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EPOS Thematic Core Service Anthropogenic Hazards in the operational phase

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Abstract

The problem of hazards induced by the exploitation of geo-resources focuses growing interest of science, industry, public administration, non-governmental organizations and the general public. Anthropogenic seismicity, i.e. the undesired dynamic rock mass response to geo-resources exploitation, is one of the examples of unwanted by-products of the technological operation of humans. The socio-economic impact of the induced seismicity is very significant. Induced earthquakes can cause material loss, injuries and even fatalities. Restricted access to data constitutes a barrier to assessing and mitigating the associated hazards. To respond to the need of the scientific community the Thematic Core Service Anthropogenic Hazards (TCS AH) has been created within the framework of the European Plate Observing System, a solid earth science European Research Infrastructure Consortium (ERIC). TCS AH is an open consortium of 13 European institutions. TCS AH provides access to a novel e-research infrastructure, the EPISODES Platform (former name: IS-EPOS platform) to foster both research and training on induced seismicity and geo-hazards related to the exploration and exploitation of geo-resources. The EPISODES Platform is connected to international data nodes which offer open access to multidisciplinary datasets, called episodes. Episodes comprise geoscientific and associated data from industrial activity along with a large set of embedded applications for their efficient data processing, analysis and visualization. The EPISODES Platform opens also the possibility to create new applications and combine implemented applications with the user's codes. The team-working features of the EPISODES Platform facilitate collaborative and interdisciplinary scientific research, public understanding of science, citizen science applications, knowledge dissemination, and the teaching of anthropogenic hazards related to geo-resource exploitation. This study presents the current results of the TCS AH research infrastructure integration and also indicates the benefits of their usage for science, education, and innovation.

Keywords: EPOS TC AH; EPISODES Platform; Integrated research infrastructure; Anthropogenic seismicity; Seismic hazard

1. Introduction

Thematic Core Service Anthropogenic Hazards (TCS AH) is one of the ten solid Earth science community-specific services (e.g., seismology, volcanology, geodesy, experimental laboratories, etc.) of the European Plate Observing System (EPOS) program. The community-oriented services represent transnational governance frameworks for data and bespoke services provision to answer scientific questions and discuss community-specific implementations, best practices and sustainability strategies. Thematic Core Services (TCS) form one of the three levels of EPOS architecture [Cocco et al., 2022]. The other two levels of EPOS are the national research infrastructures (NRIs), where data are generated, processed, analyzed and archived. These data are then integrated by TCS and distributed through the centralized integrated core services (EPOS ICS-C) [Atakan et al., 2022] EPOS entered the European Strategy Forum on Research Infrastructure Roadmap in 2010 after the international evaluation. It is a long-term research integration program that represents a collaborative framework aimed at integrating research data and scientific products ensuring data management and interoperability through e-science innovation [Bailo et al., 2022].

Thematic Core Service Anthropogenic Hazards is a consortium of 13 European scientific, industrial, and private sector institutions. TCS AH consortium members are: Instituto Nazionale di Geofisica e Vulcanologia (IT), Centre national de la recherche scientifique (FR), Helmholtz Zentrum Potsdam Deutsches Geoforschungszentrum (DE), Institute of Geophysics Polish Academy of Sciences (PL), L'Institut National de l'Environnement et des Risques (FR), Geofyzikalni Ustav AV CR (CZ), Oulun Yliopisto (FIN), Lulea Tekniska Universitet (SE), University of Keele (GB), University of Science and Technology – Academic Computer Centre Cyfronet (PL), Central Mining Institute (PL), Polish Mining Group (PL), the Drobot Popławski Przybyłowicz Liszka-Gronek Radcowie Prawni Spółka Partnerska (PL). TCS AH's internal structure is built by the Executive Office led by IG PAS and 4 following sections: (1) The implementation of TCS AH Services led by ACK – UST, (2) Episode integration and application implementation led by GFZ, (3) Promotion and dissemination led by CNRS and GB, and (4) Projects and partnership, led by LTU. TCS AH provides open data and services through the EPISODES Platform (former name: IS-EPOS platform) to foster both research and training on induced seismicity and geo-hazards related to the exploration and exploitation of geo-resources.

The research infrastructure integrated within TCS AH is related to anthropogenic hazards accompanying geo-resources exploitation, e.g. anthropogenic seismicity. Anthropogenic seismicity is a frequent unwanted companion of geo-resources exploration and exploitation. It can be generated by stress changes due to pore pressure changes, a volume change, the mass transfer in the rock mass, and combinations of such causes. Hence, under suitable unfavourable geological conditions, the anthropic activities: underground and open-pit mineral exploitation, hydrocarbon production, surface reservoir impoundment, geothermal energy production, underground gas storage, and many other technological processes that perturb the boundary conditions in the affected rock mass can trigger/induce earthquakes. Although most human-induced seismic events are weak and recorded only by sensitive seismic networks, the hazard posed by anthropogenic seismicity can be considerable. The M5.7 event triggered by hydraulic fracturing operations in China in 2019 [Lei, et al., 2019; Tan, et al., 2020], the M5.5 earthquake associated with geothermal energy production in Pohang, South Korea in 2017 [Ellsworth, et al., 2019], the M5.8 event linked to wastewater disposal in Oklahoma, US. in 2016 [Yeck, et al., 2017], and the M6.1 earthquake triggered by open-pit mining in Kuzbass, Russia in 2013 [Emanov, et al., 2014] are only a few examples of destructive possibilities of the technology-induced seismic processes. Adding the M7.9 2008 Sichuan earthquake in China that took over 69 thousand lives and might have been triggered by the construction and filling of the Zipingpu Dam [Ge, et al., 2009], we obtain a picture of the hazardous potential of anthropogenic seismicity.

