (e.g., contour of municipalities, or higher resolution if available).
- For each zone, application of the fragility or vulnerability models of choice and aggregation of damage distribution statistics.

7. MONITORING STRATEGIES FOR SAFETY USE OF POST-MINING TERRAINS[7]

Underground mining operations are performed producing substantial structural and stress changes in the shallow underground. It is well known that mining can be accompanied by surface and underground deformation processes as well as seismicity. Such hazards are still present during the post-mining time period, i.e. after the closure of underground mines.

Underground instabilities of mine structure, formation and failure of deep cavities, fault friction reduction in response to mine flooding and triggering of local post-mining earthquakes are all processes which can take place during post-mining. The identification of such processes, their full understanding and discrimination and their modelling is possible, but still very difficult and challenging. A major challenge is the lack of underground monitoring, as underground facilities are generally no longer safe or accessible after the mines closure.

In the frame of the PostMinQuake project were investigated seismic and aseismic processes in former European mines to derive some monitoring guidelines and general recommendations towards surface monitoring of post-mining sites.

Understanding physical processes at former mines requires a multi-disciplinary monitoring, which is able to capture both seismic and aseismic processes and both shallower and deeper ones. Such monitoring should include at least the following components, whose contributions are discussed in the following sections:

- Near-surface geophysics (Section 7.1).
- Gravity (Section 7.2).
- Seismology (Section 7.3).
- Surface deformation (Section7.4).
- Hydrology (Section 7.5).

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General and method specific recommendations are summarised at the end of the chapter (Section 7.6).

7.1. Temporary near-surface geophysical surveys

The intensity of hazard of the surface deformation during the mine flooding process depends on the structure of the geological strata. These are not a continuous medium, but a set of rock blocks separated by tectonic discontinuities. In some regions, the coal seams and hard rock bodies are covered by sediment layers with variable thicknesses. Studies on the behaviour of post-mining landscapes show that the probability of surface deformation is high in areas of shallow exploitation of minerals and faults. In shallow exploitation regions, we can expect surface deformation processes, such as formation of sinkholes or subsidence throughs. In faulted zones, we can expect linear deformation of the surface (steps) or fissures, that can form a set of morphologically separated regions, partly undergoing uplift and/or subsidence. The rock mass near a central faulting plane is usually fissured. The detailed structural characteristics of the fissures are very important to constrain mechanical models and to assess the subsurface deformation hazard.

The structural characterization of fissuring processes in faulting zones can be inferred from temporary geophysical surveys. A long-term observation of the post-mining deformation patterns is crucial for shallow exploitation mining, especially in regions where the ratio between the primary mining void depth ($h+hn$) and its height (g) is lower than 10 (Fig. 7.1). Those regions are the most prone to the occurrence of sinkholes. The void migration ratio, usually denoted as Z, can be used as sinkhole hazard indicator, providing a proxy for the length of the void travel path to the surface (Kotyrba, 2005; Didier, et al., 2008).

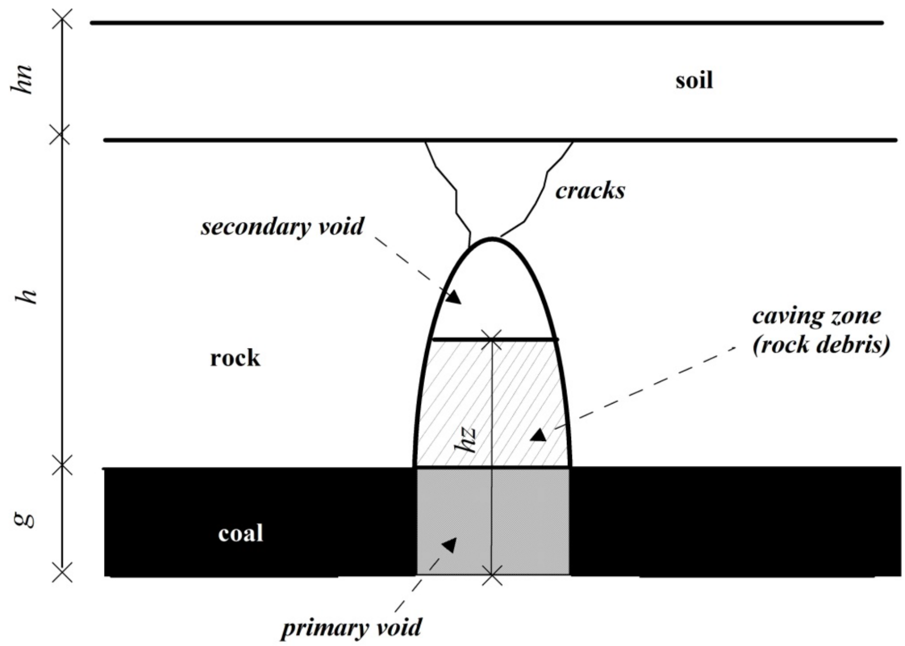

Fig. 7.1. Model of mining and post-mining voids embedded in the rock mass in regions of a shallow room and pillar mining (*hz* - the height of caved rock, *g* - primary void height, *h* - thickness of rock, *hn* - thickness of soil)

Due to various geotechnical conditions, which can be found in specific regions, the void migration ratio can change within wide limits. Post-mining rock mass can present two kinds of voids: primary (galleries, roadways, not collapsed chambers) and secondary ones (voids over collapsed regions in the rock mass). The process of transformation of the primary void to a secondary one is dynamic and more likely to occur during the flooding process. This justifies the need for periodical geophysical surveys in areas of high sinkhole deformation hazards. Modelling and interpretation of geophysical data from those surveys allow for mapping the position of voids in the rock mass. This applies in particular to gravimetric, electro-resistivity and seismic measurement data.

Data from temporary geophysical surveys supplemented by test borehole results can be used to discriminate among the presence of primary and secondary voids and to estimate their dimension. This, in turn, enables a progressive update and re-quantification of the related threat.

For example, the analysis of seismological data collected in the PostMinQuake project allowed us to infer that seismic signals recorded at the Kazimierz-Juliusz mine were mostly induced by the collapse of post-mining voids left in geological strata. If these events occur at depth, only the resulting ground shaking can pose a threat at the surface. Conversely, shallow collapses may additionally produce a significant surface deformation. Since each of these events contribute to changing the internal structure of the rock mass, it is mandatory to repeatedly perform geophysical surveys and to repeatedly analyse seismic data, which enable monitoring temporal changes in the former mining structure and the near-surface strata. The behaviour of these relatively thin layers in most cases controls whether local deep processes in the rock mass will impact the surface and pose a danger to people and infrastructures.

Different techniques can be used for the characterization of the geological structure, detection and imaging of post-mining voids and observation of their temporal evolution, either relying on surface (Kotyrba et al., 2015) or borehole (cross-hole tomography with the use of elastic or electromagnetic waves. As the penetration depth (PD) of land geophysical methods is limited, we recommend grouping them depending on the PD factor, as follows:

- Ground penetrating radar - GPR (PD up to 20 m).
- Microgravity (PD up to 30 m).
- Electro-resistivity profiling and ERT (PD up to 60 m).
- Seismic refraction without explosives or vibrators as a source of elastic waves (PD up to 50).
- Seismic reflection with explosives or vibrators as a source of waves (PD unlimited).

It should be outlined that only the GPR method allows the detection of single cracks due to its high horizontal resolution (potentially detecting cracks with opening < 1 cm). Formed cracks cause diffraction phenomena of electromagnetic waves that can be observed in GPR data sets (Toshioka et al., 1995; Kotyrba & Stańczyk, 2017; Kotyrba & Kortas, 2023). The other above-mentioned geophysical methods allow the detection only of groups of fissured rocks as fractured zones in the rock mass, with a thickness larger than 2-5 m. Therefore, we recommend the GPR method for a detailed characterization of the complex geological structures with faults in regions where the depth to the top of the rock mass is lower than 20 m.

The mining leaves in geological strata voids, cracks and zones of variously defragmented rocks, which are subjected to gravity. To study the behaviour of a rock mass transformed by mining operations, it is necessary to know the near-surface layers structure. These new elements interact with discontinuities in rock strata caused by natural geological processes such as faulting and weathering. The rock mass in the vicinity of the faulting plane is usually fissured. The fissured zone width, as well as the fracture intensity and its characteristics, depend on the fault length and throw. These geometrical factors may not be determined without a specific site examination. This issue is of great importance in hydro-mechanical modelling as well as in the determination of the causes and liability for mining damages on post-mining lands. Therefore, the data from temporal surveys is used in hydro-mechanical studies.

7.2. Continuous and periodic monitoring of gravity

The seismicity in areas of abandoned mines in the process of flooding has a similar origin as the seismicity observed during the process of mining in the rock mass. Both these processes change the density distribution in the rock mass over time and create local areas where additional stresses appear in the geostatic stress field. Such seismogenic processes take place in particular in the following regions:

– regions where the mining (primary) and secondary post-mining voids are collapsing,
– regions unevenly saturated by water,
– regions with residual tectonic stress (faults).

The main force which enables and governs these phenomena is gravity. Gravity can be monitored by continuous and periodic measurements. Continuous monitoring can detect the Earth's tides (Fig. 7.2), which can be temporarily disturbed by ground movements and seismic vibrations produced by near and distant sources. For sources which are located near gravity observation point (e.g. epicentral and near epicentral zones of mining and post-mining earthquake) were observed additional deflections to the plumb line caused by the shock wave travelling from the source of the mining and post-mining earthquake. This feature can be used to discriminate local mining and post- mining earthquakes from natural earthquakes.

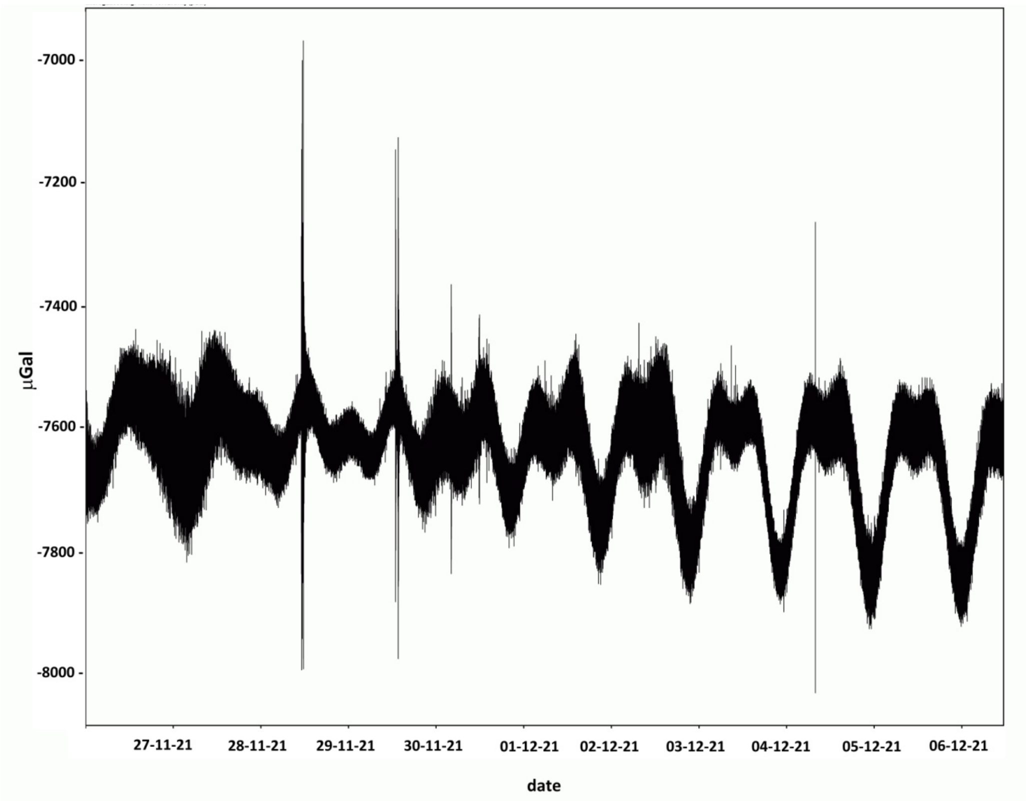

Fig. 7.2. Gravity oscillations *g* (vertical axis) recorded by a MicroLacoste station in Katowice over a period of 9.5 days. Long-term oscillations correspond to the tides of the Earth's crust, while short-duration anomalies correspond to ground movements and vibrations caused by mining induced earthquakes and earthquakes. Live gravity data are available (www.gog.gig.eu)

Experiences gathered during the realisation of the EPOS-PL project show that the data from continuous gravity measurements correlate well with seismic data collected from seismological networks and supplement them with additional information about the characteristics of ground motion and the source mechanism of specific mining earthquakes (Mutke et al., 2019; Kotyrba, 2022, and Siwek, 2022). The relation between amplitude of the gravity perturbation as a function of the epicentral distance from mining earthquakes in the Upper Silesia Coal Basin region, for a data set of mining earthquakes collected by GRSS (Upper Silesian Regional Seismological Network) net with local magnitude higher than M_L 2 is shown in Fig. 7.3 (Kotyrba et al., 2020; Kotyrba & Kortas, 2020).

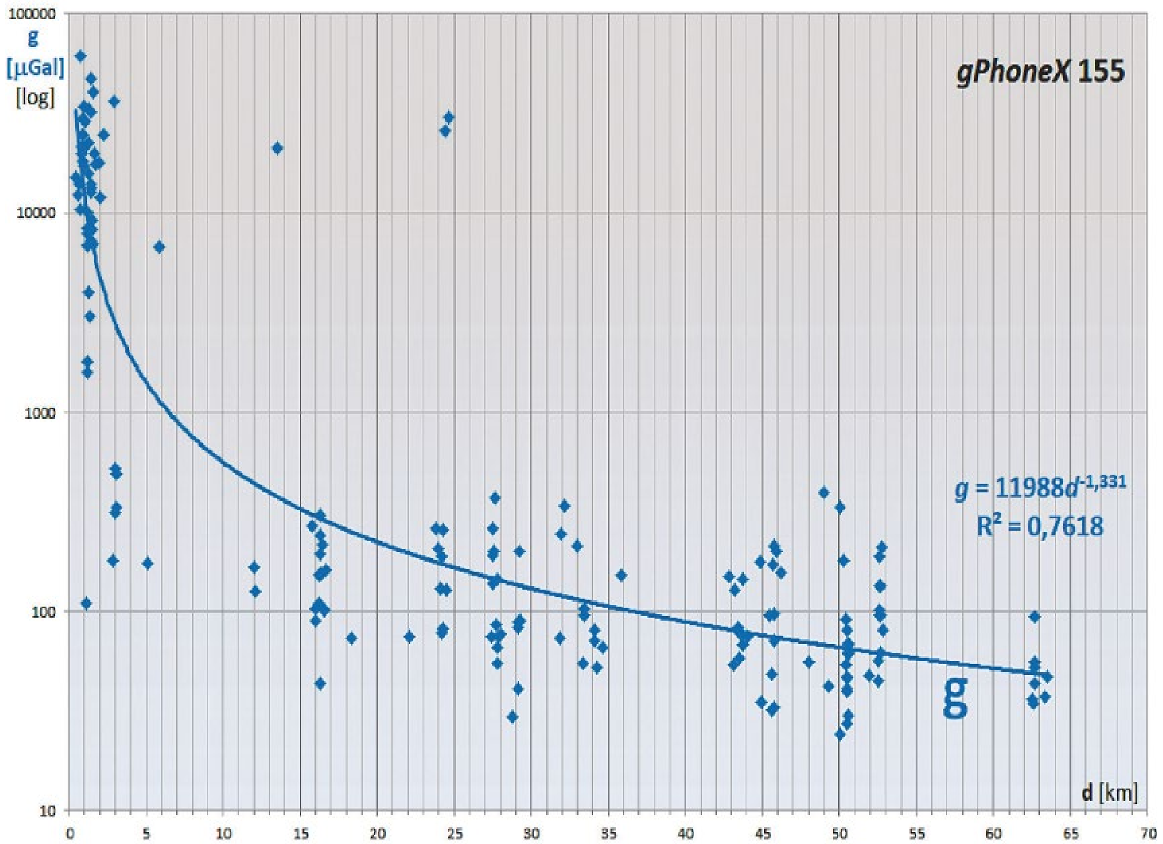

Fig. 7.3. Relationship between the maximum amplitude of gravimetric signals *g* (logarithmic scale) and the epicentral distance *d* from the mining earthquake

In the case of periodical measurements, were observed temporal changes in the bulk density of the surveyed rock mass. This can be caused by the rock mass relaxation and release of seismic energy, followed by changes of the surface morphology (e.g. subsidence, uplift).

Filling the voids left after mining with water changes the mechanics of the rock mass. Key points of that mechanics are borders of exploitation regions and fault planes depicted in a structural model of rock mass (Fig. 7.4) and the amplitude of the gravity field change observed (Fig. 7.5).

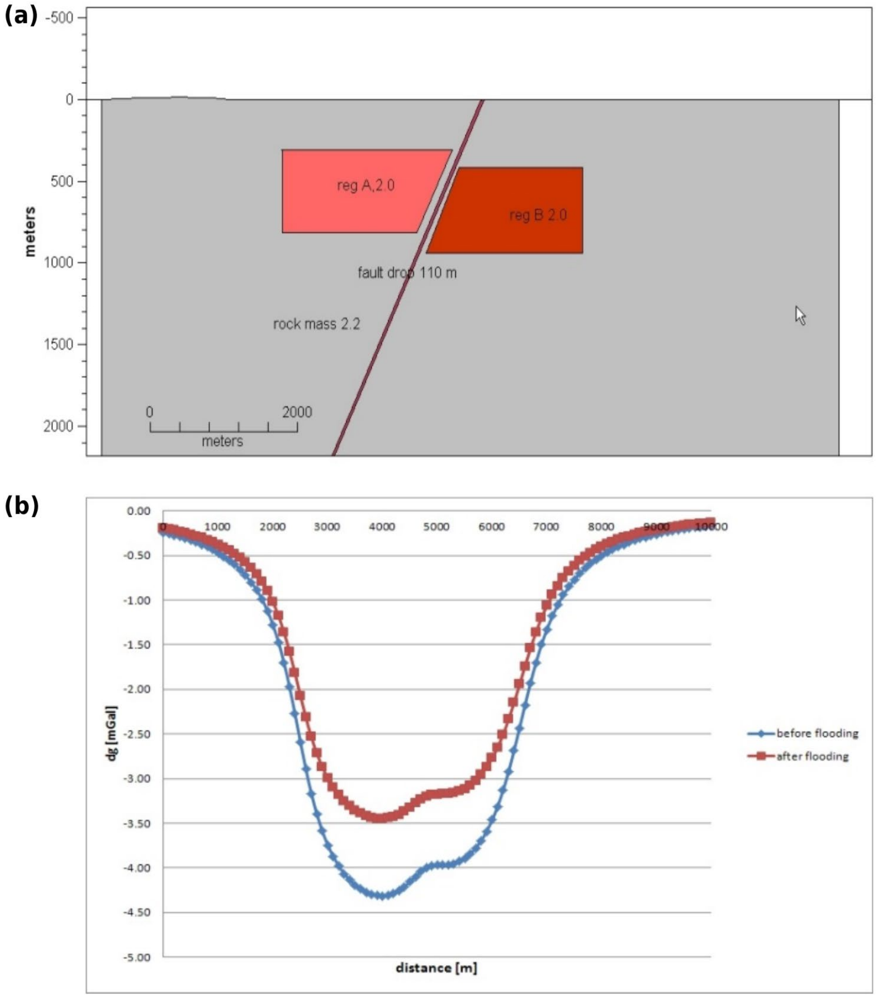

Fig. 7.4. Conceptual, structural 2D density model of the rock mass with two abandoned mining regions at different depths, separated by fault plane (a) and the simulated change of gravity (dg) after water rebound (b)