In the anthropogenic hazard cases, the efforts are not only directed to reduce the hazard-related risks but also to mitigate the hazard itself by improving the technology and reducing the impact of the activity on the surrounding natural and societal environment. Despite progress concerning hazard mitigation, anthropogenic hazards are an unavoidable component of life, permanently surrounding and accompanying people. It is crucial then to carry out hazard-posing technological activities to maintain this hazard at an acceptable level. To reach the above-formulated goal, one must first answer situation-tailored research questions on the relationships between the activity that can imply damaging or destructive phenomena and the processes that lead to such phenomena and the related hazard. The datasets required to research relationships between the technological and technology-generated hazard-posing processes must enable cause-effect studies. They, then, should comprise correlated data on both the technological activity and the activity-induced hazardous process under investigation. In line with such needs, the EPOS TCS AH consortium "integrates, within European Plate Observing System (EPOS), the research infra-

structure related to studies of hazards of anthropogenic origin, in particular those caused by the exploration and exploitation of geo-resources" (from the Thematic Core Service Anthropogenic Hazard Consortium Agreement). Among these hazards, special attention is devoted to the anthropogenic seismic processes.

The datasets to be fruitfully used in studies of anthropogenic hazards linked to the exploitation of geo-resources must include data on the hazard-posing technological activity. Such data owned by companies may have economic value and be proprietary. Furthermore, companies are often not willing to release their data for fear that it will be used to incompetently spread information about the hazard posed by the companies' activities. To overcome the problem of industrial data accessibility EPOS TCS AH introduced three principles. First, TCS AH does not gather the most recent data, which could have economic or social value, and its dissemination would disagree with the companies' policy. The comprehensiveness of data enables studies of industrial cause – seismic effect relationships and not the recentness of the induced seismicity case matters to such research. In some instances, at the request of our industry partners, TCS AH limits the access to selected datasets to scientists only and reports to the data owner the data usage.

Second, TCS AH indicates to the industrial partners the benefits of supporting research with their data. The industry gains that stem from the increasing technical knowledge of hazard-generating processes are apparent. TCS AH also pinpoints the role of education and disseminating competent information on hazards linked to geo-resources exploitation in developing public resilience to anthropogenic hazards, reducing the social seismic risk.

Finally, TCS AH offers the industrial partners free access to well-tested specific solutions, worked out utilizing the integrated infrastructure. An example of such a solution ready for direct implementation – a pilot service "Time- &Technology-dependent Anthropogenic Seismic Hazard Assessment" is presented below. The described above industry cooperation strategy has led to receiving a lot of excellent datasets from the industry.

In addition to its role in science, the EPOS TCS AH integrates also high-quality educational material, including popular science articles, presentations and movies, that is used to disseminate knowledge on anthropogenic seismic processes and related hazards among scientists of various backgrounds and levels. A multitude of accessible datasets that comprehensively describe seismic processes induced by vastly different geo-resources exploitation technologies can be reviewed and also processed using the implemented hazard assessment software tools. Some examples of outreach actions carried out with the use of the integrated data and services of EPOS TCS AH are discussed below.

The details of the TCS AH research infrastructure, i.e. data and services, architecture, the TCS AH consortium, scientific and sustainability strategy, can be found in Orlecka-Sikora et al. [2020]. Here we provide the general picture of TCS AH, and we focus on the new services developed within the operational phase of TCS AH, which lasts from 2019. We briefly describe the present state of the TCS AH implementation and the ongoing projects which will result in further TCS AH development. We also sketch some benefits that stem from this integration for research.

2. Integrated research infrastructure of EPOS TCS AH

The innovation of TCS AH lies in the uniqueness of the integrated research infrastructure (RI) which comprises three main deliverables [Orlecka-Sikora et al., 2020]. The first is the exceptional datasets, called "episodes", which comprehensively describe a geophysical process, induced or triggered by human technological activity, posing a hazard for populations, infrastructure, and the environment. Each episode consolidates industrial and geophysical data on anthropogenic activities in a time-related fashion, thus allowing researchers to evaluate the temporal evolution of the seismic hazard parameters throughout time. Episodes are collected and organized in the EPISODES platform. Through the workspace, users can process the open access episodes, tailor the data visualization and analysis according to their needs with custom packages, and collaborate with others. Currently (October 2021), 37 anthropogenic seismicity episodes are available. They comprise data on seismicity cases induced by six industrial activities (Table 1). Every episode has a DOI identifier.

The second deliverable of TCS AH are applications. Applications are problem-oriented, bespoke, and standard software tools to process and analyze the data. Currently, there are 66 applications grouped in 14 categories (Table 2). Much attention has been devoted to the implementation of applications for hazard analyses. The category "Probabilistic Seismic Hazard Analysis" includes 12 items.

The data, data processing tools, and IT facilities, including HPC, are organized and accessible on the EPISODES e-Research Platform (https://tcs.ah-epos.eu). The platform being an IT environment for efficient and convenient

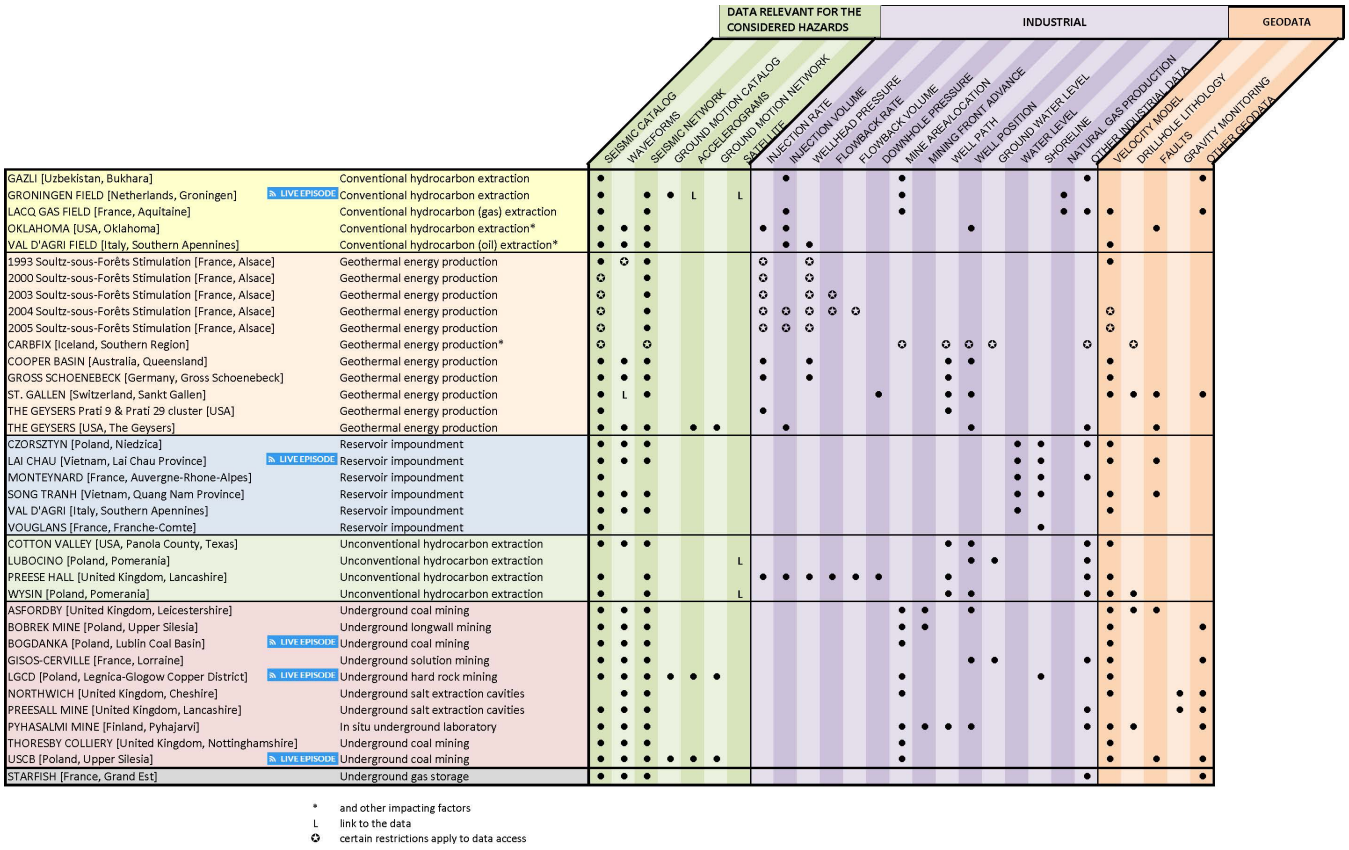

Table 1. Anthropogenic seismicity episode datasets available on the EPISODES Platform.

data processing is the third and core component of the integrated infrastructure. The registered user has access to the full potential of the system: an own user's workspace where the users can carry out their data processing and analysis, and to many collaborative functionalities, e.g. sharing the workspace, sharing data, applications, and results of analyses, etc. The unregistered users may only browse the platform contents but they do not own the workspace and they cannot perform any analysis.

Application Category	Application
Collective Properties of Seismicity	Anderson-Darling test for exponentiality of inter-event time
	Coefficient of randomness
	Completeness Magnitude estimation
	Magnitude conversion
	Priestley-Subba Rao (PSR) test
	Stress and strain changes induced by fluid injection and temperature change driven by geothermal injection
Converters	CSV to Catalog converter
	Catalog to CSV converter
	Catalog to Vectors converter
	GDF to CSV converter
	GDF to Vectors converter
	Ground Motion Parameters Catalog builder