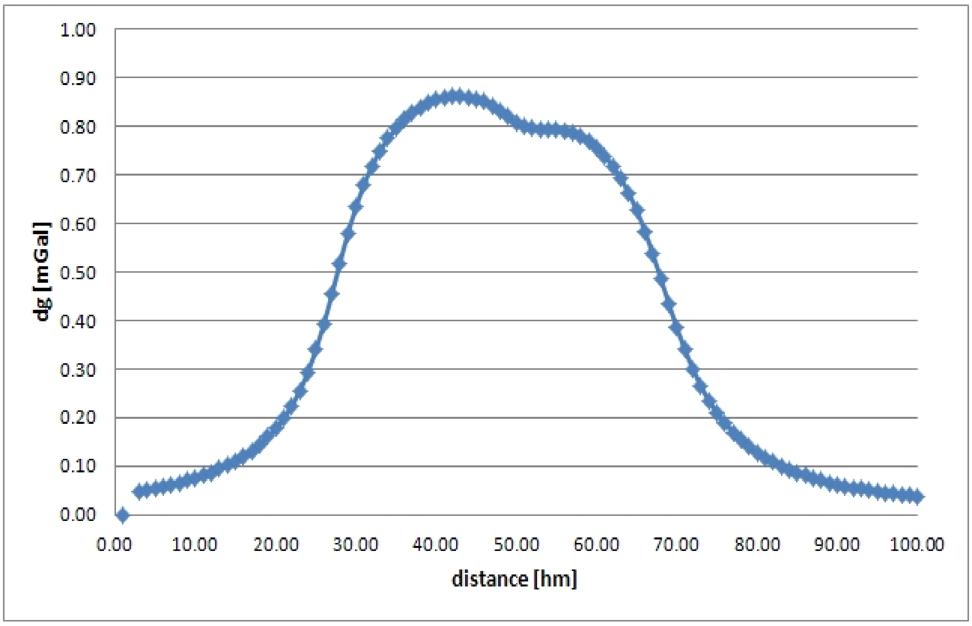

Fig. 7.5. 2D differential simulated gravity (dg) distribution after the flooding of regions A and B, as shown in Fig. 7.4

Gravity measurements have been introduced relatively recently to study and monitor the seismic activity induced by mining and post-mining, and at present, remains in a development phase. Similar to seismological observations, the possibility to detect post- mining earthquakes in continuous gravity recordings depends on the earthquake magnitude and its distance to the gravity station. Based on the experience collected from the gravity monitoring in the Upper Silesian Coal Basin, we recommend using this method only as a supplement to seismological monitoring. In such a case, the deployment of one gravity measuring station in the area of the former mine during flooding can be sufficient for an integrated seismological-gravimetric monitoring. Periodic gravity measurements provide spatial information about the location of regions where the gravity changes are anomalous. These can be identified by comparing time series (differential data). Differential maps created from measurement data obtained at different times allow for mapping areas where the processes of lowering or increasing the average density of the rock mass occur. As a rule of thumb, it is good practice to carry out periodic gravity measurements at a grid of points, with a lateral spacing of ~500-1000 m. Such measurements are useful for the interpretation of the gravimetric data, and specifically to identify temporal changes of the absolute gravity and Bouguer anomaly values.

7.3. Seismic monitoring and seismological techniques

Post-mining seismicity has been observed at several closed mines, e.g. in France, Germany, Poland and Czech Republic (Primo Doncel et al., 2023), and can locally pose a considerable seismic hazard. Current observations indicate that post-mining seismicity is heterogeneous in terms of maximum magnitude, seismicity rate and spatiotemporal evolution of seismicity. Furthermore, differences in lateral and depth extent of seismicity, as well as in the range of magnitudes of seismic events, have been observed, when comparing mining and post-mining seismicity.

A successful monitoring and analysis of post-mining seismicity depends in large measure on the setup of an adequate seismic monitoring. Seismic monitoring setups at different post-mining sites tend to be very heterogeneous, resulting in significant differences regarding the quality and completeness of post-mining seismic catalogues. Poor monitoring setups may not be able to detect post-mining seismic events when they have too low magnitudes or when they occur far from seismic stations.

Post-mining seismic monitoring is in general challenging, for the following reasons:

- the seismic monitoring targets, in most cases, relatively weak magnitude earthquakes,
- the seismic monitoring generally lacks underground seismic stations within the former mines, and it relies on surface seismic records only; in particular, the on-accessibility to

former underground infrastructures may substantially decrease the quality of the seismic monitoring in comparison to mining periods.
- surface stations which compose the post-mining monitoring installation are often affected by large anthropogenic noise, being often within or close to urbanised areas.

These premises make clear the challenges of post-mining monitoring, which is even more difficult than during active mining. Preserving the monitoring performance and detection completeness as in the active mining period, which is important for a robust comparison of mining and post-mining seismicity, may only be achieved through the installation of additional seismic stations at the surface.

The second condition for successful assessment of post-mining seismicity concerns the adoption of advanced seismological techniques, able to identify and characterise weak to moderate seismicity. These advance methods do not only allow for detection and location of post-mining seismicity, but also enable the study of focal mechanisms or moment tensors, which describe the type of failure and the orientation of active faults, and a relative characterization of seismic clusters, which include seismic events with similar locations or similar characteristics.

Network optimization procedures (Hardt & Scherbaum, 1994; Kraft et al., 2013; Toledo et al., 2018) can substantially improve the monitoring performance, particularly for the challenging case of post-mining seismicity.

SeisNetPy (https://git.gfz-potsdam.de/pniemz/seisnetpy), a free, open-source python toolbox, was specifically designed for network optimization in post-mining environments. The tool implements the algorithm of Toledo et al. (2018) and offers a range of new features, such as for the assessment of noise conditions via online satellite-based land-use maps.

The analysis of post-mining seismicity should focus on the following targets: detection, location, magnitude estimation, focal mechanisms or moment tensor inversion, classification and clustering, and statistical analysis of the seismicity. Since the characteristics of post-mining seismicity are not specifically different from those of induced seismicity affecting mines or other geomechanical operation sites, the techniques to be applied for the analysis of post-mining seismicity are similar to those used in those environments. We review them below, sorted by the different types of analyses.

Detection. The detection of post-mining seismic events, requiring the manual or automated identification of post-mining events, based on the identification of their seismic signals. As introduced above, earthquake detection can be challenging in post-mining environments, because of the weak magnitudes of the target seismicity and the monitoring conditions. Ideally, automated detection tools can be implemented, with several tools available for this goal, including automated full-wave form-based earthquake detection (López Comino et al., 2017; Niemz et al., 2020) or automated phase pickers (Zhu & Beroza, 2019; Shi et al., 2022). Template matching (Shelly et al., 2007; Peng &Zhao, 2009; Vuan et al., 2018) can be used to search for weaker, undetected signals, using the waveform of larger amplitude signals as templates; the application of template matching techniques helps enhancing standard seismic catalogues, with successful applications also for induced seismicity (Cesca et al., 2021).

Earthquake location. The hypocentral location of post-mining events, aimed at identifying spatial coordinate and origin time of the seismic event, is generally based on the identification of P and/or S seismic phases. Post-mining seismicity has been generally located within the mined structure or very close to it, in most cases suggesting the activation of similar fault structures. In some cases, however, post-mining seismicity clustered at locations that were not particularly active during mining (Primo Doncel et al., 2023). The depth of post-mining seismicity has been generally reported to be comparable to the depth of seismicity during active mining (Primo Doncel et al., 2023). However, it is worth noting that hypocentral depths for post-mining earthquakes are often poorly constrained, mostly because of the lack of underground stations, which hinders an accurate comparison with seismicity during mining. A broad range of tools is available for the location of post-mining seismicity, which share similar challenges as other types of local, weak, induced seismicity (Cesca & Grigoli, 2015). However, particular caution should be used to assess the earthquake depth and to quantify its uncertainty. Beside standard location methods, migration and stacking approaches, able to process automatically continuous data, can support both detection and location procedures (Grigoli et al., 2013; Cesca et al., 2021).

Earthquake magnitudes. Post-mining seismicity is characterised by weak magnitudes, which may in some cases reach comparable maximum magnitudes as during active mining. The magnitude estimation for post-mining seismicity should generally use common magnitude definitions, such as local magnitudes (M_L) or moment magnitudes (Mw). Local magnitudes can be estimated using empirical attenuation laws, which are often available after the assessment of mining seismicity during active mining. Preserving the same approach and equations to estimate magnitudes as during active mining is a good practice, that allows for a direct magnitude comparison during mining and post-mining periods. Moment magnitudes can be estimated by waveform-based moment tensor inversion (Sen et al., 2013; Heimannet al., 2018; Cesca et al., 2021) or waveform modelling approaches (Eulenfeld et al., 2022).

Focal mechanism determination and moment tensor inversion. Focal mechanisms and/or moment tensor inversion are procedures devoted to the identification of the seismic source radiation pattern, which provide information on the source of the seismic event (e.g. shear faulting, tensile crack, collapse, pillar burst or other) and its geometry. Focal mechanisms estimated based on first motion polarities or amplitude ratios may provide a first hint on the geometry of active fault structures. In general, however, full waveform approaches (Heimann et al. 2018) are suggested to more reliably model the source of post-mining earthquakes. These methods can be used to infer accurate estimate of moment tensors under different configurations (i.e. pure double couple, deviatoric and full moment tensor), which are important to resolve combinations of shear, tensile and volumetric source components (Fig. 7.6), that may occur during mining and post-mining (Sen et al., 2013; Ma et al., 2018; Caputa et al., 2021; Cesca et al., 2021). They provide information on the geometry of seismogenic processes accompanying post-mining (Fig. 7.7).

Fig. 7.6. Example of moment tensor inversion for a post-mining seismic event at Gardanne, France. The upper part of the figure shows the best moment tensor (red line) and range of acceptable solution (overlayed grey focal spheres), the moment tensor decomposition for the best and mean moment tensor solution, and the distribution of stations used in a polar plot. The bottom part of the figure provides some examples of data fit, comparing observed seismograms (black) and synthetic ones for the best moment tensor solution (red). The analysis was performed with the software Grond (Heimann et al. 2018)

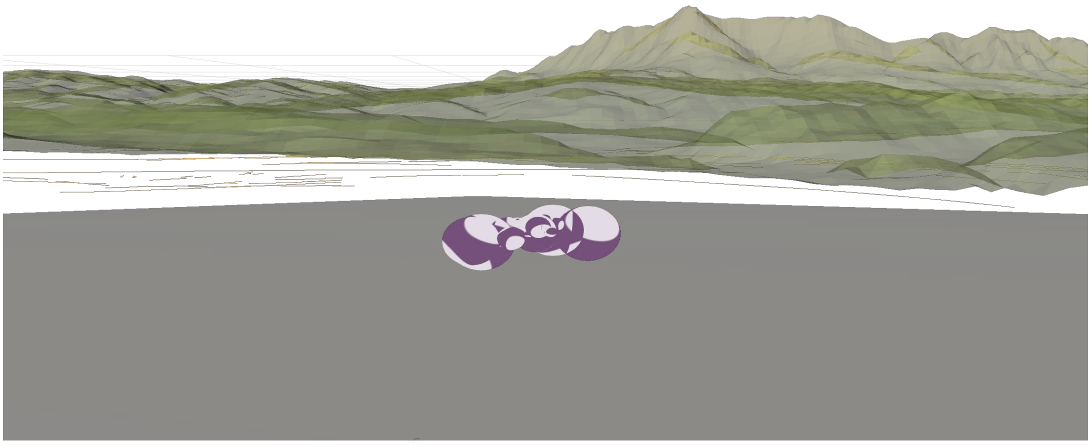

Fig. 7.7. Lateral 3D view of the Gardanne site, showing selected moment tensor solutions (focal spheres, back hemisphere projection) in the shallow underground (topography is exaggerated); similar sub-vertical pressure axes characterise the moment tensor solutions

Classification. Classification and clustering analysis are useful to identify families of seismic events, which share similar properties (e.g. location, magnitude, occurrence time, focal mechanisms, or simply producing similar waveforms). Focal mechanism studies of small-magnitude seismic events can be supported by a waveform-based event classification (Petersen et al., 2021). While post-mining deformation can occur both seismically and aseismically, seismic characteristics of post-mining earthquakes appear similar to tectonic earthquakes, with clear P and S onsets. Still, investigating the range of different recordings in post-mining environments is important to classify typical earthquakes and other types of signals, such as anthropogenic sources, such as blasts or anthropogenic noise, or low frequency events, which can take place in response to fluid-rock interaction in flooded mines.

Statistical analysis of seismicity. Statistical analyses of post-mining seismicity, generally including a number of analysis, devoted to tracking the temporal evolution of seismicity, earthquake magnitudes, location and depths, but also their temporal evolution; they are important to understand the seismicity behaviour and to link such patterns to other time series, such as the water table height and surface deformation. Post-mining seismicity should be continuously analysed to assess the short-term and long-term evolution of seismicity rates and moment release after the end of mining operations. Assessing the spatial distribution of seismicity and the presence of seismic clusters (Cesca et al., 2014; Cesca, 2020) is useful for identifying active seismic structures. Spatial clusters of post-mining activities may resemble the location of mining seismicity, implying the reactivation of active faults, or affect regions which were previously aseismic (Primo Doncel et al., 2023), suggesting the triggering of faults which were previously inactive or the formation of new fractures. Tracking the temporal evolution of seismicity and the water table is also important to assess the role of mine flooding as a seismicity driver. Indeed, flooding can partially control post-mining seismicity, with changes in the water table level affecting rates and hypocentral location of seismicity and its migration. Estimating b-values in Gutenberg-Richter relation, and tracking b-value variations over time, comparing mining and post-mining seismicity, is important to assess changes in the stress conditions (Schorlemmer et al., 2005; Mutke et al., 2016). Other statistical indicators, such as the coefficient of variation, CV (Kagan & Jackson, 1991; Zöller et al., 2006; Passarelli et al., 2015), the skewness, μ (Roland & McGuire, 2009; Chen &Shearer, 2016), and the normalised time of the mainshock, t_m (Zhang & Shearer, 2016) can be used to judge the temporal behaviour of seismicity. The CV is a measure of the temporal clustering, while μ and, t_m can be used to verify if the seismicity occurs in form of seismic swarm or mainshock-aftershock sequence, which can be important to assess the seismicity driver (Zhang & Shearer, 2016).

7.4. Monitoring of surface deformations

Various techniques are used to monitor post-mining induced ground deformation, including seismometers, geodetic monitoring (e.g. Synthetic Aperture Radar Interferometry -InSAR and Global Navigation Satellite System - GNSS), Light Detection and Ranging (LiDAR) systems, Ground-Based Synthetic Aperture Radars (GB-SAR), tiltmeters, extensometers and acoustic emission monitoring.

Monitoring carried out to determine the indicators of land deformation, such as vertical and horizontal displacements, generally requires the use of surveying techniques that ensure high accuracy and reliability of measurements. To date, the most common methods used to determine displacements have been the methods of classical geodesy, i.e. precision levelling to determine vertical displacements and angle-linear measurements to determine horizontal displacements. It should be noted that the methods of classical surveying make use of different techniques of measurement, instrumentation and processing of results to determine displacements. In addition, apart from the determination accuracy involving the displacement of points, the choice of a method for studying land deformation is conditioned by a number of other factors. The main ones include the size and shape of the control network, the type of displacements to be determined (relative, absolute, vertical, horizontal, 3D) and the velocity of occurring of changes. Measurements are generally carried out periodically, which results in the loss of information on the dynamics of displacement changes, e. g. when a mine is being flooded, under conditions of post-mining seismicity.

Owing to the use of GNSS satellite techniques, it has become possible to integrate the determination of horizontal and vertical displacements, which is carried out in a single measurement using a single instrumentation, and furthermore the measurement is characterized by a high degree of automation and processing of the observation results. High level of measurement of automation also makes it possible to realise continuous measurements (point monitoring). An important aspect in the study of deformation with the geodetic approach is the of realisation method of the reference system. When using classical geodetic measurement techniques in the study of deformation, it is necessary to stabilise individual reference points in the vicinity of the study area. A significant disadvantage of such an approach is the risk that a given reference point will fall within the range of mining impacts on unstable ground, prone to displacement. In contrast, the use of GNSS surveys provides an opportunity to reference the control network to reference points at a greater distance from the surveyed site, thereby reducing the possibility of displacement of the reference point. In addition, if permanent reference stations belonging to the so-called Active Surveying Networks, which operate continuously and are controlled in real time, are used as reference points, we further reduce the displacement probability of the reference point.

Taking into account the above, in order to implement monitoring of surface deformation in post-mining areas, especially under conditions of seismicity, it is advantageous to apply GNSS satellite technology, using observations to multiple GNSS, by means of which, through precise measurement of the position of control points, it is possible to detect and then analyse land surface deformation associated with seismic activity.

Since GNSS continuous monitoring is performed on single points, large-area monitoring of elevation changes of the land surface can be performed using satellite radar interferometry (Interferometric Synthetic Aperture Radar, InSAR) as a method to complement traditional survey methods such as levelling and Global Navigation Satellite System.

Nowadays, radar systems are widely used for land surface imaging due to significant developments in radar imaging from satellite orbits and the access to operational satellite systems, designed to operate for many years with programs that can operate more satellites. It should be noted that these data are now available at high temporal and spatial resolution. The InSAR method has been successfully used in surface displacement measurements around the world. It makes it possible to determine the course of vertical displacements over relatively short time intervals, which is important for monitoring surface movements in seismically active areas (Krawczyk & Grzybek, 2018).

The above-mentioned in situ measurements, including GNSS, combined with spaceborne Interferometric SAR techniques, offer a comprehensive approach to monitoring ground stability in post-mining areas, enabling timely detection of potential hazards and facilitating appropriate remediation measures. InSAR offers several advantages compared to other in situ geodetic techniques for monitoring ground displacements. A key advantage is its ability to detect even subtle motion of the Earth's surface, with millimeter-level accuracy. A further advantage refers to its ability to capture spatially continuous data over a wide area. These features hold particular significance in the context of post-mining, contrary to other in-situ instrumental techniques, as it allows for the assessment of impacts that can extend over significantly large areas.

The use of InSAR in post-mining context has gained significant attention in recent years and its importance has been well-demonstrated (Declercq et al. 2023; Modeste et al., 2021; Samsonov et al., 2013; Raucoules et al., 2008) for mapping ground movements caused by mining-induced earthquakes, detection of land subsidence in the area surrounding mines, highlighting the capacity to help identify areas of potential risk, to monitor and access the stability of a tailing dams, help preventing catastrophic failures and used to identify surface and subsurface fractures in post-mining areas. It is currently well accepted that InSAR can provide valuable information for managing and mitigating the environmental impact during the post-mining phase (Guéguen et al., 2009).

7.4.1. General principles of implementing satellite GNSS measurements

GNSS is the Global Navigation Satellite System, which allows the users around the world to determine position, velocity and time based on signals transmitted from a constellation of satellites orbiting the Earth. GNSS is the common name for all currently available navigation systems, which include four global systems and two regional systems. The global systems include the U.S. Navstar GPS, Russia's GLONASS, European Galileo and China's BeiDou. Regional systems include India's IRNSS (Indian Regional Navigation Satellite System) and Japan's QZSS (Quasi-Zenith Satellite System). In addition, global and regional positioning systems are complemented by "augmentation" support systems. These include two types of augmentation systems: satellite-based SBAS (Satellite Based Augmentation System) and ground-based GBAS (Ground Based Augmentation System). All satellite navigation systems follow the same general operation principle and can be used simultaneously, as a so-called multi-GNSS.

The best-known GNSS system is the U.S. Global Positioning System (GPS), which has become synonymous with satellite measurements, with a history dating back to the early 1970s. Modern GNSS systems include three main segments:

- space segment - which is a constellation of artificial satellites of the Earth transmitting navigation information,
- ground segment - supervising the operation of the system, consisting of stations that supervise and control the operation of the space segment,
- user segment - all users or technical devices equipped with GNSS signal receivers.