Application Category	Application
	SEED to ASCII (SLIST) converter
	SEED to FDSN Station XML converter
	SEED to SAC converter
	SEED to datalessSEED converter
	SEED to miniSEED converter
	Signal Processing
	Time Series builder
	miniSEED to ASCII (SLIST) converter
	miniSEED to SAC converter
	miniSEED to miniSEED converter
Correlation Analysis	Autocorrelation
	Cross-correlation
Data Processing Applications	Basic Vector Operations
	Cluster Analysis
	Transformation to Equivalent Dimensions
Download Tools	Signal download tool
	Waveform download tool
Earthquake Interactions	Earthquake interactions: Geo-resource scale
	Earthquake interactions: Mainshock scale
	Earthquake swarm (reshuffling analysis)
	Time correlated earthquakes (Seasonal trends)
Event Detection Algorithms	Template-matching based detection algorithm
Filtering Tools	Catalog filter
Probabilistic Seismic Hazard Analysis	Estimate of maximum possible magnitude for reservoir triggered seismicity
	Estimation of source parameters in time-varying production parameters geometry
	Ground Motion Prediction Equations: Final model analysis
	Ground Motion Prediction Equations: GMPE calculation
	Ground Motion Prediction Equations: Residuals analysis
	MERGER: Dynamic risk analysis using a bow-tie approach
	Source size distribution functions/Stationary Hazard
	Stationary Hazard: Exceedance Probability
	Stationary Hazard: Maximum Credible Magnitude
	Stationary Hazard: Mean Return Period
	Time dependent hazard in mining front surroundings
	Time dependent hazard in selected area
Seismogram Analysis Tools	Seismogram picking tool

Application Category	Application
Source Parameter Estimation	Coda Wave Interferometry detection of velocity changes
	Effective stress drop estimate
	FOCI
	Localization
	Mechanism: Full Moment Tensor
	Mechanism: Shear Slip
	Mechanism: Shear-Tensile crack
	Spectral Analysis
	Waveform-based seismic event location
Statistical Properties of Seismicity	Anderson-Darling test for magnitude distribution
	Test for multimodal magnitude distribution
Stress Field Modelling	Stress inversion
Visualizations	Fracture Network Models – Mechanical Stresses
	Front Advance histograms
	GDF with Seismic Activity data visualization
	GDF with Seismic Activity histogram data visualization
	Integrated Google Maps data visualization
	Seismic Activity with Front Advance

Table 2. Applications available on the EPISODES Platform.

The EPISODES Platform is linked to the EPOS ICS-C (EPOS infrastructure central hub), making the episodes also available there. The system architecture, organization, and details on its use have been presented in Orlecka-Sikora et al. [2020].

Recently, the existing research potential of the EPISODES Platform has been enriched with functionalities for building codes and workflows. The users have now the possibility to create their own codes to perform custom analyses on the data from episodes or their data uploaded to their workspace. Thanks to these new features, developed within EPOS PL (Polish national project co-financed by European Regional Development Fund [EPOS PL][1]), the Platform has become a virtual laboratory that opens unconstrained opportunities for virtual experimentation.

Such custom applications are displayed alongside other EPISODES Platform applications but are visible only to the application author and the users appointed by the author as their collaborators[2]. As with other applications, the custom application can be added to the workspace and run – triggering computation of the analysis defined by the user. The user-coded applications are treated the same way as those implemented on the platform and made available for general use. In this connection, both types can be freely combined, creating advanced processing chains according to the requirements of a concrete analysis that the user wants to carry out. It also allows for custom results manipulation to accommodate them, e.g., to a specific publication. What is more, such processing chains can be further automated by creating a workflow [Makuch et al., 2020], allowing the whole chain to execute in one run. The computation is performed on the distributed computing resources connected to the EPISODES Platform, provided by the PL-Grid Infrastructure [PLGRID] which is part of the European Grid Initiative and en-

1 Abbreviation in square brackets refers to projects referenced to at the end of the reference list.

2 Depending on the permission settings configured by the author, the collaborators can either be able to only see the application or also modify the code.

sures access to computer clusters. Each application runs in a dedicated sandboxed environment to ensure the security of the servers executing the code.

The codes of the custom applications are stored in a newly integrated component of the EPISODES Platform, i.e. Application Workbench (Figure 1). The Application Workbench is based on Gitea [GITEA], a service for managing Git version control system [GIT] projects. The Git system and services similar to Gitea are standard solutions in software development. Owing to the usage of Git, all the changes made to the code are tracked. The user can check which parts of code were changed, when, and, in case of working on the code collectively, by whom. The code can also be versioned, allowing for creating different variants of the same application (e.g., using other algorithm options). All the versions are accessible on the EPISODES Platform; therefore, different application variants can be easily run and compared in the Platform's workspace.

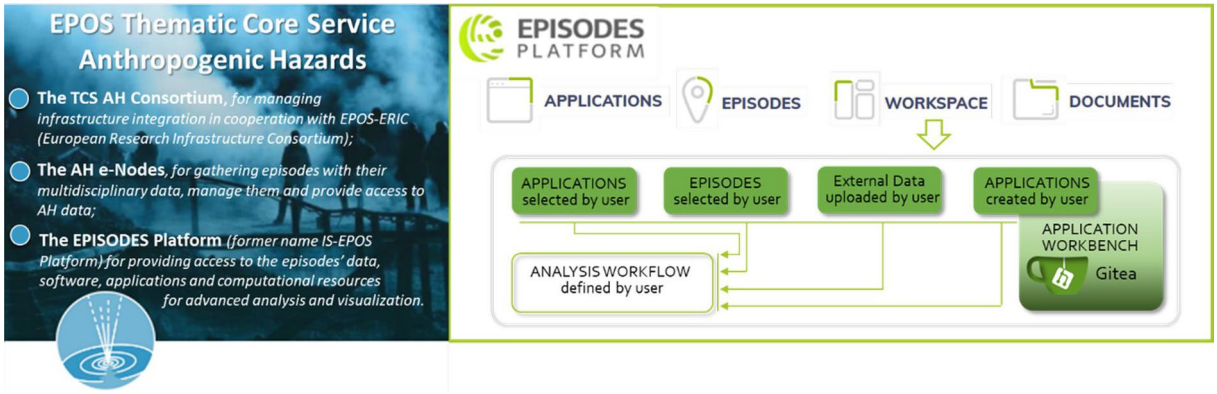

Figure 1. The major components of the EPOS Thematic Core Service Anthropogenic Hazards.

The creation of a new application is facilitated by a dedicated wizard (Figure 2) that initializes a Git repository inside Application Workbench in which the code of the new application will be stored, adding all files required by the EPISODES Platform to load the application correctly.

The files required to be present within the application's repository are:

1) the application definition file (appDefinition.json) – a descriptor file providing information required by the Platform to identify the application inputs, outputs, executable files, and other properties essential for the application's execution;

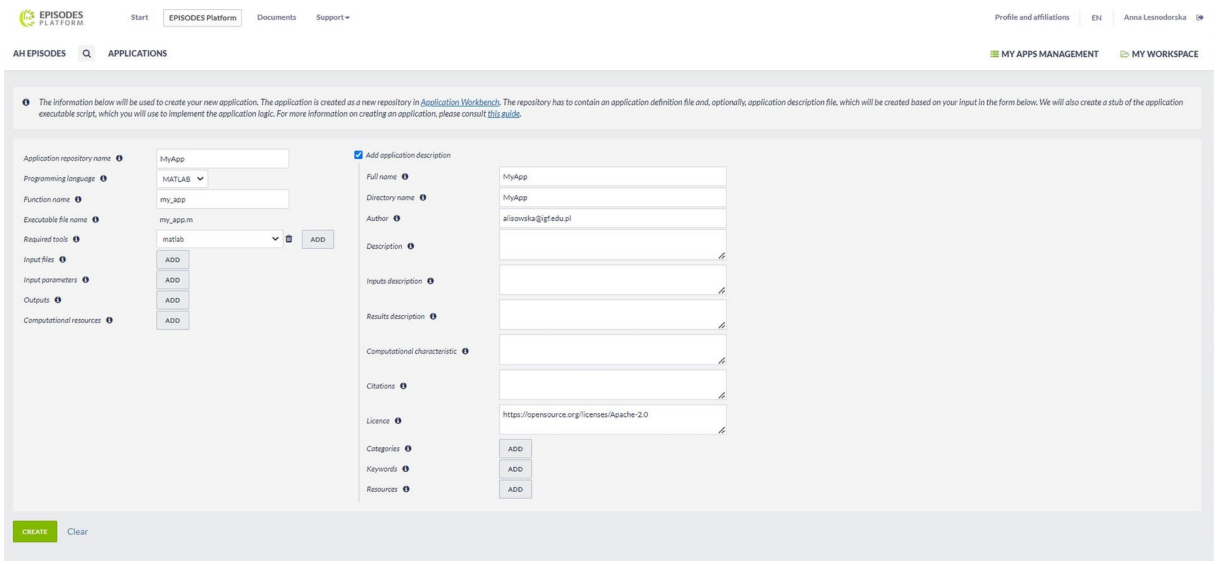

Figure 2. Wizard used to generate a new application.

2) executable script – a script containing the code to be executed by the EPISODES Platform. Both files have to be compatible, i.e., the script has to take inputs and return results as they are declared in the application definition file, be written in the programming language specified therein[3], etc. If using the wizard for creating the repository (Figure 2), the files are automatically generated with coherent content, according to the values specified within the wizard. In such a case, the user would only have to fill the function generated in the executable script with the logic implementing the analyses of their choice.

3. Impact of TCS AH research infrastructure

EPOS TCS AH makes a significant contribution to the research into anthropogenic hazards. Presently, the document repository on the EPISODES Platform informs about 48 scientific publications acknowledging the TCS AH, EPISODES Platform and its resources. The integrated infrastructure, accessible to scientists on the EPISODES Platform, supports the development of new methods for assessing environmental impacts and mitigation of anthropogenic seismic hazards resulting from technological activities [e.g. Czarny et al., 2018; Garcia- Aristizabal et al., 2019; Gunning et al., 2019; Lasocki and Orlecka-Sikora, 2020; Leptokaropoulos and Lasocki, 2020; Orlecka-Sikora and Cielesta, 2020]. The episodes and applications integrated on the EPISODES Platform have been selected using strict quality and research utility criteria. The data are related to a broad spectrum of seismicity-inducing technologies, with quantitative information on seismic/aseismic deformation and production history as a minimum dataset requirement. Such a broad spectrum of data gives room to study the parameters that signify the evolution of seismic and aseismic deformation within episodes associated with the one type of the geo-resources operations or episodes from various geo-resources operations and thus to assess the universality of these parameters [e.g. Staszek et al., 2017; Grasso et al., 2018, Molina et al., 2020, Orlecka-Sikora and Cielesta, 2020, Rudziński, et al., 2021]. The EPISODES Platform is used not only as a source of data, either seismic signals and catalogues, but also provides wide opportunities to work with seismograms. These raw data can be used to obtain physical parameters of seismic sources i.e. hypo-locations, spectral parameters as well as source mechanisms [e.g. Dębski and Kleiment,