Satellite measurements are based on signals transmitted by the Earth's artificial satellites, which are the main component of all navigation systems referred to by the common synonym GNSS. Artificial satellites orbiting the Earth continuously emit electromagnetic waves at specific frequencies, which contain packets of additional information or data necessary to determine their current position and make measurements of the distance from the satellites to the phase center of the satellite receiver antenna.

Receivers use satellite radio signals to calculate their position in a process called trilateration. To determine the 3D position, the receiver must receive radio signals from a minimum of four satellites. These signals contain precise information about the time the signal was sent and the satellite's position. Once the signal is received, the receiver measures the time that elapses between the satellite sending the signal and receiving it. Based on the differences in time from when the signal was sent by the satellite and when it was received at the receiver, and on the known radio wavelength and propagation velocity, the distance from the receiver to each satellite is calculated. The determination of coordinates is based on three-dimensional trilateration, which involves finding the intersection of three spheres with radii equal to the measured distances from the satellites (Fig. 7.8).

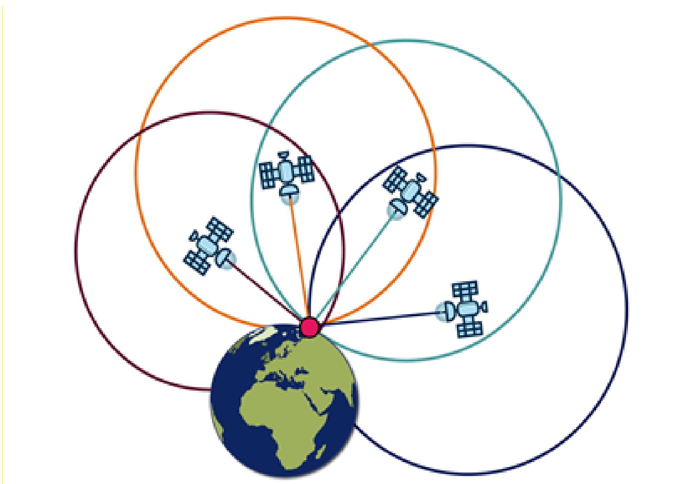

Fig. 7.8. GPS operating principle (source: https://creativecommoms.org/licenses/by-sa/3.0/, accessed June 24, 2023)

The fourth satellite is used to correct errors related to the receiver's clock. A user equipped with a satellite receiver which is able to receive and process such signals can determine their position with an accuracy that depends on the technical sophistication of the receiver, its software and the ability to use additional data to reduce measurement errors. For higher accuracies, the receiver should use additional information such as satellite clock corrections, atmospheric or orbital data.

The mathematical principle of satellite coordinate measurements is to solve a spatial linear intersection in which the current coordinates of the positions of the Earth's artificial satellites are the reference points, while the distances between them and the phase center of the receiver making measurements on the Earth's surface or in its immediate vicinity are the observation data.

The determination of the coordinates of the measured point is based on the solution of a system of equations for spatial linear intersection. By default, the distances to the satellites are calculated as a function of flight time of the wave, i. e. with time correction (7.1):

$$D_k = c\,(\Delta t_k + \delta t_k) \tag{7.1}$$

where: D_k - distance of the satellite k from the receiver antenna, c - velocity of light in a vacuum, Δt_k - time of flight of an electromagnetic wave along the way satellite-receiver, δt_k - difference in the gait of the clocks on the satellite and the receiver.

The distances to the satellites calculated using the equation (7.1) are referred to as pseudo-distances.

Knowing the coordinates of k satellites at the time of signal transmission described in a geocentric coordinate system (X_k, Y_k, Z_k) and the signal transit time to the receiver, the equation (7.1) can be expanded into the form (7.2):

$$D_k = \sqrt{(X_k - X)^2 + (Y_k - Y)^2 + (Z_k - Z)^2} + c\,\delta t_k \tag{7.2}$$

Solving a system of at least four equations of this type (7.2), up to four satellites, we can explicitly calculate the X, Y, Z coordinates of the receiver antenna and the time correction. The above general principle is the mathematical basis for determining the coordinates of points based on GNSS satellite measurements. However, for precise position determination, it is necessary to solve a number of additional technical problems and to take into account numerous factors, interfering with the movement of the satellite in orbit, satellite perturbations and signal interference on the satellite-receiver path during the passage through successive layers of the atmosphere. Currently, precision and accessibility by means of satellite-based positioning methods can be significantly improved by using multiple navigation systems simultaneously.

There are two main methods of GNSS measurements. Absolute measurements, which can be realised with a single receiver, are less accurate and generally used in navigation. The second method is referred to as relative (differential) measurements, and it requires the simultaneous use of a minimum of two receivers that make synchronous measurements to the same satellites.

Such measurements have high millimeter-level accuracy, and therefore they are most commonly used in surveying. There are two basic techniques for surveying: the static technique and the kinematic technique.

The static method is the basic technique of GNSS satellite surveying, implemented with a minimum of two (or more) receivers that perform synchronous measurements at the designated and reference points. This technique currently provides the highest accuracy in determining the coordinates of points. Its main disadvantage is that the results of the measurements are obtained with some delay as a result of the so-called post-processing. Independent calculations in post-processing also have their advantages, the delay of the calculations relative to the time of measurement makes it possible to introduce corrections to the calculations and additional information such as precise satellite position data.

Nowadays, more popular than static measurements developed in post-processing are differential measurements realised by real-time kinematic technique RTK/RTN (RTK - Real Time Kinematic or RTN - Real Time Network). Both measurement techniques are based on phase-corrected distance measurements in real time (with a delay, 1-3 seconds) based on observation data sent from a single base station (RTK) or from a network of base stations (RTN). We apply the relationship consisting in the fact that there are almost identical errors within a few kilometers of a reference station or set of reference stations for a given navigation system, which can be eliminated by a differential method.

In order to obtain precise coordinates through phase measurement, it is necessary to initially determine the number of full wavelengths (full phase cycles, ΔN_i), which largely depends on the class of GNSS receiver. Then, in the process of determining coordinates (receiver initialization), it is necessary to determine the so-called phase indeterminacy N_0 , the unknown random initial number of full phase cycles of the signal to a given satellite. Due to the new, introduced additional unknown N_{0i}, in the process of coordinate determination, continuous measurement to a minimum of five satellites is required for real-time (RT) measurements.

Currently, the most recommended in geodetic measurements are RTN surface corrections. In this solution corrections for the observation site are generated on the basis of data interpolated in the system management center from at least several reference stations. Several methods of generating surface corrections are currently used, i.e.: the VRS (Virtual Reference Station) method, MAC (Master and Auxiliary Concept) method, FKP (Flachen-Korrekteur-Parameter) method. All RTN surface corrections take into account atmospheric errors such as GNSS signal delay due to the influence of the ionosphere and troposphere.

7.4.1.1. Methodology for GNSS monitoring in seismically active post-mining areas

The methodology of GNSS monitoring in seismically active post-mining areas presented below was developed in the results of the PostMinQuake project. GNSS monitoring was carried out under the project at a testing site in Poland in the area of the closed, currently flooded Kazimierz-Juliusz mine.

In order to monitor surface movements in the area of seismic hazards in post-mining areas, it is advantageous to carry out continuous monitoring, based on permanent GNSS observations carried out using the phased and coded methods. In particular, the phased method provides very high precision measurements with errors at the submillimeter level.

Displacement measurements should most preferably be carried out in dedicated control networks consisting of surveyed (monitored) points and reference points. It is recommended to carry out measurements with reference to at least 5 reference stations. In the study area, in order to determine planar spatial changes, monitoring should be carried out at least 3 points located in the post-mining area. The design of the measurement network for the study of land deformation should be characterised by high supernumerary of reference points, which ensures full mutual control of observations and leads to high accuracy and a high degree of reliability of the determined displacements. The location of survey points, should take into account:

- mining and geological situation in the post-mining area,
- field situation with regard to the possibility of locating GNSS receivers,
- analysis of the stress states in the rock mass resulting from the mining operations carried out and from the simulation of stresses related to hydrogeological processes during the period of mine flooding.

Points belonging to Active Geodetic Networks, national or commercial, and other independent positioning systems should be used as reference points. This is because reference station networks of this type have been conducting observations for many years and are characterised by high precision in conducting measurements and processing them. This is due to a number of factors that can affect the determined coordinates, including high-class measurement equipment which they are equipped with.

It is also reasonable to make periodic control measurements using other surveying techniques. In the case of changes in vertical displacement, it is advantageous to carry out control measurements by means of the precision levelling method, and in the case of changes in horizontal displacement – with the application of the GNSS static method, using a minimum of 3-hour observations to satellites carried out synchronously at all determined points.

Registration of observations at the monitored and reference points should be carried out with a data registration interval of minimum 1 Hz. The development of GNSS observations for displacement monitoring should be carried out in a local control network, preferably using specialised and dedicated firmware for a particular type of receiver. Such solutions offer the possibility of determining precise positions using various measurement techniques and calculation strategies. Such a system should use, as a basic solution, the development of static phase and code measurements in post-processing mode with reference to a network of reference stations, adopting several alternative calculation strategies at different time resolutions.

The second independently applied technique should be the RT (Real Time) measurement technique. Such a solution provides data on the initial characteristics of the phenomenon in terms of the magnitude of the movement of the controlled points in real time with a temporal resolution of 1 second, which is particularly important in the process of analysing displacement changes during the period of seismic phenomenon.

Reporting and visualisation of the results of continuous monitoring would advantageously take place on an ongoing basis with the access to selected information also for end users of the system through a dedicated web portal. The adopted concept of determining the indicators of land surface deformation in post-mining areas, such as horizontal and vertical displacements, makes it possible to achieve high accuracy of their determinations in the study area. The obtained accuracies of point displacement determinations match those obtained from the measurements of classical geodesy.

The proposed solution provides a high degree of automation of the works and the possibility of conducting continuous monitoring in three-dimensional space. The analyses of displacement changes should be carried out in a continuous mode, which will allow an ongoing assessment of the dynamics of the observed changes also in connection with the recorded seismic activity. A diagram of the procedure to implement surface deformation monitoring using GNSS satellite technology in seismically vulnerable post-mining areas is shown in Fig. 7.9.

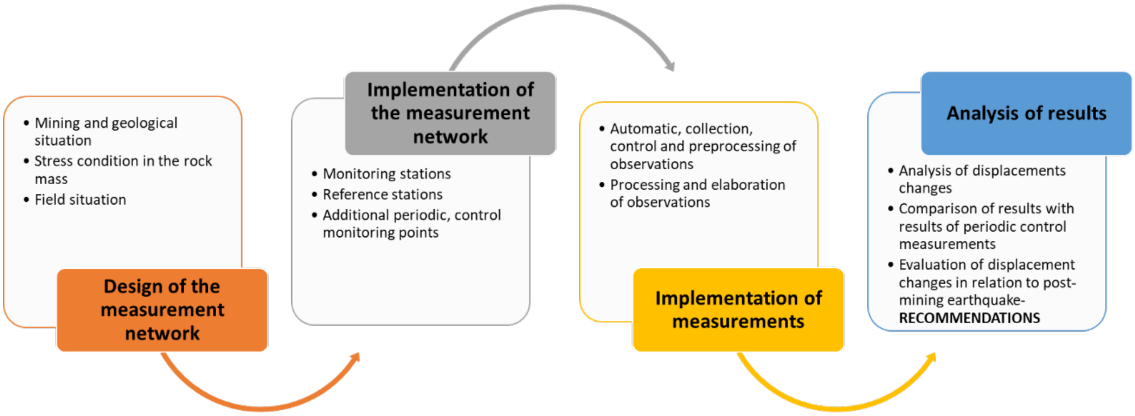

Fig. 7.9. Schematic of the procedure to implement surface deformation monitoring using GNSS satellite technology in seismically vulnerable post-mining areas

7.4.1.2. Practical application

Continuous monitoring with GNSS satellite technology was carried out as part of the PostMinQuake project in the area of the closed, currently being flooded Kazimierz-Juliusz mine, located in Upper Silesian Coal Basin in Poland. The design of the spatial observation network of surface movements was developed after the determination of stress concentration zones generated by the previously conducted mining operation, with particular attention to fault zones. The possibility to stabilize monitoring points based on detailed field interviews was taken into account. A sketch of the comprehensive GNSS continuous monitoring network for the Kazimierz-Juliusz mine site is shown in Fig. 7.10. The network consisted of GNSS continuous monitoring points (including monitoring stations for the study area labelled with numbers: 8104, 8105, 8106 as well as five reference points - reference stations: BORO, OLKU, JAWO, GLIW, KRAK, located outside the area of completed mining exploitation) with which continuous high-frequency, multisystem synchronous satellite observations were made. All reference points were stations belonging to Active Geodetic Networks.

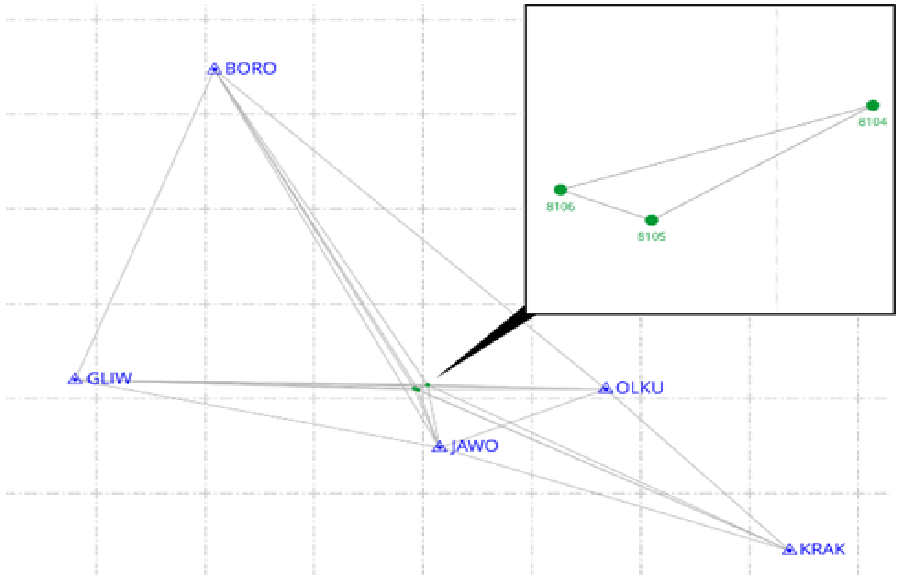

Fig. 7.10. Sketch of the GNSS continuous monitoring network at the Kazimierz-Juliusz site, source: (Sokoła & Siejka, 2022)

The design of the network was adapted to the local conditions and requirements of the studied object and to the correctness of the location of reference points (reference stations). The network developed as shown above, (Fig. 7.10), additionally equipped with devices for remote communication of the monitoring and reference stations, formed a control and monitoring network, which was the first module of the automatic GNSS continuous monitoring system developed for the project and implemented at the area of Kazimierz Juliusz mine.

The applied solution enabled continuous monitoring based on multi-frequency and multi-system GNSS observations. The management of the active monitoring network constructed in that way was based on Trimble 4D Control Server software, which allows monitoring and analysis of deformations and movements of land surface in post-processing and in real time, based on data from GNSS receivers. The second component of the continuous monitoring system was made up as a module for automatic collection, control and preprocessing of observations, which operated based on the IP addresses of field receivers and on a local data collection and processing server. The third element of the monitoring system was made up as a module for processing and elaboration of the observations, as the main component of the entire system. The fourth component was made up as a module for reporting and presentation of the results. A block diagram of the applied system is shown in Fig. 7.11.

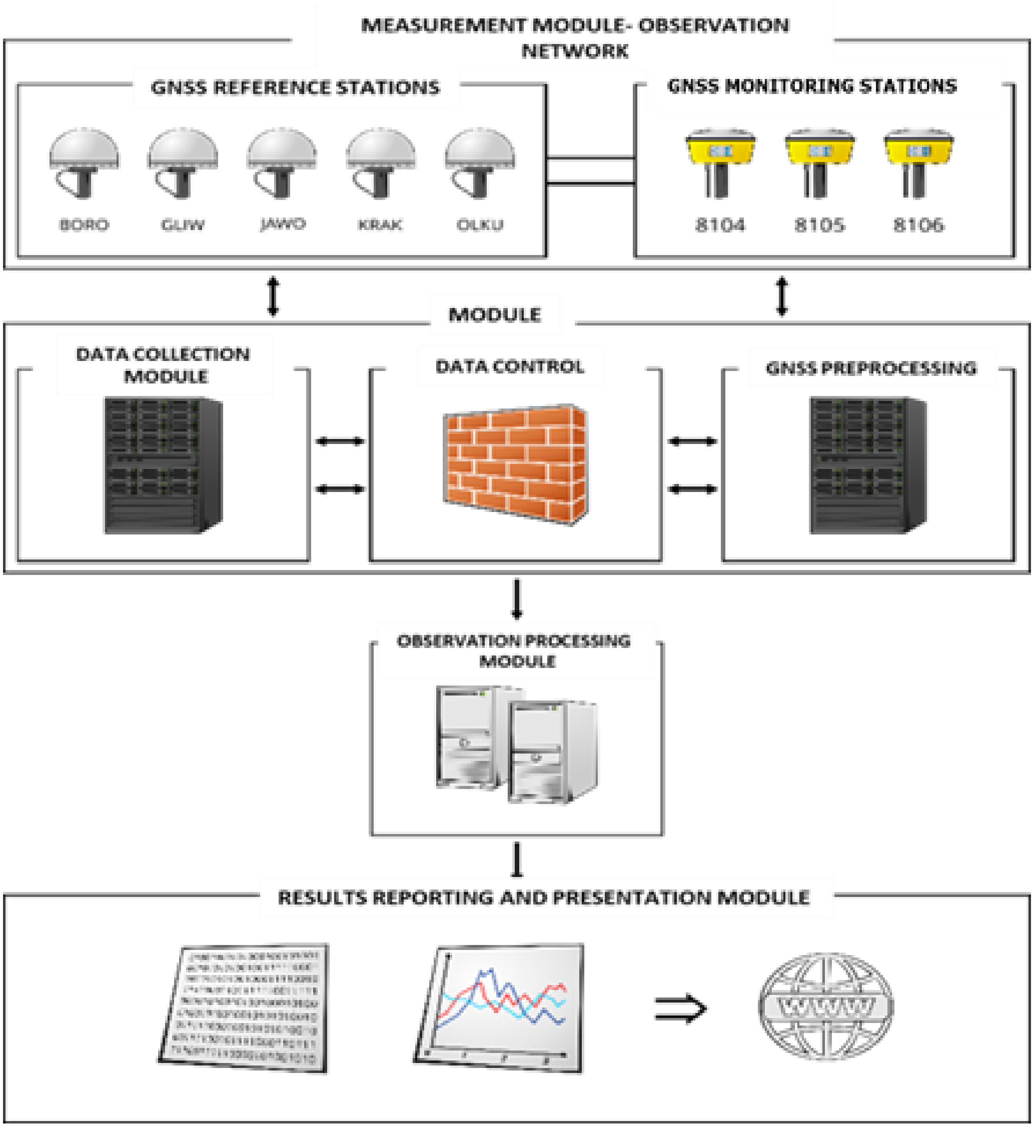

Fig. 7.11. Block diagram of the construction of an automatic monitoring system of GNSS observations in the mine Kazimierz-Juliusz, source: (Sokoła & Siejka, 2022)

The monitoring system built in this way operated in a continuous automatic mode. First, continuous GNSS observations were made at the measurement stations (monitoring and reference stations), which were recorded in the form of hourly observation files in the internal memory of the receivers. Then, using Moxa remote communication modules, the observations were sent to the data collection server. Subsequently, the raw observation data were converted to RINEX 3.03 format, in packets of one-hour observations using the conversion and preprocessing module. At the same time, navigation files for all observed GNSS satellites were generated using the "Ephemeris Manager", necessary to estimate station coordinates, and to take into account a number of physical model phenomena required for precise determination of observation results. After these preparatory activities, the main computational module of Trimble 4D Control Server began in post-processing mode the process of determining the coordinates of the monitored points and their displacements in the network solution with reference to the five reference stations.

The said solutions were based on algorithms for precise point coordinate determination from multi-GNSS observations, taking into account the problem of the modelling of inter-system receiver hardware delays, which were developed with a measurement interval of 1 Hz, at time resolutions: 1 h, 2 h and 4 h. The results of successive calculations in the form of time series of coordinates and their changes were recorded on an ongoing basis in a local database in a numerical form. In addition, they were visualised on an ongoing basis in the form of displacement diagrams for the defined time periods. The results of the solutions obtained for the above-mentioned three computational strategies were subjected to processing in accordance with the methodology developed for the project, presented in (Siejka & Sokoła, 2022). The structure and operating principles of the entire monitoring system were presented in detail in the work (Sokoła & Siejka, 2022).

The information and communication system used and the GNSS positioning technique with real-time (RT - Real Time) processing of results, using phase and code observations, enabled the detection of displacements of controlled points with a time resolution of 1 second, which was used for detailed analysis of displacements changes associated with the occurrence of the post-mining earthquake.

Analyses of displacement changes were performed in continuous mode, detailed in a time window of two weeks covering the moment of occurrence of a post-mining earthquake based on solutions obtained from the development of observations in post-processing with a resolution of 1 hour, and in a period of 24 hours covering the moment of occurrence of an post-mining earthquake additionally based on observations of RT solutions with a temporal resolution of 1 second.

In order to control the changes in displacement obtained as a result of the implementation of continuous monitoring, control measurements were carried out at the points of the observation network located in the vicinity of the GNSS continuous monitoring points. Changes in elevation were determined on the basis of the results of levelling measurements using the precision levelling method. The changes in vertical displacement were controlled based on measurements made by the GNSS static method.

General recommendations for conducting deformation monitoring with GNSS techniques, including the development of results and their interpretation, are included in the section 7.6.

7.4.2. Interferometric SAR Technique

Satellite-based InSAR is a powerful non-invasive and cost-effective tool of measuring elevation-change of the Earth surface using satellites orbiting continuously around the globe at an altitude of about 800 km. It operates by analysing the phase differences (called ‘interferometric phase’) between two or more SAR imagery of the same area taken at different times to detect changes in the distance between the ground and the Radar sensor. InSAR measurements are made along the Line of Sight (LOS) of the satellite, namely the oblique direction of propagation of the radar signal from the satellite to the ground target and back to the satellite.

Conventional Differential InSAR (DInSAR) technique works by comparing a pair of SAR images acquired before and after an event. The applicability of DInSAR for mapping earthquake-induced ground deformation is significant, being a powerful tool to detect and quantify these changes with high precision over large areas (Malinowska et al., 2018; Rudziński et al., 2018; Hejmanowski et al., 2019). An example interferogram developed with the DInSAR technique within the PostMinQuake project for the post-mining region of the Kazimierz-Juliusz mine, located in Poland, covering the occurrence of post-mining earthquakes is shown in Fig. 7.12.

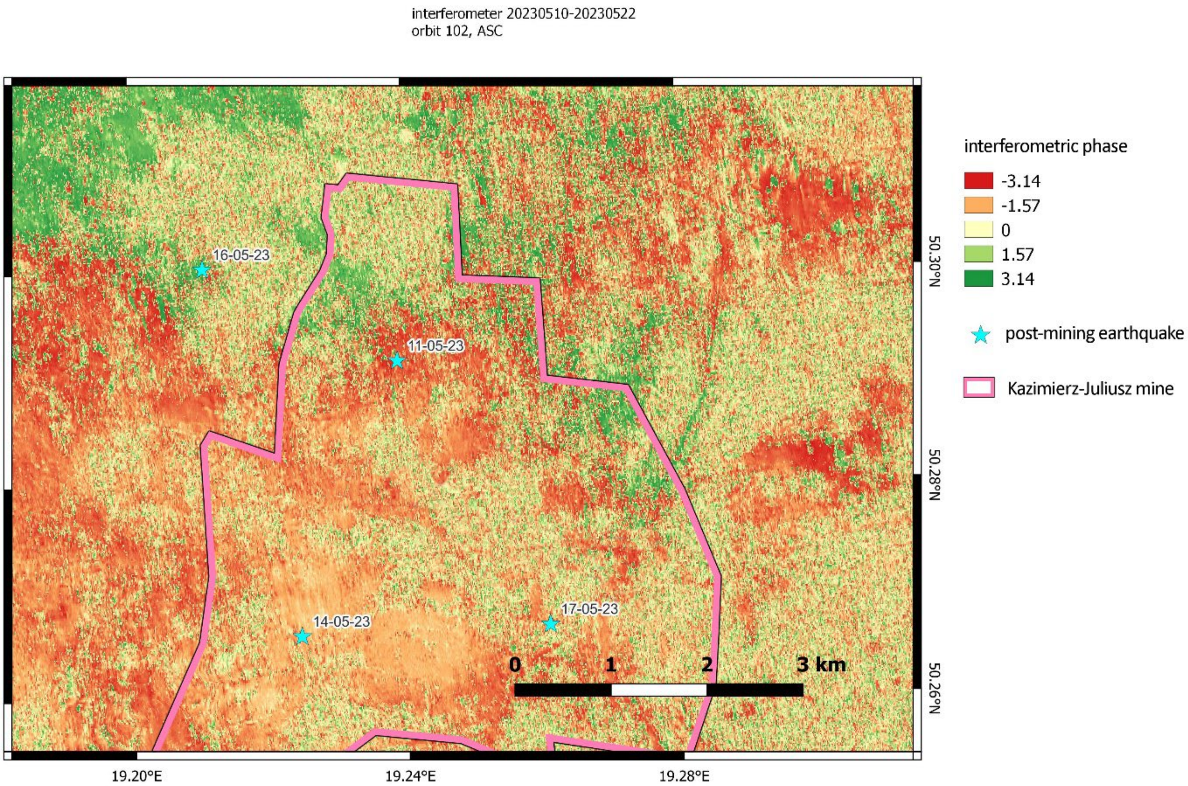

Fig. 7.12. Interferogram developed with the DInSAR technique for the period from May 10, 2023, to May 22, 2023, covering the occurrence of post-mining earthquakes (epicenters marked in blue) - Kazimierz-Juliusz post-mining area, Poland

Apart from abrupt seismic events, a straightforward technique to extract long-term displacement rates from a stack of SAR images is by Interferometric Stacking (IS). This basic method relies on multiple interferograms which are selected either through a visual evaluation, or based on a quantitative criterion, such as the average temporal coherence, the perpendicular baselines, and the temporal baselines (Raucoules et al., 2007). In this approach, the temporaldependency is neglected, and the focus is on constraining the geometry of the area affected by ground deformation, which is difficult to achieve with more sophisticated InSAR techniques.

Advanced Multi-Temporal InSAR (MT-InSAR) techniques can be broadly categorised into two families, single reference approaches and multi-reference approaches, whereas within each family different processing schemes have been proposed. Single reference approaches such as the Persistent Scatterer Interferometry (PSI) use a single SAR image, or "reference" image, to compare with the subsequent images of the stack to detect and measure displacements (Ferreti et al., 2001; Hooper et al., 2004; Wegmüller et al., 2004). In PSI, the technique identifies and tracks the radar signal from specific objects on the grounds, such as buildings, bridges, or other man-made structures, that remain coherent over time, i.e. stable in terms of surface characteristics point targets (often referred to as “Persistent Scatterers” or simply PS) and measure ground motion at those targets. These PS targets have a high coherence and are visible in multiple images acquired over a long period.

An example of the result of processing a series of radarograms within the PostMinQuake project in the Kazimierz-Juliusz post-mining area, located in Poland, using the PSInSAR technique is presented in Fig. 7.13.

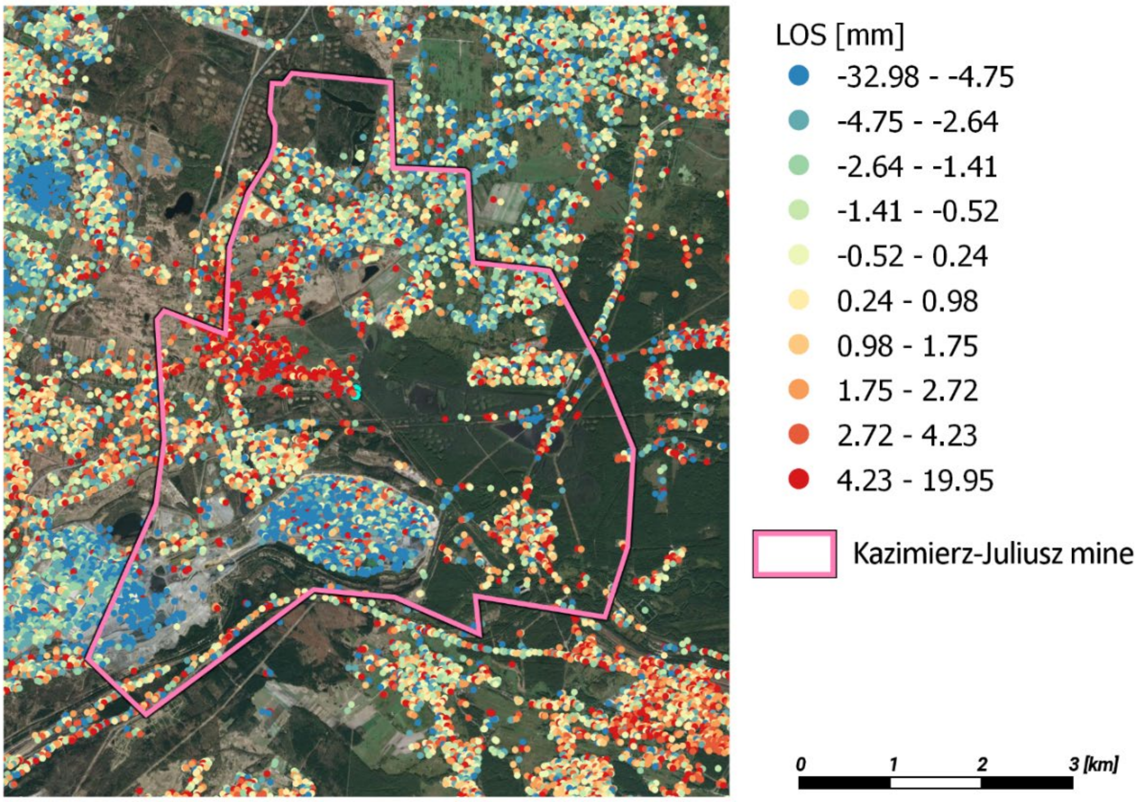

Fig. 7.13. Elevation changes of the land surface (LOS, in mm) in the period from December 3, 2020, to November 28, 2021 - Kazimierz-Juliusz post-mining area, Poland

On the other hand, multi-reference approaches, such as the Small Baseline Subset (SBAS) (Berardino et al., 2002; Casu et al., 2014), use multiple reference images to improve the accuracy of deformation measurement. These techniques involve comparing pairs of images in the dataset, the selection of which relies on different rules and criteria. SBAS approach is particularly useful in areas with low coherence or high noise, whereas single reference techniques may be more appropriate for urban environments.

One of the key advantages of PSI approaches is their ability to provide high spatial resolution deformation measurements. However, they may be less effective in areas with complex deformation patterns or low coherence (i.e. sparse point scatterers). In contrast, multi-reference approaches, such as SBAS, can provide more dense measurements and resolve more complex temporal behaviours, but at the cost of reduced spatial resolution. The choice of InSAR technique depends on the specific application and the surface characteristics of the study area.

In practice, interferometric stacking tends to provide better geometry characterization and requires smaller data sets than advanced MT-InSAR techniques (Fig. 7.14). On the other hand, InSAR time series methods (PSI or SBAS-like) provide significantly more precise motion estimates and enable characterising the temporal evolution of the displacements. Therefore, both approaches have their respective interests, and their combination can provide valuable information.

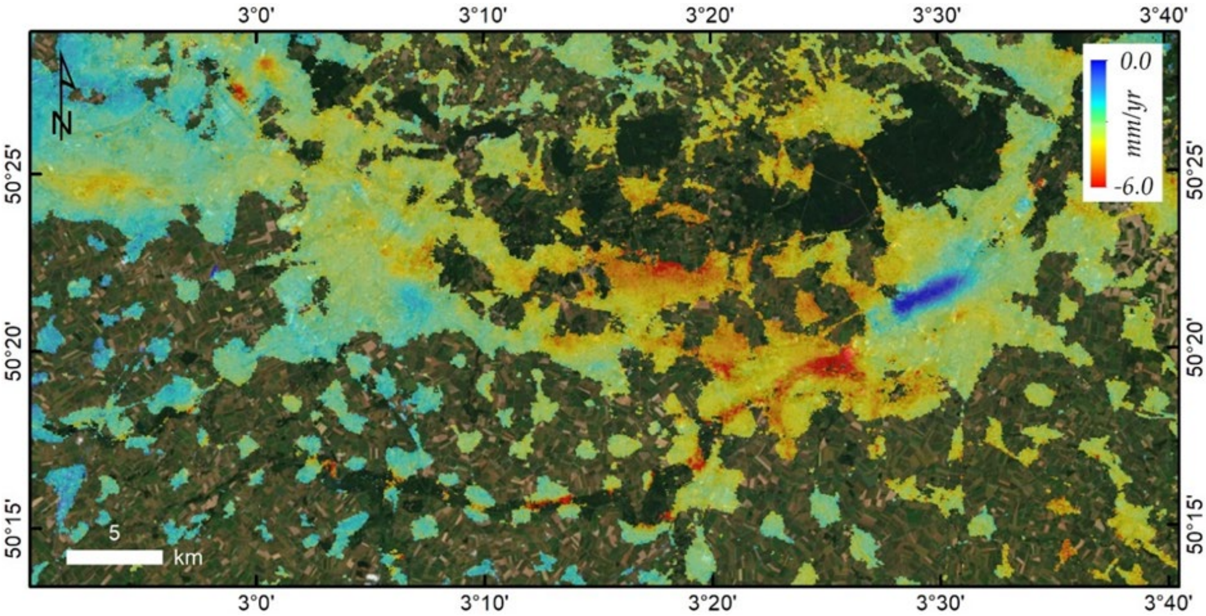

Fig. 7.14. Subsidence along a channelled river and localised uplift in the urban area of Valenciennes (Nord-Pas de Calais, France), as shown by Copernicus Sentinel-1 InSAR (2015-2018), source: (Morel et al., 2022)

7.4.2.1. InSAR monitoring of post-mining areas

In post-mining context, the choice of processing technique may depend on the specific post-mining application and the properties of the area being monitored. For example, in areas where there are many man-made structures or other persistent scatterers, such as tailings dams, waste dumps, or mine infrastructures, PSI may be more appropriate for monitoring purposes. This is since PSI relies on the coherence of specific objects on the ground, which can be 'stable' over long periods and provide a reliable reference for motion measurement. On the other hand, in areas where there are fewer scatterers or natural features, such as barren lands or vegetation-free areas, SBAS-like InSAR may be more appropriate. It is worth noting that a common practice is to apply both PS and SBAS-like interferometric techniques in a common processing framework to ensure enhanced density of measurements, while capturing a wider range of displacement patterns.

The availability of SAR data is a critical component for the monitoring of post-mining sites, as it provides the necessary inputs for InSAR processing and analysis. In recent years, the Copernicus Sentinel-1 mission has revolutionised the field of SAR-based monitoring by providing global, systematic, and free access to C-band SAR data with a high temporal resolution (every 6 to 12 days, depending on the region of interest). This high revisit allows for frequent monitoring of post-mining sites, which is crucial for detecting changes that may occur over time. In addition to Sentinel-1, various national and commercial SAR missions contribute to the available SAR data. It's important to note the specific characteristics of the SAR missions, as they influence the selection and application of SAR imagery for monitoring post-mining sites. The selection process should consider factors such as the desired spatial resolution, revisit frequency, and the ability to penetrate vegetation or adverse weather conditions.

By leveraging the availability of SAR data from multiple sources, including the national and commercial SAR missions mentioned above, the monitoring of post-mining sites can benefit from combining and comparing different datasets, while mitigating the limitations of each mission. However, it should be kept in mind that commercial SAR data can be expensive, may not have the same level of global coverage and the availability of sufficient number of archived data is not guaranteed.

To ensure the success of InSAR applications in post-mining context, it is important to follow best practices in processing, interpretation, and reporting. Processing considerations include the selection of appropriate SAR sensor and satellite acquisition geometry as well as proper selection of processing scheme and procedure to compensate for the various error sources (atmospheric signal, noise filtering etc.). Interpretation and reporting considerations include the integration of InSAR measurements with other geodetic and instrumental data, the use of appropriate visualisation techniques, and the provision of analysis ready data and regular reports to stakeholders.

7.4.2.2. InSAR practices for post-mining applications

Several best practices can be proposed for the application of InSAR in post-mining contexts, based on the experience and lessons learned from prior efforts in utilising the technology in relevant environments:

- Ensure the quality and accuracy of the InSAR measurements. This can be achieved by carefully selecting appropriate satellite sensors in terms of radar wavelength and spatial resolution. It is important to select SAR images with interferometric capability, offering appropriate geometric and temporal baselines. The choice of the processing methods applied should be carefully evaluated to ensure optimal results for the specific post-mining context.

- In the context of induced seismic activity, it is recommended to prioritise the use of the simpler and straightforward conventional DInSAR technique. This approach provides approximate yet timely information on the observed motion gradient and enables the detection of the affected area. However, when considering the magnitude and depth of post-mining earthquakes and earthquakes, the application of advanced InSAR algorithms should be evaluated. Specifically, for shallow earthquakes with moderate to large magnitudes, resulting in centimetre-level motion, DInSAR is sufficient to offer the necessary information for response and mitigation efforts. On the other hand, for small-scale seismicity, the precise millimetric accuracy of MT-InSAR techniques such as Persistent Scatterer Interferometry (PSI) or Small Baseline Subset (SBAS-like) is required to accurately measure induced ground deformation and monitor the temporal evolution of the activity.
- In the process of InSAR analysis, it is necessary to identify a reference area that remains relatively stable and unaffected by both mining activities and seismic ground deformation. This reference area shall demonstrate negligible deformation signals in the interferometric results. By selecting such an area, accurate differencing can be performed, enabling precise quantification of the induced ground motion specifically associated with post-mining earthquakes.
- Depending primarily on the presence and density of vegetation a decision should be made on the optimum radar wavelength to be utilised. In principle, the denser the vegetation the longer the wavelength of the radar sensor to be selected to penetrate the vegetation and ensure higher coherence values, in turn more robust motion measurements. Still, it should be noted that the longer wavelengths (e.g. L-band SAR) are less sensitive to motion compared to those of short wavelength SAR systems (e.g. X-band). Although this is somehow imposed by the characteristics of open and free SAR data (e.g. Copernicus Sentinel-1), especially over site with records of anthropogenic earthquakes, agreements between mining operators and satellite data provider could be beneficial. This will ensure availability of SAR archived data previous of the event and fast acquisition of imagery following the event.
- For monitoring phenomena occurring over longer time scales an important best practice is to ensure that the InSAR measurements are regularly analysed and reported to all relevant stakeholders. This includes providing regular updates on any changes or trends observed in the InSAR data, as well as providing clear and transparent communication regarding the interpretation and significance of the data. It is critical to acknowledge the limitations and uncertainties associated with InSAR data and to use it in conjunction

with other monitoring techniques, such as ground-based surveying, to ensure a comprehensive understanding of the post-mining environment. The establishment of a local reference network is often another best practice for InSAR applications in post-mining contexts. These networks consist of a series of well-monitored reference points (e.g. corner reflectors equipped with GNSS receivers) that can be used to aid interferometric processing. However, the reference network should be established using ground-based surveying techniques and should be regularly maintained and updated.