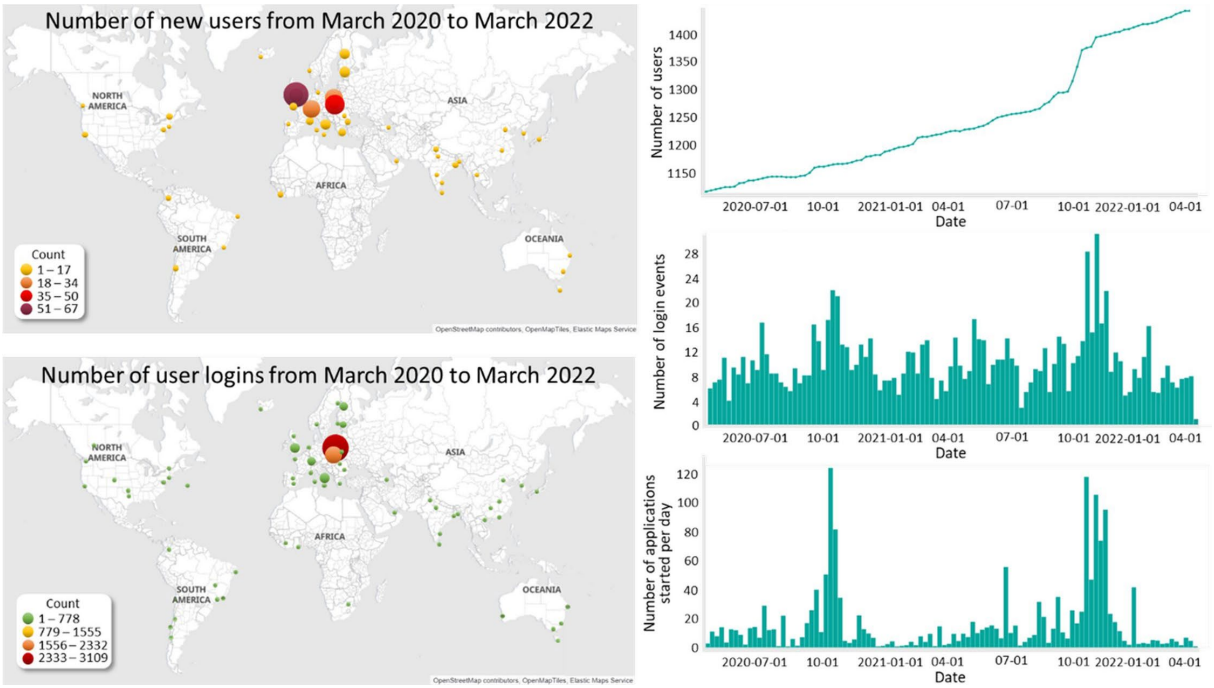

Figure 3. Statistics of the new EPISODES Platform users, all logins and the number of applications running on the EPISODES Platform from March 2020 to March 2022.

3 Currently Matlab and Octave are supported, Python support is planned to be added in the nearest future.

2016, Lasocki et al. 2017, Rudziński and Dineva, 2017]. The provided access to the multidisciplinary data and the specialized software applications and the availability of dedicated guides and tutorials, dissemination, and training tools enhance the capacity to provide novel services to users and facilitate research and innovation to support worldwide society now and in the future. Figure 3 presents the distribution of the new TCS AH users who registered on the EPISODES Platform during the last two years, since March 2020, together with the number of all users and the distribution of logins per day.

The new functionalities of the EPOS TCS AH research infrastructure integrated on the EPISODES Platform open a multitude of research possibilities. Apart from unlimited options of prescribed target use of the implemented applications along with their codes to process either the data from available episodes or their uploaded data, users can develop higher-level research projects built on top of existing integrated data and applications. The on-hand information from many different sites on source and propagation characteristics of recorded signals from slow and dynamic processes and their collective, statistical properties, and measurements of static in-situ deformations can be used to develop robust proxies of the space-time evolution of stress and deformation prior to an anthropogenic extreme. A user has the opportunity to comprehensively relate multidisciplinary and multi-parametric data from ground-based and remote observation systems (on-site monitoring networks and satellites) to both probabilistic and geomechanical modeling of rock mass response to geo-resource exploitation [e.g. Rudziński et al.; 2019, Ilieva et al., 2020].

The education and outreach capabilities of the research infrastructure integrated by EPOS TCS AH and accessible on the EPISODES platform should also be emphasized. The EPISODES platform has been used for educational purposes and the dissemination of scientific results. For example, in the doctoral studies at the Institute of Geophysics of the Polish Academy of Sciences (IG PAS), the platform serves as one of the tools to familiarize students with both primary seismological analyses and advanced time-dependent seismic hazard studies. The platform is used during classes in "Contemporary Geophysics: Seismology" and in a specialist course in Seismology. The platform has also been successfully used in courses for students in Sweden and Finland. In addition, workshops on anthropogenic seismicity using virtual access to data and applications provided by the EPISODES platform have been conducted for students in Germany, Poland, Sweden, the USA, Finland, and Italy. The potential of the EPISODES platform has been presented during online workshops and training dedicated to researchers at all career levels. During such training, the platform was presented by showcasing episode data from across four continents and four different industries. The online training events provided a significant introductory step toward more advanced training sessions that could take place in the future.