Overall, the application of InSAR in post-mining contexts requires careful planning, implementation, and interpretation of the data. By following best practices and considering the specific context and stakeholders involved, InSAR can be a powerful tool in monitoring and mitigating the environmental impacts of post-mining sites.

As technology continues to evolve, there are numerous opportunities to further improve the applicability of InSAR. One such opportunity is the use of online cloud-based platforms that allow for automatic processing of Earth Observation (EO) data. The Geohazards Exploitation Platform https://geohazards-tep.eu is one such example that provides a user-friendly environment for the interferometric processing and analysis of Copernicus Sentinel-1 data. Utilising EO platforms can contribute to large-scale processing of significant historical events, enabling a better comprehension of the limitations of conventional DInSAR and the potential of MT-InSAR techniques in accurately detecting and quantifying small-scale mining and post-mining earthquake movements. This approach allows for the assessment of the relationship between the magnitude and depth of seismic activity and its surface expression.

Finally, initiatives for national or multi-national InSAR coverage, such as the European Ground Motion Service (EGMS) (https://land.copernicus.eu/pan-european/european-ground-motion-service), based on Sentinel-1 data are recently implemented. Such services propose regularly updated ground motion maps, generally based on PSI techniques, providing valuable information for post-mining risk management. However, such services since based on standard/automated procedures might not fulfil all the requirements in terms of points densities and suitability to the motion characteristics for all the post-mining contexts, thus a continuous interaction with users is often required to properly assess and tailor the analysis.

7.5. Monitoring of water in soils and rock mass

The water saturation of the rock mass is the main factor impacting the mechanics of rock strata. This applies in particular to regions where the geological environment is transformed by mining activities and the rock mass is in the process of re-irrigation, as in the case of mines being in the process of flooding. When the water is deep (several hundred meters), a re-saturation of the rock mass can locally cause continuous surface deformation and movements of rock blocks separated by tectonic faults. Such phenomena are generally accompanied by post-mining earthquakes. When the water table is getting closer to the surface, the hazard of discontinuous deformations (sinkholes) increases significantly. Therefore, the water table position in the rock mass needs to be controlled and managed in post-mining environments. The water feeding the rock mass mostly comes from atmospheric rainfalls, which migrates from the surface into the rock mass. The impact of the water on the rock mass structure is time-dependent. The optimal monitoring system should include automatic devices, monitoring the water positions in deep and shallow parts of the rock mass. Such devices can be placed in abandoned shafts, if this is technically possible. Whenever possible, hydrostatic probes measuring the water level should be mounted in dedicated boreholes. If the coal-bearing deposit presents younger stratigraphical series with water horizons, it is recommended to sense each of them. While this increases the number of monitoring points, it will also ensure to identify the origin of the water, which overfloods the mine.

Monitoring the water level in a post-mining area can be done manually, via periodic measurements, or automatically. Manual water level measurements (with a hydrogeological gauge) are usually performed at monthly or several-month intervals. They provide only indicative data on the long-term trend of the speed of changes in the water level in the rock mass. These data are of little use in the analysis of seismic events. Data collected in the EPOS-PL and PostMinQuake projects from measurements using automatic systems indicate that short-term changes in the rate of increase or decrease of water levels occur in the rock mass before and after post-mining earthquakes. In the set of data from measurements of the water level in a deep piezometer in the Kazimierz-Juliusz mine, the average monthly rate of water level increase is 0,033 m/day (Contrucci et al, 2023). There are also periods when this rate drops to zero. In periods of several hours before and after registered seismic events, it reaches values of +/- 0,20 m/day (cases 1 and 2 in Fig. 15). These data indicate that some post-mining earthquakes cause blockage or opening of flow paths in the rock mass (Fig. 15).

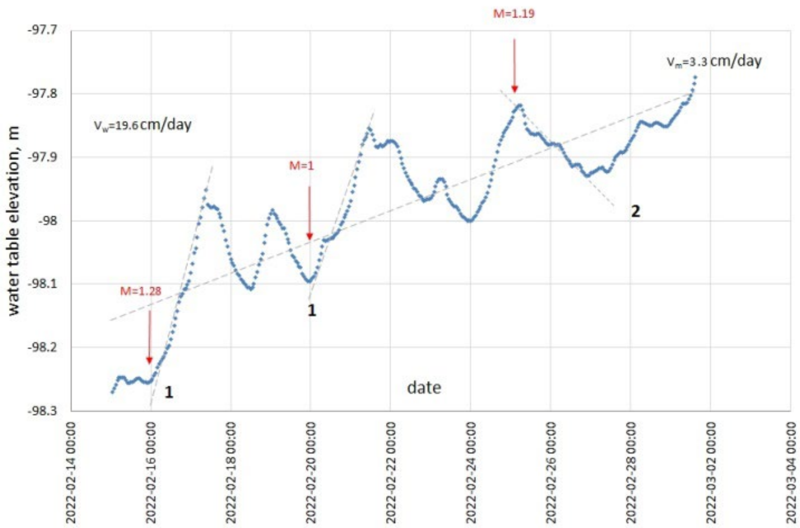

Fig. 7.15. Short-term water oscillations recorded in deep piezometer PMG1 at the area of Kazimierz-Juliusz mine and selected post-mining earthquakes (magnitude and earthquakes marked in red)

The use of automatic systems is recommended, as data can be provided in real-time, which allows for a quick and detailed remote analysis of water movements before and after each seismic event. Such monitoring systems can be equipped with other sensors, additionally measuring the physical and chemical properties of the water. One of those systems, developed by Central Mining Institute (CMI) in the framework of the PostMinQuake project for the Kazimierz-Juliusz test site, can also measure the water conductivity and its temperature: here, the data from the sensors are transmitted by GPRS net to a dedicated CMI server and shared in real-time, in the application Hydrowskaz (Fig. 7.16) (data from this system are accessible at https://gig.hydrowskaz.pl/).

In the case of hydrostatic probes with a higher sampling frequency (1-2 Hz), co-seismic water movements caused by mining and post-mining earthquakes can be detected (Frolik et al., 2020; Kotyrba et al., 2020).

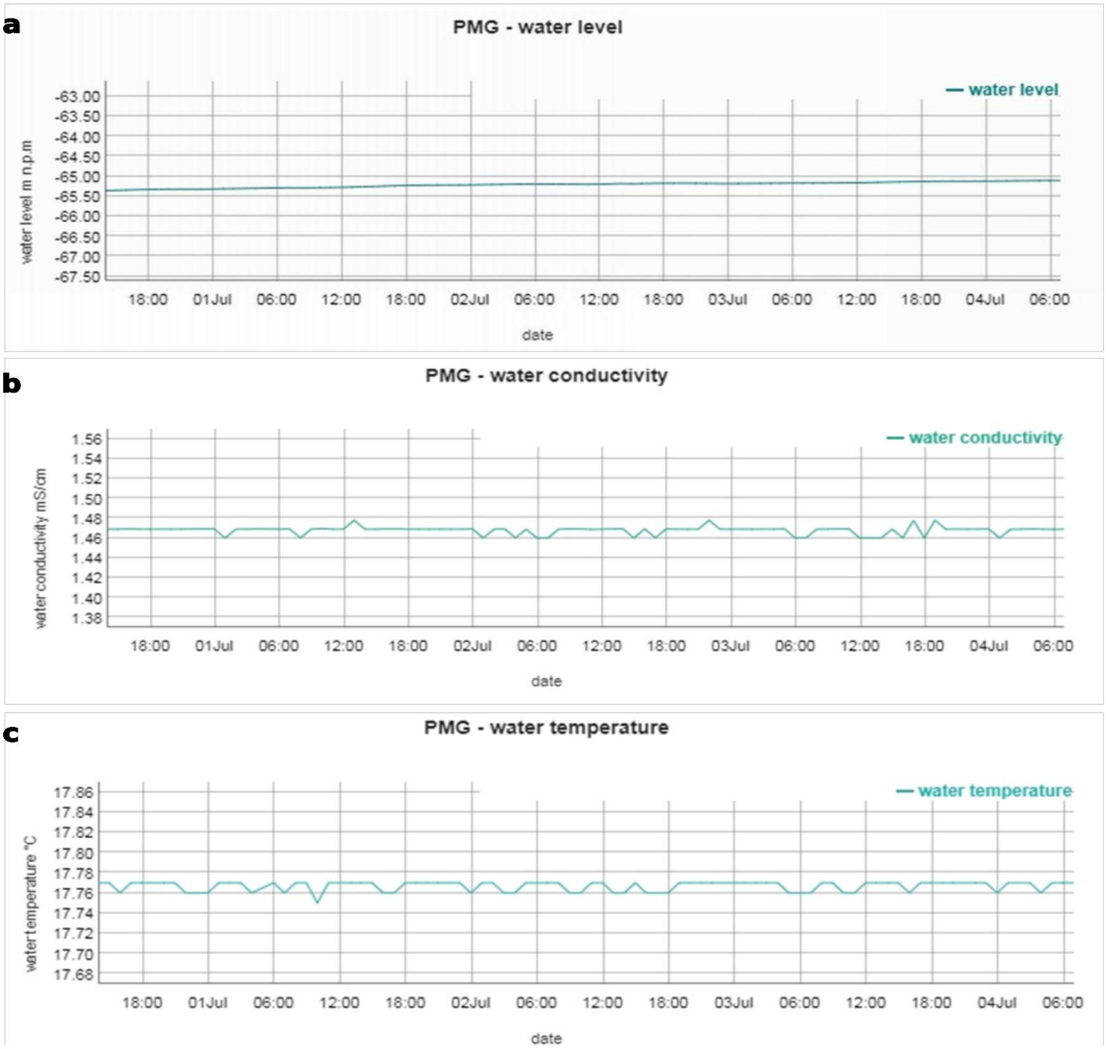

Fig. 7.16. Live data showing the water table level (a) water conductivity (b) and water temperature (c) in deep piezometer PMG1 in Kazimierz-Juliusz mine. The data are presented as plots of each parameter value over time in 1h increments. Graphics taken from Hydrowskaz application developed for water data visualization (https://gig.hydrowskaz.pl/)

7.6. Best practices for post-mining monitoring

Some of the recommendations proposed by the PostMinQuake project are transversal and valid for all monitoring components. In this sense, the establishment of a clear and well-defined monitoring plan is mandatory and common to all approaches, in the frame of a broader multi-disciplinary attempt. Such a broader monitoring plan should outline the monitoring aims, its major components, techniques and integration approach, its frequency and duration. Monitoring objectives should be in line with the overall goals, such as the mitigation of environmental impacts or the restoration of the landscape. The monitoring plan should be developed in collaboration with all stakeholders including the mining company, regulators, and local communities.

Another common result concerns the integration of multiple data. The integration of deformation, seismicity, the hydrological level of the mining aquifer, and other geodetic or in-situ monitoring techniques is crucial for establishing a comprehensive monitoring system. This integration facilitates the correlation between the hydrological level of the mining aquifer, post-mining seismicity and ground deformations, leading to a deeper understanding of the relationship between post-mining behaviour of rock-mass and earthquakes. Such an assimilation system aids in making informed decisions regarding the most effective monitoring strategies and actions to be taken following for a seismic and deformation events.

When implementing any monitoring techniques in the context of post-mining operations, it is crucial to not only adhere to best practices, but also consider the ethical and social implications. One aspect of this entails actively engaging with local communities and stakeholders to foster a comprehensive understanding of the technology being employed and to address any potential concerns they might have regarding the safety of the post-mining operations. Taking these ethical and social considerations into account demonstrates a responsible approach of the post-mining operator for addressing safety by fostering a sustainable monitoring framework. By involving local communities and stakeholders it becomes possible to establish a mutually beneficial relationship built on transparency and trust.

Specific recommendations are recompiled in the following Table 7.1 (colours correspond to the different monitoring components).

Table 7.1

Recommendations for post-mining monitoring. Different colours correspond to different monitoring components: near surface geophysics (red), gravity (orange), seismicity (yellow), deformation (green) and hydrological (blue)

Near-surface geophysics	Surveys	Perform temporary geophysical surveys to characterise fissuring processes in faulting zones; long term observations of deformation processes is crucial after shallow exploitation mining, that are the most prone to sinkhole occurrence.
		Perform periodical geophysical surveys, specifically gravimetric, electro-resistivity and seismic measurements, in areas of high sinkhole deformation hazard.
		Use data from temporary geophysical surveys data together with test borehole results to discriminate primary vs secondary voids and to estimate their dimension.
		Perform repeated geophysical surveys and seismic data analysis to monitor temporal changes in the former mining structure and the near-surface strata.
	Techniques	Different techniques can be used to characterise the geological structure, detect and image post-mining voids and observe their temporal evolution; they should be chosen and/or combined taking into account their penetration depth (PD).
Gravity	Monitoring	Continuous and periodic gravity measurement is useful to monitor regions prone to post-mining seismogenesis: those with potential void collapsing, unevenly saturated by water, or presenting residual tectonic stress and faults.
		Performing continuous monitoring helps the identification of mining and post-mining earthquakes and discriminant them from natural earthquakes.
		Performing periodical gravity measurements helps tracking temporal changes in the bulk density of the surveyed rock mass, which may reveal rock mass relaxation or seismic energy release, sometimes followed by surface morphology changes.

		Continuous gravity data can supplement seismic data, helping the assessment of ground motion and source mechanism. However, such a development remains at an early stage and we recommend using it only as a supplement to seismological monitoring; in such a case, the deployment of one gravity station during mine flooding can be sufficient for an integrated seismological-gravimetric monitoring.
		It is good practice to carry out periodic gravity measurements at a grid of points with a lateral spacing of ~500-1000 m, to help the interpretation of gravimetric data and identify temporal changes of the absolute gravity and Bouguer anomaly.
Seismicity	Monitoring	Post-mining seismicity poses a hazard comparable to mining seismicity and should be accurately monitored.
		Monitoring post-mining seismicity should allow the detection of earthquakes of similar size and with similar location accuracy as mining earthquakes.
		A combination of dense seismic monitoring and full-waveform analysis techniques allows an improved analysis of post-mining earthquakes and a better understanding of seismic processes.
		Adopting seismic network optimization procedures is envisaged to optimally design the deployment or the extension of seismic networks; network optimization tools provide network geometry solutions accounting for the target of seismological activity (e.g. location, source characterisation), accounting for accessibility, land use and/or seismic noise information.
	Methodologies	Full-waveform techniques are recommended for detection and location, as they can overcome challenging identification and picking of seismic phases in noise post-mining environments.
		Consider that accurate depth estimations are difficult for surface, post-mining monitoring: even with dense deployments and seismic sensors very close to or directly above the source, the small scale of the

		location problem requires very detailed seismic velocity models.
		Moment tensor (MT) analysis is a useful tool to investigate earthquake sources and discriminate among different processes; dense station networks providing a good azimuthal coverage, as e.g. at Gardanne (France), enables MT inversion for microseismic events.
		Implementation of detection, location and MT inversion into routine monitoring is desirable but challenging due to high uncertainties for small events.
		Full-waveform-based cluster analysis can help linking seismic events that occurred before the enhancement of a seismic network to more recent events recorded with improved station coverage.
	Monitoring optimization	Adopt seismic network optimization procedures to optimally design the deployment or the extension of seismic network; network optimization tools provide network geometry solutions accounting for the target of seismological activity (e.g. location, source characterisation), accounting for accessibility, land use and/or seismic noise information.
Deformation	GNSS	Include continuous surface deformation monitoring system based on high-frequency satellite observations from multiple GNSS, using as many satellites as possible, that allows precise determination of 3D displacements.
		The use of automated systems for monitoring surface deformation, based on differential GNSS are recommended; this allows deformation monitoring and identification of their anomalous changes, which may be precursor or result of post-mining seismicity.
		Out of many various measurement techniques and computational strategies of satellite navigation systems, adopt solutions accounting for techniques for developing observations, which will allow obtaining the maximum amount of information on the movement of the monitored point.

		It is advisable to develop the same, continuous observations on different monitored points using different computational strategies: post-processing and real-time computation, which enable a quick assessment on the level of land surface changes generated by specific seismic phenomena, thus facilitating the impact and damage assessment.
		Analyses of the course of displacement changes, based on solutions obtained from the development of observations in post-processing with a time resolution of 1 h are useful to identify increased, short-duration vertical (uplifts) velocities that may be an indicator of post-mining earthquakes. It is advantageous to carry out additional analyses based on RT solutions with a time resolution of 1 Hz, for a time interval that includes the period of the 24 hours in which the post-mining earthquake occurred.
		Use continuous GNSS monitoring when possible, specifically in areas of surface deformation exceeding the accuracy of InSAR.
	InSAR	Ensure quality and accuracy of InSAR measurements, by properly selecting (a) satellite sensors with appropriate wavelength and resolution, (b) images with valid interferometric capability, geometric and temporal baselines, (c) processing methods to ensure optimal results for the specific post-mining context.
		For induced seismicity, DInSAR technique provides approximate yet timely information on ground motions, enabling the detection of affected areas. The approach is valid for shallow and moderate or large magnitude earthquakes (centimetre-level motion). For weaker or deeper earthquakes, the higher accuracy of MT-InSAR techniques (PSI, SBAS-like) is required.
		Identify reference areas, with negligible deformation signals, that allow the quantification of ground motions induced by post-mining events.
		Choose radar wavelength based on presence and density of vegetation (i.e., the denser the vegetation the longer the wavelength), still considering that

		longer wavelengths are less sensitive to motion than shorter ones. Agreements between mining operators and satellite data providers may facilitate SAR archived data acquisition before an event and fast imagery acquisition after it.
		For phenomena occurring over long time scales, ensure regular analysis of InSAR images and report those to all relevant stakeholders, mentioning limitations and uncertainties.
		Establish a local reference network: a series of well-monitored reference points (e.g. GNSS corner reflectors) that aid interferometric processing. The reference network should be established with ground-based techniques, maintained and regularly updated.
Hydrological	Water level	Automated monitoring systems are recommended, ensuring real-time data. The sensing probes should be located in abandoned shafts or geological boreholes.
	Water origin	In mines where coal-bearing formations are covered with younger sediments, it is recommended to monitor water in each stratigraphic series.
	Physical-chemical properties	Simultaneous measurements of water properties (e.g. temperature, conductivity) are preferred.

8. GUIDELINE TO DESIGN AND MANAGE AN EARLY WARNING SYSTEM FOR POST-MINING SEISMIC RISK[8]

The aim of this chapter is to provide guidelines to monitor post-mining induced or triggered seismicity and suggestions to set up microseimic early warning system for public safety.

The main step to design an early warning system is to identify and characterise the hazard expected in the post-mining area. Mining hazard studies are carried out to determine the type of ground movement to be expected after closure and flooding, considering mainly parameters in relation with mine workings stability and with the geotechnical properties of the rock mass (Salmon et al., 2019). In France, in post-mining areas, the expected mechanisms of post-mining instability have been thoroughly studied by GEODERIS (GEODERIS, 2003 and 2016). In general, mining works located between 50 and 250 metres depths, usually exploited by the room-and-pillar method, on several levels and with a significant rate of extraction correspond to hazardous areas. Because of this shallow or intermediate depths, pillars failure could have ground surface effects, producing brittle massive collapse and subsidence. The objective of the microseismic monitoring is to anticipate the risk of brittle collapse by detecting microseismic precursor signs.

8.1. Design of post-mining early warning system applied to ground movement

As discussed in the guideline, the induce seismicity is not predictable, in the sense that their time and place of occurrence cannot be predicted. The early warning system allows to organise the actions based on the level of the seismicity. In the following section, we will describe the main physical parameter, the technical requirement, the data analysis and data governance.

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[1)] Ineris, Institut national de l'environnement Industriel et des risques - Mines Nancy, France.

8.1.1. Physical parameters to monitor

To design an early warning system, it is necessary to already have a precise idea of the expected hazard to be monitored. Here, 2 types of hazards must be considered: subsidence and post-mining seismicity.

The post-mining seismicity should be monitored where the relevant physical quantities to consider at least to anticipate these phenomena are as follows:

- The local and moment magnitudes which make it possible to quantify the energy released at the source of the earthquake.
- The number of events over a time sliding window, which makes it possible to quantify the acceleration of the phenomenon.
- The PGV (Peak Ground Velocity) which makes it possible to quantify the level of surface vibration, independently of the magnitude of a seismic event as the seismicity is usually located at shallow depth.

Other parameters can be considered in the early warning system, such as the underground water table level, especially if this level is maintained by pumping, and the precipitations.

Surface subsidence is as well an useful parameter because it enables to quantify the effects of the ground instability on the surface as the result of the underground mining works collapse. This means that surface ground movement monitoring does not allow to trigger emergency plans as it provides useful information only when the instability reaches the surface. That is why, we strongly recommend combining microseismic monitoring with surface movement measurements.

8.1.2. Technical requirements

The design of a post-mining seismic monitoring network can be quite delicate because several aspects need to be considered to ensure the best performances of the seismic network, in terms of detection and location of seismic events. First of all, it seems judicious to install the seismological monitoring network before starting the flooding operations. Indeed, when the old mining works are still accessible, the probes can be directly installed at the level of the mining works, with a water-resistant device that will resist to the future flooding. To complete this installation surface sensors can be as well installed at the surface to distinguish anthropogenic seismic event coming from the surface from events coming from underground instabilities.

If the mine is no longer accessible, installing sensors in boreholes drilled from the surface is a solution to isolate the instrument from anthropogenic noise and bring it closer to the target zones to be monitored, i.e., old mining works and seismic faults likely to be reactivated. The seismic probes will be thus placed in the well as a vertical antenna in the borehole for instance, or with other geometry. It will be necessary to place probes on the surface and also at intermediate depths to distinguish the events coming from the underground to those coming from the surface, generally correspond to noises or mechanical vibrations.

In both cases, the number and distribution of sensors depend on the excepted magnitude of completeness and the desired location precision as well as the extent of the area to be monitored. The design of the network can be carried out based on a numerical simulation, which proposes a seismic network geometry, with a minimum number of sensors, according to the level of ambient noise and the technical constraints of the environment. Indeed, the zones to be monitored are generally located in areas where there is significant human activity. This activity generates noise that degrades network detection performance. But sometimes, it's not possible to choose the locations of the sensors, because of too many constraints, such as the distribution of the habitations or of the infrastructures, the availability of power supply, etc ... In any case, the numerical simulation can still be carried out to quantify the theoretical performance of this network, detect biases induced by the network geometry and estimate the magnitude of completeness. If the objective of the microseismic monitoring network is also to be able to calculate focal mechanisms, it may be interesting to enlarge the extent of the zone to be monitored in order to have greater azimuthal coverage.

Two types of sensors can be used, however, the installation of triaxial sensors will be preferred to uniaxial sensors. Indeed, they allow a better characterization of the polarization of the seismic wave, and the estimation of the source parameters as well as of the focal mechanisms (which is not possible with 1-component sensors). The choice of the type of sensors, velocimeter or accelerometer can also have an important role in the design and in the performances of the network. The velocimeter is generally more suitable for recording a low magnitude earthquake at a long distance. On the other hand, it is more sensitive to installation conditions and temperature variations. The accelerometer is particularly suitable for recording strong movements at short distance, without risk of saturation of the seismic signal.

8.1.3. Seismic data processing

As the objective of the monitoring network is to alert as soon as possible of the occurrence of an abnormal situation, this implies that the microseismic data need to be processed in near real time. This involves the use of automatic algorithms for detecting, locating and calculating the magnitude of seismic events as well as the PGV and the errors associated to these parameters. The results obtained must then be regularly validated by the operator in charge of this monitoring. This validation includes reprocessing to refine, if necessary, the results from automatic processing.

An attention should be paid for the error calculation. The location errors, calculated from a unique vertical seismic antenna located in a borehole, can be reduced if the angles of polarization are used both with the arrival times of the P and S (Contrucci et al., 2010). In addition, if the old mining works are still accessible, calibration blasts can be carried out from these old works. This kind of experimentation can be helpful to test the seismic sensor response, especially to verify the orientation of the 3-component sensors. It will help as well to calibrate the velocity model use for the location calculation. If it is not possible to carry out this type of experiment, the velocity model could be built from geophysical, geological and structural data acquired on the site at the time of exploitation (drilling, VSP, logs, etc.) or thanks to natural earthquakes or carry blasts.

In addition, one of the most important tasks of microseismic monitoring is to be able to separate the relevant seismological data which demonstrate an underground instability from that resulting from anthropogenic activity. In a first step, this work could be carried out by an operator to build a waveform library that corresponds to each type of phenomenon expected on the site: surface noise, drilling noise, noise due to storms, quarry blast, seismic event coming from the basement etc… once the catalogue has been established, an automatic or semi-automatic sorting strategy must be put in place. For example, surface noises can be easily recognized automatically, because the amplitude of the event is usually stronger on the surface probe than on the bottom. More advanced algorithms based on artificial intelligence can also be used to carry out an automatic sorting of the seismic data after a period of machine learning based on the reference catalogue previously produced (Kazmierczak et al., 2020).

8.1.4. Alarm criteria and monitoring procedure

The aim is to monitor both mining related instabilities and post-mining seismic hazard. In other words, it is necessary to define a monitoring criterion that will enable to:

- detect the underground initiation of mining instability before the occurrence of surface effects like subsidence.
- evaluate the surface vibration levels to quantify the perception of seismic events and assess any damage to buildings and/or infrastructures.

To effectively monitor these feared phenomena, criteria such as the seismicity rate over a 24-hour sliding window, the local and moment magnitudes as well as the PGV associated with the intensity scales are relevant parameters.

From an operational point of view, two levels of alarm can be adopted (Fig. 8.1):

- level I, exceeding predetermined thresholds will activate the vigilance mode. This level is associated with activity above the background noise regime, indicating the detection of underground precursory signs and/or an abnormal level of surface vibrations.
- level II, exceeding thresholds will trigger the alarm mode. This level qualifies the acceleration of the phenomenon or the perception of vibration on the surface. At this

stage, it is necessary to promptly convoke a committee of experts to analyse the situation and, if necessary, inform the local authorities.

The criteria for exiting alarm levels I and II should be defined according to the specific site being monitored. For example, it could be proposed that if no additional activity is observed within 7 days after the activation of a level I or II alarm, a return to the normal regime can be declared.

The absolute values of the various alarm thresholds must be specific to the site being monitored. These threshold values are not always easy to define without existing on-site data. Therefore, to ensure the reliability of these criteria, a test period will be conducted before operational applying of these values. It should be kept in mind that the onset of a mining instability, as mentioned earlier, can begin with small fractures sizes. Therefore, the initial vigilance alert threshold on number of microseismic events originating from the underground should be relatively low, on the order of ten within a time window of the order of 24 hours. Similarly, the first alert threshold on magnitude should be set at relatively low levels, around 0, since mining instabilities typically result in low-magnitude events.

The first threshold of PGV can be of the order of 1 mm/s which corresponds to a weak human perception, without causing any damage to buildings (refer to chapter 5 and 6). In the case of a more intense seismic event, real-time shaking maps can be generated to assess the areas that will experience the strongest motions. Indeed, as the magnitude increases and the earthquake source becomes shallower, the seismic motion on the surface becomes stronger. To estimate the expected ground movements, it is necessary to establish a Ground Motion Prediction Equation (GMPE), which depends on factors such as epicentral distance, magnitude, and other parameters related to the seismic source or wave propagation conditions at the site (refer to the section 5). Finally, the link between ground motion and potential surface damage can be established using intensity scales, as developed within the framework of the PostMinQuake project (Section 5).

In summary, exceeding the alarm thresholds of level I aims to alert the monitoring operator that abnormal activity, above the background noise level, is occurring (Fig. 8.1). In this case, it is necessary to switch to a vigilant mode, which involves closer monitoring (operator checking at less 2 times a day) and validation of data trends and, if possible, comparing them with other available data (such as groundwater levels, nearby mining activity if the closed mine is located close to an active mine, etc.). Exceeding the alarm thresholds of level II indicates an acceleration or intensification of the monitored phenomena. In such cases, it is necessary to be on duty 24/24 for data processing and analysis. It is also strongly recommended to convene a committee of experts who will assess the ongoing evolution of the phenomenon. Depending on the legislation in the respective country, this committee may inform the competent authorities, who will then take the necessary measures to ensure the safety of people and property. This general alert process should be documented in a procedure that is approved in advance by all stakeholders. Additionally, to ensure the smooth functioning of this process and to ensure that everyone understands their role, regular exercises can be conducted to simulate a crisis. A logigram can resume all the actions to perform in case of alarm as presented in figure 8.1 for instance.

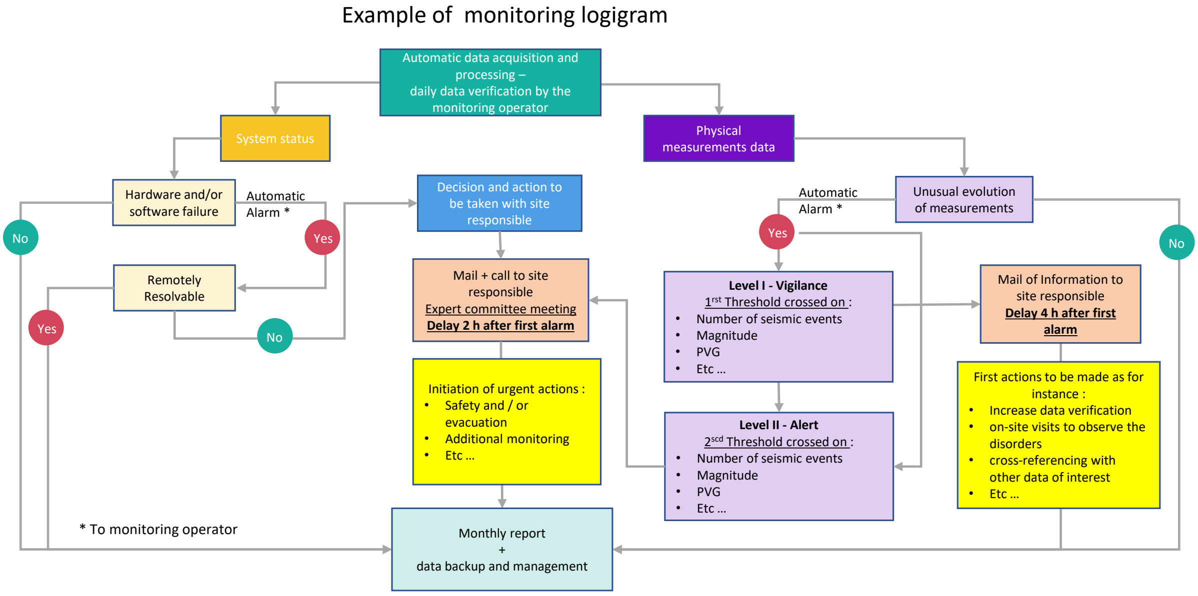

Fig. 8.1. Example of monitoring logigram

The deployment of additional seismological monitoring stations or other measures, such as GPS, can be considered. Indeed, such deployment can aid in understanding ongoing phenomena and assist experts in decision-making. Furthermore, conducting a thorough back analysis can enhance the understanding of these phenomena and address concerns regarding post-mining issues, benefiting to a wider audience.

8.2. Data governance

Data governance in the context of post-mining hazard management is of crucial importance to ensure effective management of data in the long term. It covers several aspects such as the:

- Preservation of archives and mining history after cessing the mining activities: Data preservation should include measures for the preservation of archives and mining history once miners have left the site. This involves defining protocols for document management, digitizing relevant information, and secure storage to ensure long-term access to this data.
- Operational management of networks, maintenance, and long-term surveillance: Data administration needs to address the operational management of networks, maintenance, and long-term surveillance of post-mining equipment and infrastructure. This includes

implementing protocols for monitoring, preventive maintenance, replacement of defective equipment, and regular surveillance to ensure the continuous functioning of systems.

- Archiving and long-term storage of data, preservation of processing parameters and changes in measurement chains: Data archiving must ensure the long-term storage of data. It is crucial to preserve the processing parameters used and changes in the measurement chain for complete data traceability. Data should be stored in universal and easily convertible formats to facilitate accessibility and reuse.
- Updating procedures based on acquired knowledge: Data management should provide mechanisms for updating procedures based on acquired knowledge over time. New insights and lessons learned should be incorporated into surveillance and management procedures to continuously improve practices and ensure optimal data handling.
- Compliance with FAIR principles for data: Data oversight should ensure that data follows the FAIR principles (Findable, Accessible, Interoperable, Reusable). This involves implementing strategies to make data easily findable, accessible, interoperable, and reusable, both within and outside the organization.
- Cost of long-term post-mining surveillance: Data governance should consider the cost associated with establishing and maintaining post-mining surveillance. It is essential to define policies and procedures to optimize resources and ensure continuous monitoring while minimizing costs.

Thus, it is necessary to establish clear protocols for collecting, storing, and sharing the information generated by the microseismic surveillance network, as well as by other instruments installed on site such as piezometers. This ensures that the data is accessible to all relevant stakeholders, including scientists, post-mining operators, and competent authorities, for transparency, collaboration, and a better understanding of post-mining seismic phenomena.

8.3. Recommendation and conclusions

Post-mining surveillance is particularly effective when planned before the mine's closure. The design of a microseismic surveillance network, such as an early warning system, depends on the expected ground instability mechanisms and their kinetics. This system is intended to detect precursor signs of underground mine failure or detect seismic movements due to seismic fault reactivation, enabling a rapid response to ensure the safety of individuals and infrastructures at the surface.

To achieve this, it is important to consider the mine's historical context during its operational phase. This allows for an understanding of the geological characteristics and potential risks associated with past mining activities. Additionally, we recommend installing the surveillance network prior to the mine's flooding and conducting a retrospective analysis of the initial data to enhance comprehension of the anticipated seismic phenomena, such as post-mining instability and fault reactivation caused by flooding. This analysis will aid in defining alarm thresholds, forming the basis for the surveillance procedure. Exceeding these thresholds will trigger predetermined actions by the involved stakeholders to ensure the safety of people and property.

Furthermore, it is advisable to publish seismic catalogs and epicenter maps in near-real-time on accessible websites for all relevant parties. This transparency promotes knowledge dissemination and contributes to better management of mining-related risks.

9. CONCLUSIONS AND GENERAL RECOMMENDATIONS[9]

The guidelines were developed to assess and control negative dynamic phenomena (vibration, deformation) observed on the ground surface in areas of closed underground coal mines, especially at different stages of their flooding process. The guidelines are based on research conducted as part of the PostMinQuake project on induced seismicity and surface stability in post-mining areas and represent the completion of Deliverable 7.2. **entitled: "A comprehensive book (transnational guidelines) on a method on assessment and monitoring of seismic hazard in post mining areas".** The guidelines developed can be applied to post-mining coal areas in the EU and around the world, particularly during the period of mine flooding. The guidelines are addressed mainly to mining consultants, potential investors and decision-making bodies in post-mining areas, including authorities responsible for managing closed mines. Detailed methodologies for carrying out the work are included in the chapters from 3 to 8.

The following important conclusions relating to the content of the guidelines have been formulated:

- Coal mine closures are accompanied by numerous environmental hazards, whereof one of the most significant is post-mining seismic activity, which is one of the earliest indicators of rock mass instability and can cause minor or severe damage to buildings and surface infrastructure. It can be the cause of the reactivation of shallow goafs, and it can bring about sinkholes or other discontinuous deformations.. Such dangerous phenomena can threaten the safety of the population and cause difficulties in the development of land after the closure of a coal mine.
- The assessment of seismic hazard in post-mining areas, particularly related to mine flooding, should be carried out using data that are essential for coal mine decommissioning, mine flooding design, the flooding process, and for the assessment of hazards (induced seismicity and surface deformation) associated with mine flooding, i.e. geological data on the rock mass and land surface, hydrogeological data, mining data, and seismic data and other geophysical data.

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- In areas affected by mine decommissioning, particularly during the period of mine flooding, hydro-mechanical perturbations in the rocks can be a potential cause of triggering seismic activity. Due to the flooding process of mines and fluctuations in the water table, rocks around such mines are subject to changes in their mechanical equilibrium. Seismic events may occur due to the fractures of mine structures, such as pillars, or the reactivation of existing geological discontinuities.
- In order to assess the impact of the flooding process and the fluctuation of the water table on the triggering of seismic activity in closed coal mines, it is beneficial to conduct hydro-mechanical numerical predictive simulations. The most relevant solution in this case is to collect data linking water level evolution and the recorded seismic events during the same period. In practice, these models should be implemented before mine closure based on seismicity information obtained during the mining period. At this stage, key parameters should be extracted and a monitoring protocol established, as well as recommendations for characterization and further modelling. Models should in each case take into account faults, as they have a high potential for seismic triggering.
- Ground vibrations caused by post-mining earthquakes can affect the response of surface infrastructure, the perception of earthquakes by people and disrupt daily life and bring about disruptions in the normal use of buildings. To determine the level and effects of post-mining earthquakes, it is necessary to know the parameters of ground motion at the site being evaluated. For this purpose, it is necessary to implement seismic monitoring (regional, local), develop a prediction equation for ground motion and spatial variation of ground motion for the observed areas.
- To assess the impact of post-mining earthquake vibrations on buildings, the perceptibility of vibrations to people, the level of inconvenience of building use and an empirical criterion for the dynamic resistance of buildings, the Mining and Post Mining Seismic Instrumental Intensity Scale, MSIIS-22, developed as a result of the project, can be used. This scale, in particular, allows empirical assessment of the resistance of buildings to mining and post-mining earthquakes. Comparison of the dynamic resistance of buildings, considering the type of building and its technical conditiSons, with the prediction of instrumental levels of intensity of post-mining earthquakes, allows assessing the safety of the transmission of dynamic impacts by buildings. For the assessment of damage to buildings and surface infrastructure due to the occurrence of a post-mining earthquake, the macroseismic intensity of the MSIIS-22 scale or the macroseismic intensity of the EMS-98 scale and the Risk-UE Level 1 method can be used, or together the macroseismic intensity of the MSIIS-22 scale with an adaptation of the Risk-UE Level 1 method.
- The process of mine closure, particularly at the stage of mine decommissioning and flooding, is accompanied by surface and rock mass deformation processes, as well as

seismicity. Underground instabilities in the mine structure, the formation and destruction of deep voids, the reduction of fault friction in response to mine flooding and the triggering of local post-mining earthquakes are processes that can occur in the post-closure period. Identifying such processes, fully understanding and distinguishing them, and modelling them is possible but very difficult and requires multidisciplinary monitoring. Therefore, in post-mining areas, especially during the period of mine flooding, it is important to conduct comprehensive monitoring that includes: temporary near-surface geophysical measurements, continuous and periodic gravity monitoring, seismic monitoring, surface deformation monitoring, monitoring of water in deep and shallow parts of the rock mass. The integration of monitoring results is the key to establishing a comprehensive monitoring system. The monitoring plan should be developed in cooperation with all stakeholders, including the mining company, regulatory authorities and local communities.

- In order to ensure public safety in seismically active post-mining areas, it would be beneficial to establish an early warning system for ground movement. Such a system should be designed after identifying and characterizing the hazard expected in a post-mining area, in this case surface deformation and post-mining seismicity. Therefore, it should use the results of microseismic monitoring and surface movements. Other parameters such as the level of the groundwater table and precipitation may also be taken into account. Post-mining surveillance is particularly effective when planned before mine closure.