Apart from the scientific and educational activities, the TCS AH resources are also exploited in the social programs. A recent example of such a program is an action carried out within the framework of the Horizon 2020 EPOS SP project (EPOS Sustainability Phase, GA: 871121). The action called "Seismic hazard impact on local societies in areas of induced seismicity, on the example of the areas surrounding the copper mine in Poland", aims to elaborate the procedures, critical elements of products, and services with enhanced value for society. That goal shall lead to exemplary pathways demonstrating how to increase best the value of the products and services dedicated to the society struggling with hazard risk. Parties involved in the action represent legal authorities, local communities groups, and local entrepreneurs. The action is a four-step process: (1) interaction – gathering information and data; (2) training and promotion – workshops, meetings, school education, societal education, adapting services to the needs of local communities, language translation, EPISODES Platform training; (3) survey – monitoring the satisfaction and opinion about services presented during workshops, meetings, etc.; and (4) TCS AH Consortium feedback – decisions regarding the implementation of the elaborated services. Main activities are gathered around sharing and dissemination of the data and information on local seismic hazards induced by mining works in a copper-ore mine in Legnica-Głogów Copper District in Poland. This information is presented in webinars and disseminated by social media – TCS AH Facebook fun page, IG PAS website igf.edu.pl, and Edu-arctic.pl, edu-arctic2.eu websites.

TCS AH consortium is a unique forum for strengthening cooperation between academia and industrial partners in the area of geo-resources exploitation and the environment. Presently, the TCS AH develops a pilot service within the EPOS SP project, which aims to strengthen the interaction with the private sector and the added value for society. The pilot demonstrates the potential of the EPISODES platform software applications for the technology-related probabilistic assessment of time-dependent seismic hazard. Industrial activities for the extraction of geo-resources and, therefore, the factors that cause the occurrence and development of seismicity change over time. Consecutively, the anthropogenic seismic hazard is time-dependent. This observation is the basis for the

developed seismic hazard assessment methods [e.g., Lasocki, 2017 and the references therein; Leptokaropoulos and Lasocki, 2020], some of which have been implemented on the EPISODES platform. The pilot service "Time- & Technology-dependent Anthropogenic Seismic Hazard Assessment" (TTASHA) combines the platform's relevant hazard assessment applications and other complementarily supporting applications into one service. This user-friendly service can be used by people with only basic seismicity and hazard expertise. It is an offer to the geo-resources industry for routine use to monitor the hazard and the effectiveness of hazard-mitigation procedures.

TTASHA applies a probabilistic approach. The hazard is parameterized by the occurrence probability of an event whose magnitude exceeds a prescribed reference undesired value. This exceedance probability at time t is estimated based on the data on events that occurred in a prescribed volume and a prescribed-length time window preceding t. It is assumed that, in the time window, the seismic process is a marked Poissonian, where the marks are event magnitudes. Widely used in natural seismicity, the exponential model of magnitude distribution is usually not accurate enough for the hazard analysis in anthropogenic seismicity [Lasocki, 2001; Urban, et al. 2016]. Therefore, the magnitude distribution is modelled by a non-parametric kernel estimator [e.g., Lasocki and Orlecka-Sikora, 2008; Lasocki, 2021 and the references therein]. At the end of the analysis, the user receives the point and interval estimates of the exceedance probability [Orlecka-Sikora and Lasocki, 2017]. In addition to this core block, TTASHA also comprises two complementary blocks of applications. The first one enables waveform analysis to pick and parameterize events. As a result, the seismic catalogue used in the hazard analysis is updated. In the second one, the seismic hazard is forecasted based on the activity rate forecast and the most recent magnitude distribution. The activity rate forecast, in turn, is carried out, including relationships between the activity and parameters of technological operations that are the origin of seismicity. So far, a method for injection-induced seismicity, in which seismic activity rate is related to injection rate, has been developed and implemented [Garcia Aristizabal, 2018]. A TTASHA user may introduce thresholds defining a Traffic Light System [Bommer, et al., 2006; Mignan, et al., 2017]. Then, the street-light colors will accompany the hazard estimates.

4. Discussion and conclusions

EPOS Thematic Core Service Anthropogenic Hazards is a unique achievement of the European Earth science community. The TCS AH technical, organizational and legal framework concept has been developed and implemented within the European Plate Observing System. The European induced seismicity community has been transformed from a relatively isolated group, apart from the solid Earth mainstream science, to a worldwide recognized TCS AH consortium, with a defined mission and outlined strategic path forward. The accepted principles of synergic collaboration with industry, with mutual respect for partners' interests and concerns, have broken down the barrier to technological data availability. As a result, unique data sets have been collected, in the form of episodes, for the scientific study of the relationships between industrial processes and potentially threatening geophysical processes. At the same time, a high-quality environment has been created to process shared or own user data. Software implementations of the tailored to problem, state-of-the-art scientific solutions, together with the recently launched possibility to combine them with the user's codes, have been supported by a high-performance IT environment. The collaborative functionalities make the infrastructure integrated from the EPISODES Platform an excellent environment for consortial research and innovation projects. These possibilities were already used in the Horizon 2020 SHEER [SHEER] and S4CE [S4CE] projects, where the EPISODES Platform maintained projects' data, making them available exclusively to the projects' consortia. Moreover, after the projects' completion, the project data have remained on the EPISODES Platform, increasing the EPOS TCS AH resources and becoming open to all users.