Based on the experience resulting from the implementation of the project, the table 9.1 presents the monitoring actions, during the period of coal mine flooding. The monitoring program depends on the depth of water level in the rock mass, i.e. in the conditions when water level in the rock mass is up to a depth of 100 m (Case 1) and above 100 m (Case 2). In the first case, the scope of monitoring indicated in the table should be treated as obligatory, and in the second case the indicated range should be considered as recommended. It should be noted that the following indications may be changed by the user, depending on local conditions in the post-mining area.

Table 9.1

Obligatory and recommended monitoring program in coal mines in the process of flooding (+ indicates the need to use a monitoring method)

No.	Monitoring method	Water level in rock - mass at depth ≤100m -Case 1-	Water level in rock-mass at depth>100m -Case 2-
		Obligatory	Recommended
1	Regional seismological continuous observations	+	+
2	Local seismological continuous observations	+	
3	Continuous water level observations in stratigraphic series in depth range from surface to the point of deepest shaft in a mine	+	
4	Temporary water level observations in stratigraphic series in depth range from surface to the point of deepest shaft in a mine		+
5	InSAR	+	+
6	GNSS		+
7	Continuous gravity observations		+
8	Periodic gravity surveys in areas of shallow room and pillar mining	+	

The mine decommissioning plan should provide a hydro-mechanical model of the rock mass, which should be used to assess the impact of the flooding process and water table fluctuations on the triggering of seismic activity.

The assessment of the impact of post-mining earthquake vibrations on buildings, the perceptibility of vibrations to people, and the assessment of the safety of transmission of dynamic impacts through buildings and the assessment of damage to facilities should be carried out on an ongoing basis, based on seismic monitoring data and data on the technical condition of facilities, throughout the period of mine flooding.

In order to ensure public safety and effective management of the post-mining area, especially during the period of mine flooding, it would be advisable to implement the proposed early warning system. Such a system should be developed before the start of the mine flooding process.

REFERENCES

1. Aki K.: Generation and propagation of G waves from the Niigata Earthquake of June 16, 1964. Part 2. Estimation of earthquake moment, released energy, and stress-strain drop from the G wave spectrum. *Bulletin of the Earthquake Research Institute*, vol. 44, pp. 73-88, 1966.
2. Atkinson, G.M.: Ground-motion prediction equation for small-to-moderate events at short hypocentral distances, with application to induced-seismicity hazards. *Bulletin of the Seismological Society of America,* 105(2A), 981-992, 2015.
3. Bal, I.E., Dais, D., Smyrou, E.: "Differences" between induced and natural seismic events. „16th European Conference on Earthquake Engineering", Thessaloniki, Greece, 2018.
4. Bamler R., Adam N., Hinz S., Eineder M.: SAR-Interferometrie für geodätische Anwendungen. – Allg. Vermess.-Nachr., 115(7): 243–252, 2008.
5. Barton, N., Lien, R., and Lunde, J.: Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, Vol. 6, No. 4, 1974.
6. Berardino, P., Fornaro, G., Lanari, R., Sansosti, E.: A new algorithm for surface deformation monitoring based on Small Baseline Differential SAR Interferograms. IEEE Trans. Geo. Rem. Sens. 40(11): 2375-2383, 2002.
7. Bieniawski, Z.T.: Rock mass classification in rock engineering, [in:] Proceedings of the Symposium Exploration for Rock Engineering. Johannesburg, South Africa 1976.
8. Bragato P.L.: Systematic Triggering of Large Earthquakes by Karst Water Recharge: Statistical Evidence in Northeastern Italy. „Frontiers in Earth Science", Front. Earth Sci. 9:664932, DOI: 10.3389/feart.2021.664932, 2021.
9. Broccardo, M., Mignan, A., Grigoli, F., Karvounis, D., Rinaldi, A. P., Danciu, L., Wiemer, S.: Induced seismicity risk analysis of the hydraulic stimulation of a geothermal well on Geldinganes, Iceland. *Natural Hazards and Earth System Sciences*, Vol. 20, No. 6, 2020.
10. Burshtein L.S.: Effect of moisture on the strength and deformability of sandstone. *Soviet Mining Science*, Vol. 5, No. 5, 1969.
11. Busch W., Coldewey W.G., Walter D., Wesche D., Tielmann I.: Analyse von Senkungserscheinungen außerhalb prognostizierter Einwirkungsbereiche des Bergwerks Prosper-Haniel. – Gutachten der TU Clausthal und der WWU Münster vom 31.8.2012 im

Auftrag der Bezirksregierung Arnsberg (Abt. 6), 140 p.; Clausthal-Zellerfeld, https://www.bezreg-arnsberg.nrw.de/presse/2012/09/160_12/gutachten.pdf, 2012.
12. Camelbeeck T., Van Noten K., Lecocq T., Hendrickx M.: The damaging character of shallow 20th century earthquakes in the Hainaut coal area (Belgium). *Solid Earth,* Vol. 13, No. 3, 2022.
13. Canadian Standards Association, 1991. Risk Analysis Requirements and Guidelines. CAN/CSA-Q634-M91, 42p.
14. Caputa A., Rudziński Ł., Cesca S.: How to Assess the Moment Tensor Inversion Resolution for Mining Induced Seismicity: A Case Study for the Rudna Mine, Poland. *Frontiers in Earth Science*, *9*, 671207, 2021.
15. Casu, F., Elefante, S., Imperatore, P., Zinno, I., Manunta, M., De Luca, C., Lanari, R.: SBAS-DInSAR Parallel Processing for Deformation Time-Series Computation. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 2014, 7, 3285–3296.
16. Cesca, S.: Seiscloud, a tool for density-based seismicity clustering and visualization. *Journal of Seismology*, *24*(3), 443-457, 2020.
17. Cesca S., Grigoli F.: Full waveform seismological advances for microseismic monitoring. *Advances in Geophysics*, *56*, 169-228, 2015.
18. Cesca, S., et al.: Seismicity at the Castor gas reservoir driven by pore pressure diffusion and asperities loading. *Nature communications*, *12*(1), 4783, 2021.
19. Cesca, S., Şen, A.T., Dahm, T.: Seismicity monitoring by cluster analysis of moment tensors. *Geophysical Journal International*, *196*(3), 1813-1826, 2014.
20. Chen, X., Shearer, P.M.: Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *Journal of Geophysical Research Res. 116*, B09309, doi:10.1029/2011JB008263, 2011.
21. Contrucci, I., Klein E., Bigarré P., LizeurA., Lomax A., and Bennani M.: Management of Post-mining Large-scale Ground Failures: Blast Swarms Field Experiment for Calibration of Permanent Microseismic Early-warning Systems, *Pure Appl. Geophys.*, *167*(1-2), 43-62, 2010.
22. Contrucci, I., Namjesnik, D., Niemz, P., Primo Doncel, P., Kotyrba A., Mutke, G., Konicek, P., Dominique, P., Rudolph, T., Möllerherm, S., Kinscher, J., Klein, E., Cesca, S.: European feedback on post-mining seismicity, *Journal of Sustainable Mining*, 2023.
23. Cremen, G., Werner, M.J.: A novel approach to assessing nuisance risk from seismicity induced by UK shale gas development, with implications for future policy design. *„Natural Hazards and Earth System Sciences",* Vol. 20, No. 10, 2020.
24. Crowley, H., Pinho, R., van Elk, J., Uilenreef, J.: Probabilistic damage assessment of buildings due to induced seismicity. *Bulletin of Earthquake Engineering*, Vol. 17, No. 8, 2019.

25. Crowley, H., Pinho, R.: Report on the Fragility and Consequence Models for the Groningen Field (Version 7). Report for Groningen field seismic hazard and risk assessment, NAM, 2020.
26. Crowley, H., Polidoro, B., Pinho, R., van Elk , H.: Fragility and consequence models for probabilistic seismic risk assessment in the Groningen gas field. „16th European Conference on Earthquake Engineering", Thessaloniki, Greece, 2018.
27. Daneshfar, R., Moghadasi, J.: Clay swelling: A critical review of 50 years of research, [in:] Proceedings of the 6th International Conference on Oil, Gas, Refining and Petrochemical with focus on Relationship Between Government, University and Industry. Shiraz, Iran 2017.
28. Declercq, P.-Y., Dusar, M., Pirard, E., Verbeurgt, J., Choopani, A., Devleeschouwer, X.: Post Mining Ground Deformations Transition Related to Coal Mines Closure in the Campine Coal Basin, Belgium, Evidenced by Three Decades of MT-InSAR Data. Remote Sens. 2023, 15, 725. https://doi.org/10.3390/rs15030725
29. Deere, D.U., Hendron, A.J., Patton, F.D., Cording, E.J.: Design of surface and near surface construction in rock, [in:] Proceedings of the 8th U.S. Symposium on Rock Mechanics. Minneapolis, Minn., USA 1967.
30. Deliverable report 1.4 of COMEX project : Handbook for a New European mining seismic intensity scale MSIIS-15. Grant Agreement Number: RFCS-CT-2012-00003. Research Programme of the Research Fund for Coal and Steel, 2015.
31. Deliverable report 5.3 of the PostMinQuake project : Synthesis on Ground motion prediction equation (GMPE). Grant Agreement Number: 899192 − PostMinQuake − RFCS-2019, 2022.
32. Didier Ch., Merwe N., Betourney M., Mainz M., Kotyrba A., Aydan Ö., Jossien J.P., Song W.K.: Mine closure and post-mining management, International State of the Art. ISRM Mine Closure Commission Report, 10.13140/2.1.3267.8407, 2008.
33. Dominique P., Aochi H., Morel J.: Triggered Seismicity in a Flooded Former Coal Mining Basin (Gardanne Area, France). *Mine Water and the Environment*, 41:317-334, https://doi.org/10.1007/s10230-022-00860-z, 2022.
34. Douglas, J.: Ground motion prediction equations (1964-2022), available at http://gmpe.org.uk (last accessed July 2022).
35. Dubiński J., Mutke G., Chodacki J. : Distribution of peak ground vibration caused by mining-induced seismic events in the Upper Silesian Coal Basin in Poland, *Arch. Min. Sci.* 65(2020), 3, 419-432, DOI: 10.24425/ams.2020.133200, 2020.
36. Dudek, M., Tajduś, K.: FEM for prediction of surface deformations induced by flooding of steeply inclined mining seams. *Geomechanics for Energy and the Environment*, 28. https://doi.org/10.1016/j.gete.2021.100254, 2021.
37. Dyke C.G., Dobereiner L.: Evaluating the strength and deformability of sandstones. *Quarterly Journal of Engineering Geology and Hydrogeology,* Vol. 24, No. 1, 1991.

38. Edwards, B., Crowley, H., Pinho, R., Bommer, J.J.: Seismic hazard and risk due to induced earthquakes at a shale gas site. *Bulletin of the Seismological Society of America,* Vol. 111, No. 2, 2021.
39. Ellsworth W.L.: Injection-Induced Earthquakes. *Science*, 341 (6142), 1225942, DOI: 10.1126/science.1225942, 2013.
40. Eulenfeld, T., Dahm, T., Heimann, S., Wegler, U.: Fast and robust earthquake source spectra and moment magnitudes from envelope inversion. *Bulletin of the Seismological Society of America*, *112*(2), 878-893, 2022.
41. Ferretti, A., Prati, C. and Rocca, F. "Permanent scatterers in SAR interferometry," in IEEE Transactions on Geoscience and Remote Sensing, vol. 39, no. 1, pp. 8-20, Jan. 2001, doi: 10.1109/36.898661.
42. Frolik A., Siwek S., Kierepka W.: Wahania zwierciadła wód podziemnych pod wpływem wstrząsów górniczych w obszarze kopalni Rydułtowy. Przegląd Geologiczny 68(3), 2020.
43. Gehl, P., Douglas, J., D'Ayala, D.: Inferring earthquake ground-motion fields with Bayesian Networks, *Bulletin of the Seismological Society of America*, 107(6), 2017.
44. Geoderis : Expertise internationale du dossier d'arrêt définitif des travaux des concessions de Gardanne (13). Rapport Geoderis 03-PACA-5001R03, octobre 2003.Rep., 2003.
45. Geoderis : Bassin de lignite de Provence (13) Révision et mise à jour des aléas liés à l'ancienne activité minière, S-2016/004DE-16PAC22070.Rep., 2016.
46. Grigoli, F., Cesca, S., Vassallo, M., Dahm, T. (2013). Automated seismic event location by travel-time stacking: An application to mining induced seismicity. *Seismological Research Letters*, *84*(4), 666-677.
47. Grünthal, G.: European macroseismic scale 1998 (EMS-98). „Cahiers du Centre Européen de Géodynamique et de Séismologie", Vol. 15, 1998.
48. Guéguen, Y., Deffontaines, B,; Fruneau, B.: Monitoring residual mining subsidence of Nord/Pas-de-Calais coal basin from differential and Persistent Scatterer Interferometry (Northern France). *J. Appl. Geophys*. 2009, 69, 24–34.
49. Guha Roy, D., Sinhg. T.N., Kodikara. J., Das, R.: Effect of water saturation on the fracture and mechanical properties of sedimentary rocks. *Rock Mechanics and Rock Engineering*, Vol. 50, No. 10, 2017.
50. Hardt, M., Scherbaum, F.: The design of optimum networks for aftershock recordings. *Geophys. J. Int.* 117, 716-726, 1994.
51. Hawkins, A.B., McConnell, B.J.: Sensitivity of sandstone strength and deformability to changes in moisture content. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 25, No. 2, 1992.
52. Heimann, S., et al.: Grond: a probabilistic earthquake source inversion framework, Potsdam, GFZ Data Services. https://doi.org/10.5880/GFZ.2.1.2018.003, 2018.

53. Hejmanowski, R., Malinowska, A.A., Witkowski, W.T., Guzy, A.: An Analysis Applying InSAR of Subsidence Caused by Nearby Mining-Induced Earthquakes. *Geosciences* 2019, 9, 490. https://doi.org/10.3390/geosciences9120490.
54. Hirschwald. J.: Die Prüfung der natürlichen Bausteine auf ihre Wetterbeständigkeit. Zeitschrift für praktische geologie, Vol. 16, 1908.
55. Hoek, E., Carter, T.G. and Diederichs, M.S.: Quantification of the geological strength index chart, [in:] Pyrak-Nolte, L.J., Chan, A., Dershowitz, W., Morris, J., Rostami, J. (eds): 47th US Rock Mechanics/Geomechanics Symposium. San Francisco, CA, USA 2013.
56. Hooper, A., Zebker, H., Segall, P., Kampes, B.: A New Method for Measuring Deformation on Volcanoes and Other Natural Terrains Using Insar Persistent Scatterers. Geophys. Res. Lett. 2004, 31, L23611.
57. https://creativecommoms.org/licenses/by-sa/3.0/, accessed June 24, 2023.
58. International Society For Rock Mechanics Commission On Testing Methods (ISRM): Suggested methods for determining tensile strength of rock materials. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, Vol. 15, No. 3, 1978.
59. International Society For Rock Mechanics Commission On Testing Methods (ISRM): Suggested methods for determining the uniaxial compressive strength and deformability of rock materials. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, Vol. 16, No. 2, 1979.
60. Jeanne P., Rutqvist J., Foxall W., Rinaldi A.P., Wainwright H.M., Zhou Q., Birkholzer J., Layland-Bachmann C.: Effects of the distribution and evolution of the coefficient of friction along a fault on the assessment of the seismic activity associated with a hypothetical industrial-scale geologic CO2 sequestration operation. *International Journal of Greenhouse Gas Control*, n° 66 pp. 254–263, 2017.
61. Jimenez Gonzalez, I., Scherer, G.W.: Effect of swelling inhibitors on the swelling and stress relaxation of clay bearing stones. *Environmental Geology*, Vol. 46, No. 3–4, 2004.
62. Jiránková, E., Lazecký, M. (2016). Specifics in the formation of subsidence troughs in the Karvina part of the Ostrava-Karvina coalfield with the use of radar interferometry. *Acta Geodynamica et Geomaterialia*, *13*(3). https://doi.org/10.13168/AGG.2016.0008
63. Jiránková, E., Lazecky, M.: Ground surface uplift during subsidence trough formation due to longwall mining in the shaft protection pillar of the CSM Mine. *Bulletin of Engineering Geology and the Environment*, *81*(9). https://doi.org/10.1007/s10064-022-02896-5, 2022.
64. Joyner, W.B., and D.M. Boore : Methods for regression analysis of strong motion data, *Bulletin of the Seismological Society of America,* 83 (2), 469-487, 1993.

65. Joyner, W.B., Boore, D.M: Peak horizontal acceleration and velocity from strong motion records including records from the 1979 Imperial Valley, California, earthquake. Bull. Seismol. Soc. Am. 71 (6), 2011–2038, 1981.
66. Kagan, Y.Y., Jackson, D.D. (1991). Long-term earthquake clustering, *Geophys. J. Int*., 104, 117-133.
67. Kazmierczak J.-B., Lizeur A., Contrucci I., and Bigarré P.: Application du machine learning à la surveillance d'opérations industrielles du sous-sol, paper presented at *Journées Nationales de Géotechnique et de Géologie de l'Ingénieur*, Lyon, 2020.
68. Kijko, A.: A modified form of the first Gumbel distribution: model for the occurrence of large earthquakes. Part I. Derivation of distribution. *Acta Geophysica Pololonica*, 30, 333-340, 1982.
69. Kijko, A.: A modified form of the first Gumbel distribution: model for the occurrence of large earthquakes. Part II. Estimation of parameters. *Acta Geophysica Polonica*, 31, 147-159, 1983.
70. Kotyrba A.: Zagrożenie i ryzyko zapadliskowe terenów GZW. *Wiadomości Górnicze* nr 7-8. Katowice, 2005.
71. Kotyrba A.: Grawimetryczny system ciągłej obserwacji wstrząsów indukowanych działalnością górniczą. *Przegląd Górniczy* nr 1, 2022.
72. Kotyrba A., Frolik A., Kortas Ł., Siwek S.: Grawimetryczno-hydrometryczny system monitoringu wstrząsów górniczych na Górnym Śląsku. *Przegląd Geologiczny.* Vol. 68, nr 11, 2020.
73. Kotyrba A., Kortas Ł.: Geophysical imprint of mining-induced rock mass deformation in the area of construction disaster in Bytom (Poland). *Journal of Sustainable Mining.* Vol. 22. Issue 2, 2023.
74. Kotyrba A., Kortas Ł. Stańczyk K.: Imaging the underground coal gasification zone by microgravity surveys. *Acta Geophysica* vol. 63, no. 3, 2015.
75. Kotyrba A., Kortas Ł.: Co-seismic signals of mining tremors in continuous recordings of gravity by gPhoneX tidal gravimeters. *International Journal of Rock Mechanics and Mining Sciences.* Vol. 129, 2020.
76. Kotyrba A., Mutke G.: Impact of deep mining on shallow voids stability and sinkhole hazard. Fifth International Symposium - Mineral Resources and Mine Development. 27-28 May. AIMS, Vol. 14. Aachen, 2015.
77. Kotyrba A., Stańczyk K.: Sensing the Underground Coal Gasification by Ground Penetrating Radar. *Acta Geophysica* vol. 65, Issue 6, 2017.
78. Kraft, T., Mignan, A., Giardini, D.: Optimization of a large-scale microseismic monitoring network in northern Switzerland. *Geophys. J. Int.*, 195(1), 474-490, 2013.

79. Krawczyk A, Grzybek R.: An evaluation of processing InSAR Sentinel-1A/B data for correlation of mining subsidence with mining induced tremors in the Upper Silesian Coal Basin (Poland) E3S Web Conf., 26 (2018) 00003, DOI: https://doi.org/10.1051/e3sconf/20182600003
80. Kuehn, N.M., Abrahamson, N.A.: The effect of uncertainty in predictor variables on the estimation of ground-motion prediction equations. *Bulletin of the Seismological Society of America*, *108*(1), 358-370, 2018.
81. Lagomarsino, S., Giovinazzi, S.: Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. *Bulletin of Earthquake Engineering*, Vol. 4, 2006.
82. Lau, C.L.P.: Experimental investigation of the effect of water and temperature on mechanical properties of rocks. Bachelor thesis. The University of Queensland, Brisbane, Australia 2016, 51 pp.
83. Lee K.L., Ellsworth W.L., Giardini D., Townend J., Ge S., Shimamoto T., Yeo I.-W., Kang T.-S., Rhie J., Sheen D.-H., Chang C., Woo J.U., Langenbruch C.: Managing injection-induced seismic risks. „Science" 364 (6442), 730-732. DOI: 10.1126/science.aax1878, 2019.
84. López Comino, J.Á. et al.: Automated full waveform detection and location algorithm of acoustic emissions from hydraulic fracturing experiment. In *ISRM European Rock Mechanics Symposium-EUROCK 2017*. OnePetro, 2017.
85. Luo Y.: Effects of Water in Inactive Room and Pillar Coal Mines on Causing and Preventing Surface Subsidence. „COJ Tech Sci Res." 3(5). COJTS. 000571. 2021.
86. Ma, J., Dineva, S., Cesca, S., Heimann, S.: Moment tensor inversion with three-dimensional sensor configuration of mining induced seismicity (Kiruna mine, Sweden). *Geophysical Journal International*, *213*(3), 2147-2160, 2018.
87. Malinowska A., Wojciech T. Witkowski, Artur Guzy, Ryszard Hejmanowski: Mapping ground movements caused by mining-induced earthquakes applying satellite radar interferometry, *Engineering Geology*, Volume 246, 2018, Pages 402-411, ISSN 0013-7952, https://doi.org/10.1016/j.enggeo.2018.10.013.
88. Martinec, P., Vavro, M., Scucka, J., Maslan, M.: Properties and durability assessment of glauconitic sandstone: a case study on Zamel sandstone from the Bohemian Cretaceous Basin (Czech Republic). *Engineering Geology*, Vol. 115, No. 3-4, 2010.
89. Maystrenko Y.P., Brönner M., Olesen O., Saloranta T.M., Slagstad T.: Atmospheric precipitation and anomalous upper mantle in relation to intraplate seismicity in Norway. *Tectonics*, 39, e2020TC006070. https://doi.org/10.1029/2020TC006070, 2020.
90. Melchers, C., Westermann, S., Reker, B.: Evaluierung von Grubenwasseranstiegs-prozessen im Ruhrgebiet, Saarland, in Ibbenbüren sowie weiteren deutschen Steinkohlenrevieren und dem angrenzenden europäischen Ausland. Nachbergbau 1, Bochum, Deutsches Bergbau-Museum, 2019.

91. Milutinovic Z.V., Trendafiloski G.S.: Vulnerability of current buildings. RISK-UE, Work Package 4. An advanced approach to earthquake risk scenarios with applications to different European towns, 2003.
92. Modeste, G., Doubre, C., Masson, F.: Time evolution of mining-related residual subsidence monitored over a 24-year period using InSAR in southern Alsace, France, *International Journal of Applied Earth Observation and Geoinformation*, Volume 102, 2021, 102392, ISSN 1569-8432, https://doi.org/10.1016/j.jag.2021.102392.
93. Morales Demarco, M., Jahns, E., Ruedrich, J., Oyhantcabal, P., Siegessmund, S.: The impact of partial water saturation on rock strength: an experimental study on sandstone. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, Vol. 158, No. 4, 2007.
94. Morel, J., Raucoules, D., Foumelis, M., Lemal, S.: InSAR assets in ground movements survey on abandoned coalfields. E3S Web of Conferences 342, 02003, doi:https://doi.org/10.1051/e3sconf/202234202003, 2022.
95. Mutke G., Dubiński J.: Seismic intensity induced by mining in relation to weak earthquakes. Proc. of the 24th World Mining Congress. Part. Underground Mining. Rio de Janeiro, pp. 399−407, 2016.
96. Mutke G., Dworak J.: Czynniki warunkujące efekt sejsmiczny wstrząsów górniczych na powierzchniowe obiekty budowlane w obszarze GZW. Wybrane zagadnienia geofizycznych badań w kopalniach – Lubiatów 1991. Publications of the Institute of Geophysics, Polish Academy of Sciences, M-16(245), s. 115–130, 1992.
97. Mutke, G.: Impact of mining seismic tremors on the surface. GIG Publishing House, ISBN 978-83-65503-21-3, 189p (in Polish), 2019.
98. Mutke, G., Holecko, J. Verification of predicted influence of seismic phenomena on surface objects, developed by GIG Katowice in cooperation with Green Gas DPB a.s. in December 2010 for planned mining works in the mines of OKD, a.s. in Karviná part of OKR in the years 2011-2013, with the use of Intensity Scale of Mining Seismic Events GSI, elaborated by GIG. Główny Instytut Górnictwa, Katowice (Poland), 2012.
99. Mutke, G., Chodacki, J., Muszynski, L., Kremers, S., Fritschen, R.: Mining Seismic Instrumental Intensity Scale MSIIS-15 – verification in coal basins. „AIMS 2015 - Fifth Int. Symp.: Mineral Resources and Mine Development”, RWTH Aachen University, Vol. 14, 2015.
100. Mutke G., Kotyrba A., Lurka A., Olszewska D., Dykowski P., Borkowski A., Araszkiewicz A., Barański A.: Upper Silesian Geophysical Observation System - a unit of the EPOS project. *Journal of Sustainable Mining.* Vol.18, issue 4, 2019.
101. Mutke, G., Pierzyna, A., Baranski, A.: b-Value as a criterion for the evaluation of rockburst hazard in coal mines. In *3rd International Symposium on Mine Safety Science and Engineering* (pp. 1-5), 2016.

102. Nara, Y., Morimoto, K., Hiroyoshi, N., Yoneda, T., Kaneko, K., Benson, P.M.: Influence of relative humidity on fracture toughness of rocks: implications for subcritical crack growth. *International Journal of Solids and Structures*, Vol. 49, No. 18, 2012.
103. Niemz, P. et al.: Full-waveform-based characterization of acoustic emission activity in a mine-scale experiment: a comparison of conventional and advanced hydraulic fracturing schemes. *Geophysical Journal International*, *222*(1), 189-206, 2020.
104. Ojo, O., Brook, N.: The effect of moisture on some mechanical properties of rock. *Mining Science and Technology,* Vol. 10, No. 2, 1990.
105. Pang Y., Zhang H., Cheng H., Shi Y., Fang C., Luan X., Chen S., Li Y., Hao M.: The modulation of groundwater exploitation on crustal stress in the North China Plain, and its implications on seismicity. *Journal of Asian Earth Sciences*, n° 189, 104141, https://doi.org/10.1016/j.jseaes.2019.104141, 2020.
106. Passarelli, et al.: Aseismic transient driving the swarm-like seismic sequence in the Pollino range, Southern Italy, *Geophys. J. Int.* 201, 3, 1553–1567, https://doi.org/10.1093/gji/ggv111, 2015.
107. Peng, Z., Zhao, P.: Migration of early aftershocks following the 2004 Parkfield earthquake. *Nat. Geosci.* 2(12), 877-881, 2009.
108. Petersen, G.M., Niemz, P., Cesca, S., Mouslopoulou, V., Bocchini, G.M.: Clusty, the waveform-based network similarity clustering toolbox: concept and application to image complex faulting offshore Zakynthos (Greece). *Geophysical Journal International*, *224*(3), 2044-2059, 2021.
109. Pilecka, E., Stec, K., Chodacki, J., Pilecki, Z., Szermer-Zaucha, R., Krawiec, K.: The Impact of High-Energy Mining-Induced Tremor in a Fault Zone on Damage to Buildings. *Energies*, Vol. 14, No. 14, 2021.
110. Pöttgens J.J.E.: Bodenhebungen durch ansteigendes Grubenwasser. – Proceedings – 6th International Congress, International Society for Mine Surveying, Harrogate, 9-13 September 1985, 2: 928–938, Rotterdam (Balkema), 1985.
111. Primo Doncel P., Kotyrba A., Cesca S., Sokoła-Szewioła V., Konicek P., Kajzar V., Schreiber J., Contrucci I., Jiránková E., Dominique P.: PostMinQuake: Seismicity of selected closed European hard coal mines during flooding. Z. Dt. Ges. Geowiss. (*J. Appl. Reg. Geol.*). DOI: 10.1127/zdgg/2023/0341, 2023.
112. Raucoules D., Colesanti C. and Carnec C.: Use of SAR interferometry for detecting and assessing ground subsidence, Compte Rendus Geosciences 339(5): 289-302, 2007.
113. Raucoules, D., Le Mouelic, S., Carnec, C. and Guise, Y.: 'Monitoring post-mining subsidence in the Nord-Pasde-Calais coal basin (France): comparison between interferometric SAR results and levelling',Geocarto International, 23:4,287 − 295 To link to this Article: DOI: 10.1080/10106040801953850, 2008.
114. Rische M., Fischer, K.D., Friederich, W.: FloodRisk – Induced seismicity by mine flooding – Observation, characterization and relation to mine water rise in the eastern

Ruhr area (Germany). Z. Dt. Ges. Geowiss. (J. Appl. Reg. Geol.). DOI: 10.1127/zdgg/2023/0346, 2023.

115. Roland, E., McGuire, J.J.: Earthquake swarms on transform faults. *Geophysical Journal International*, *178*(3), 1677-1690, 2009.

116. Rudziński, L., Mirek, K., Mirek, J.: Rapid ground deformation corresponding to a mining-induced seismic event followed by a massive collapse. Nat. Hazards 2018, 96, 461–471.

117. Ruedrich, J., Bartelsen, T., Dohrmann, R., Siegesmund. S.: Moisture expansion as a deterioration factor for sandstone used in buildings. *Environmental Earth Sciences*, Vol. 63, No. 7−8, 2011.

118. Rutqvist J., Rinaldi A. P., Cappa F.,.Moridis G.J.: Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs. *Journal of Petroleum Science and Engineering*, n°107, pp. 31–44, 2013.

119. Salmon, R., C. Franck, A. Lombard, S. Thiery, and R. Hadadou: Post-Mining Risk Management in France, Ineris Cerema GEODERIS, DRS-19-178745-02406A, 2019.

120. Samsonov, S., d'Oreye, N., Smets, B.: Ground deformation associated with post-mining activity at the French–German border revealed by novel InSAR time series method, *International Journal of Applied Earth Observation and Geoinformation*, Volume 23, 2013, Pages 142-154, ISSN 1569-8432, https://doi.org/10.1016/j.jag.2012.12.008.

121. Schnabel, P.B., Lysmer, J., Seed, H.B.: SHAKE: A Computer Program for Earthquake Response Analysis of Horizontallly Layered Sites. Report No.UCB/EERC-72/12. University of California, Berkeley, December, 102p, 1972.

122. Schorlemmer, D., Wiemer, S., Wyss, M.: Variations in earthquake-size distribution across different stress regimes. *Nature*, *437*(7058), 539-542, 2005.

123. Sen, A.T., Cesca, S., Bischoff, M., Meier, T., Dahm, T.: Automated full moment tensor inversion of coal mining-induced seismicity. *Geophysical Journal International*, *195*(2), 1267-1281, 2013.

124. Seto, M., Kuruppu, M.D., Funatsu, T.: Fracture toughness testing of rockat elevated temperatures and pressures, [in:] Elsworth, D., Tinucci, J.P., Heasley, K.A (eds.): Proceedings of the 38th U.S. Symposium of Rock Mechanics (DC Rocks 2001), Washington DC, US 2001.

125. Shelly, D.R., Beroza, G.C., Ide, S.: Non-volcanic tremor and low-frequency earthquake swarms. *Nature*, *446* (7133), 305-307, 2007.

126. Shi, P., Grigoli, F., Lanza, F., Beroza, G.C., Scarabello, L., Wiemer, S.: MALMI: An automated earthquake detection and location workflow based on machine learning and waveform migration. *Seismological Society of America*, *93*(5), 2467-2483, 2022.

127. Siedel, H.: Historic building stones and flooding: changes of physical properties due to water saturation. *Journal of Performance of Constructed Facilities,* Vol. 24, No. 5, 2010.

128. Siejka Z., Sokoła-Szewioła V.: Detection of Measurement Errors in the Time Series of the Coordinates of Surface Movement Monitoring Points with the Use of Satellite

Navigation Systems. Conference proceedings- XXVII FIG Congress FIG Volunteering for the future – Geospatial excellence for a better living. Warsaw, Poland, 2022, https://www.fig.net/resources/proceedings/fig_proceedings/fig2022/papers/ts05c.

129. Singh, R.N., Sun, G.X.: An investigation into factors affecting fracture toughness of coal measures sandstones. *Journal of Mines, Metals and Fuels*, Vol. 38, No. 6, 1990.
130. Siwek S.: Earth tides and seismic activity in deep coal mining. *International Journal of Rock Mechanics and Mining Sciences*. 148(20), 2021.
131. Smith J.A., Colls J.J.: Groundwater rebound in the Leicestershire coalfield. *Journal of the Chartered Institution of Water and Environmental Management,* 10 (4) : 280-289, 1996.
132. Sokoła-Szewioła V., Siejka Z.: Monitoring of land surface movements in a seismically active post-mining area during mine closure – A case study. Conference proceedings 32nd SOMP Annual Meeting and Conference 2022, 8-14 September Namibia. Published by The Southern African Institute of Mining and Metallurgy, ISBN: 978-1-928410-33-1, pp. 167−176.
133. Taig A.R., Pickup, F.E.: Risk assessment of falling hazards in earthquakes in the Groningen region. Arup Report 229746032.0REP1008, Available from http://www.nam.nl/feiten-en-cijfers/onderzoeksrapporten.html, 2016.
134. Templeton, D.C., Schoenball, M., Layland-Bachmann, C., Foxall, W., Guglielmi, Y., Kroll, K., White, J.: Recommended Practices for Managing Induced Seismicity Risk Associated with Geologic Carbon Storage (No. LLNL-TR-818759). Lawrence Livermore National Lab (LLNL), Livermore, CA (United States), 2021.
135. Toledo, T., Jousset, P., Maurer, H. and Krawczyk, C.: Optimized experimental network design for earthquake location problems: Applications to geothermal and volcanic field seismic networks. *Journal of Volcanology and Geothermal Research*, 391, 106433, 2018.
136. Toshioka T., Tsuchida T., Sasahara K.: Application of GPR to detecting and mapping cracks in rock slopes. *Journal of Applied Geophysics* 33 (s1-3), 1995.
137. Utagawa, M., Seto, M., Katsuyama, K., Matsui, K.: Evaluation of fracture toughness of rocks in wet and chemical condition. Shigen-to-Sozai, Vol. 114, 1998.
138. VanWees J.D., Buijze L., VanThienen-Visser K., Nepveu M., Wassing B.B.T., Orlic B., Fokker P.A.: Geomechanics response and induced seismicity during gas field depletion in the Netherlands. *Geothermics,* n° 52, pp. 206–219.
139. Vásárhelyi, B., Ván, P.: 2006. Influence of water content on the strength of rock. *Enginering Geology*, Vol. 84, No. 1–2, 2006.
140. Vásárhelyi, B.: Some observations regarding the strength and deformability of sandstones in dry and saturated conditions. *Bulletin of Engineering Geology and the Environment*, Vol. 62, No. 3, 2003.
141. Vavro, L., Souček. K.: Study of the effect of moisture content and bending rate on the fracture toughness of rocks. *Acta Geodynamica et Geomaterialia*, Vol. 10, No. 2, 2013.

142. Vavro, M., Vavro, L., Martinec, P., Souček, K.: Properties, durability and use of glauconitic Godula sandstones: a relatively less known building stone of the Czech Republic and Poland. *Environmental Earth Sciences*, Vol. 75, No. 22, 2016.
143. Vuan, A., Sugan, M., Amati, G., Kato, A.: Improving the Detection of Low-Magnitude Seismicity Preceding the Mw 6.3 L'Aquila Earthquake: Development of a Scalable Code Based on the Cross Correlation of Template EarthquakesImproving the Detection of Low-Magnitude Seismicity Preceding the Mw 6.3 L'Aquila Earthquake. *Bull. Seismol. Soc. Am. 108*(1), 471-480, 2018.
144. Wald, D., Quitoriano, V., Heaton, T.H., Kanamori, H. Scrivner, C.W., Worden, C.B.: TriNet "ShakeMaps": rapid generation of peak ground-motion and intensity maps for earthquakes in Southern California. *Earthquake Spectra*, 15(3), 537–556, 1999.
145. Wegmüller, U., Werner, C., Strozzi, T.: Wiesmann, A. Multitemporal interferometric point target analysis. Remote Sens. 2004, 3, 136–144.
146. Whyte, C., Stojadinovic, B.: Spectral content of induced vs. natural seismicity. „2nd European Conference on Earthquake Engineering and Seismology", Istanbul, Turkey, 2014.
147. Younger, P.L., Banwart, S.A., Hedin, R.S.: Mine Water: hydrology, pollution, remediation. Dordrecht, Netherlands. Kluver Academic, ISBN 1-4020-0137-1, 2002.
148. Zang, A., Wagner, C.F., Dresen, G.: Acoustic emission, microstructure, and damage model of dry and wet sandstone stressed to failure. *Journal of Geophysical Research: Solid Earth*, Vol. 101, No. B8, 1996.
149. Zhang, Q., Shearer, P.M.: A new method to identify earthquake swarms applied to seismicity near the San Jacinto Fault, California. *Geophysical Journal International*, 205(2), 995–1005, https://doi.org/10.1093/gji/ggw073, 2016.
150. Zhao, J., Konietzky, H.: Numerical analysis and prediction of ground surface movement induced by coal mining and subsequent groundwater flooding. *International Journal of Coal Geology*, 229. https://doi.org/10.1016/j.coal.2020.103565, 2020.
151. Zhu, W., Beroza, G.C.: PhaseNet: a deep-neural-network-based seismic arrival-time picking method. *Geophysical Journal International*, *216*(1), 261-273, 2019.
152. Zöller, G., Hainzl, S., Ben-Zion, Y., Holschneider, M.: Earthquake activity related to seismic cycles in amodel for a heterogeneous strike-slip fault, *Tectonophysics*, 423(1–4), 137–145, 2006.

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e-wydanie

The book contains guidelines on the assessment methods of seismic hazard and monitoring in the areas of decommissioned and flooded deep coal mines in Europe and in the world with the aim of ensuring public safety. The successive chapters present methods and basic recommendations in the process of their implementation. The characteristics of the essential data relevant for the assessment and monitoring of seismic hazard were presented as well as the scope of numerical modeling and hydro-mechanical simulations, important during the period of mine flooding, issues regarding the harmfulness of the impact of ground vibrations caused by post-mining earthquakes on buildings and people, and in detail the scope and implementation method of comprehensive monitoring including continuous and periodic geophysical (seismology, gravimetry, hydrometry) and ground deformations (GNSS, InSAR) measurements. The book also contains guidelines for the development of an automatic early warning system for rock mass movements caused by post-mining earthquakes and for reporting on the harmfulness of their impact on buildings.

The guidelines are addressed mainly to mining consultants, potential investors and state administration bodies in charge of the safety of post-mining areas, including units responsible for safety and environmental management in the areas of closed hard coal mines.

The book was developed as a result of research in the field of induced seismicity and rock mass movements in post-mining areas, which was the subject of the European research project financed by the Research Fund for Coal and Steel, entitled "Induced earthquake and rock mass movements in coal post mining areas: mechanisms, hazard and risk assessment" (acronym PostMinQuake, https://postminquake.eu/). The project was implemented in 2020-2023 under the grant agreement No. 899192. The project was co-financed in Poland by the Ministry of Science and Higher Education under the grant agreements No. 5124/FBWiS/2020/2 and No. 5147/FBWiS/2020/2.

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