Sustainable exploitation of geo-resources is a critical challenge for society, including the assurance of a supply of raw materials and the security of energy. Exploration for geo-resources and their sustainable use will become even more important over the next decades since concerns about climate change will demand shifts in energy production. The EU aims to be climate-neutral by 2050 – meaning an economy with net-zero greenhouse gas emissions. The sustainable management of geo-resources will play an essential role in this energy transition. This will include wider exploitation of deep geothermal resources for heating, cooling, and energy production, carbon sequestration of CO2, sustainable management of groundwater resources, storage of hydrogen, heat, and gas using underground resources, and safe long-term storage of nuclear waste, etc. This requires sophisticated subsurface

management and environmental safety to fully exploit the potential of the geo-resources. And this, in turn, is conditioned by effective and efficient solutions for anthropogenic hazard and risk management. The long-term roadmap for TCS AH is to integrate worldwide research infrastructure to develop strategic research capacity for addressing anthropogenic hazards challenges; to further integrate and develop research infrastructure to facilitate new discoveries; to work closely with all stakeholders, contribute to increasing public understanding of anthropogenic hazards, develop outreach and drive innovation by bi-directional, industry-science, transfer of solutions and the expert knowledge.

The EPOS TCS AH is a forum bringing together academia, industry, and administrative bodies from various European countries. Such networking gives the opportunity to share knowledge and experience, and to stimulate leading-edge thinking for fundamental science, smart regulation, and best operation and monitoring practices. This may be exemplified by a new undertaking of EPOS TCS AH, namely the digital twin service for anthropogenic hazards extremes (DT-AH), which implementation will start in 2022. DT-AH is one of the components of the Digital Twin for Geophysical Extremes consisting of interrelated DT components dealing with geohazards. It spans from natural to anthropically induced earthquakes, from volcanoes to earthquake- and/or landslide-triggered tsunamis. The Digital Twin for Geophysical Extremes has been designed by the solid Earth Science and IT community in Europe [Carbonell and Floch, 2021] under the Digital Europe Programme, launched by the European Commission to accelerate the recovery of the European economy and boost the digital transition of Europe. DT-AH service is designed to reinforce and develop additional capabilities in data processing and modelling complex non-linear responses of rock mass and, in particular, geo-resource reservoirs to the exploitation activity. DT-AH aims at finding the bridge between the solutions from geophysics, geomechanics, and geology for different technological activities in various different tectonic regimes. The approach will integrate the solutions from all these disciplines, settled in the newest ICT, also supported by the economic and societal impact indicators, and will be plugged into scientific tools for AH stakeholders. The component of the digital twin, DT-AH, may serve in the future as a pilot of future projects and may promote in-silico large-scale experiments, including social acceptance prediction studies.

The EPOS TCS AH consortium within the Horizon Europe project GEO-INQUIRE (ID: 101058518) plans to promote and extend the multidisciplinary and multi-scale features of the EPISODES platform to complement the existing geo-hazard data sets with additional geo-resource/geophysical data (e.g., borehole data, geological models), technological data (e.g., injection rates), and high-resolution seismic datasets available at different scales (including laboratory, in-situ laboratory, and georeservoir scales). Together with the other EPOS communities, namely EPOS GIM – Geological Information and Modelling, will develop the required metadata and API to allow access to EPOS GIM, European Geological Data Infrastructure and the ECCSEL-ERIC (European Carbon Dioxide Capture and Storage Laboratory Infrastructure – European Research Infrastructure Consortium). The TCS AH consortium plans to integrate in the near future the following episodes: JAGUARS – deep mining induced seismicity, physics of earthquakes experiment in the Mponeng gold mine (South Africa), Äspö (Sweden, hydraulic stimulations over the dm-scale), STIMTEC (hydraulic stimulation), cross-link with other data repositories/data hubs from in-situ laboratories (e.g., Collab) and data from analogue experiments on rock samples. It will also develop links with EOSC (European Open Science Cloud). The research infrastructure of TCS AH strictly follows FAIR rules. Software applications of TCS-AH can be executed using publicly available (EGI and national) cloud resources and can be made visible under the EOSC Portal/Marketplace. The development of the EPISODES Platform is in line with the EOSC Portal/Marketplace requirements for achieving future interoperability.

The datasets of episodes and applications are available on the EPISODES *Platform of Thematic Core Service Anthropogenic Hazards: tcs.ah-epos.eu. In accordance with the EPOS Data Policy which is available at www.epos-ip.org; and in accordance with TCS AH Data Policy, which is available at www.tcs.ah-epos.eu; datasets and applications are licensed under the Creative Commons Attribution 4.0 International License, CC:BY.*

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[GITEA] Gitea Git service https://gitea.io/en-us/
[GIT] Git version control system, https://git-scm.com/
[GIT DOC] Git documentation, https://git-scm.com/doc
[PLGRID] PL-Grid Infrastructure, https://www.plgrid.pl/
[S4CE] Science for Clean Energy, https://science4cleanenergy.eu/, https://cordis.europa.eu/project/id/764810
[SHEER] SHale gas Exploration and Exploitation induced Risks, https://cordis.europa.eu/project/id/640896

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