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IS-EPOS: a platform for anthropogenic seismicity research

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Abstract

Research in the field of anthropogenic seismicity (AS) requires not only seismicity data but also data regarding the progress of the technological/production activities which is the origin of the induced or triggered seismic events. Such data are typically restricted and proprietary, and therefore, usually not available for independent researchers who wish to develop, perform and verify scientific research. The induced seismicity-European plate observing system (IS-EPOS) web portal offers to its user's access to data, applications and documents in order to facilitate AS research. IS-EPOS web portal has been designed to serve as one of the main pillars of the Thematic Core Service—-Anthropogenic Hazards belonging to pan-European multidisciplinary research infrastructure created within the EPOS program. IS-EPOS platform is open for research community and general public according to its rules of access. The platform is operating since January 2016 and is now integrated in the EPOS Integrated Core Services. IS-EPOS e-platform promotes new opportunities to study and comprehend the dynamic and complex solid earth system by integrating the use of multidisciplinary data, data products, analysis models and online applications. The integration of existing and new national and transnational Research Infrastructures increases the access and use of multidisciplinary data recorded by the solid earth observing systems, acquired in laboratory experiments and/ or produced by computational simulations. In this paper, we describe the structure and the main innovative characteristics implemented in IS-EPOS. The platform is open to accommodate data integrated within other research projects, and it is continuously being updated with improvements in existing features and implementations of new ones. An appendix at the end of the article provides a summary of acronyms and abbreviations in order to make the reader familiar with the terms used throughout the manuscript.

Keywords IS-EPOS platform · Anthropogenic seismicity · E-platform · EPOS · Multidisciplinary data

Introduction

The increasing needs for ores and energy along with the recent requirement for better usage and exploitation of the deep underground have resulted in augmentation of triggered and induced seismicity in urbanized and industrialized areas all over the globe (Lasocki and Orlecka Sikora 2016; Grigoli et al. 2017; Foulger et al. 2017). The human-induced earthquakes can cause material loss, injuries and occasionally, fatalities. The magnitudes of such events can be large enough ($M > 5.0$ and up to 7.9, Davies et al. 2013

and references therein) not only to endanger industrial facilities and the personnel employed, but also to provoke devastation of civil infrastructure and even numerous victims (Ge et al. 2009; Gahalaut and Gahalaut 2010). Due to that, anthropogenic seismicity (AS, an appendix at the end of the article provides a summary of acronyms and abbreviations in order to make the reader familiar with the terms used throughout the manuscript) results in public concern and often has significant societal and economic impacts. For these reasons, increasing scientific research on AS and the corresponding hazard is carried out.

Contrary to natural earthquakes, AS is primarily related to the inducing industrial processes. That is why it is potentially possible to control stimulated seismic activity, and subsequently not only to evaluate but also to reduce the associated hazard and to maintain it below a prescribed degree. Rapid progress in this respect, done in the recent

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decades, is documented in numerous reviews and the references therein (e.g., Gibowicz and Lasocki 2001; Gupta 2002; Gibowicz 2009; Suckale 2009; Committee on Induced Seismicity Potential in Energy Technologies 2013; Davies et al. 2013; Gan and Elsworth 2014; Zang et al. 2014). Nevertheless, further developments of the technical solutions are expected both by the related industry, as well as the general public. Such solutions will lead to the reduction in the seismic hazard induced by the exploitation of georesources to a socially acceptable level. In order to reach this goal, a holistic integrated approach to the problem is needed. An approach across the variety of inducing technologies will start from addressing common physical background of the seismic process for all inducing technologies and further consider the specific inducing processes, individually. A prerequisite for such an approach is an open-to-research community database, which comprehensively describes the cases of induced seismicity linked to diverse industrial operations. This observation was the basis for the construction and further development of the presented here IS-EPOS platform for AS research (Fig. 1). In brief, IS-EPOS maintains and provides accessibility to data associated with specified AS cases. In addition, it facilitates these integrated or user's own datasets by means of a continuously increasing number of implemented software applications.

As mentioned above, the research focused on common features of rock mass reactions to diverse inducing technologies is a way to accelerate the recognition of the induced seismicity problem. This can be only accomplished through the integration of research and RI such as databases and software tools, based on the most advanced information and communication technologies (ICT) solutions. IS-EPOS platform is a digital research space, for providing to the AS Community a permanent access to advanced RI. It is a response to the needs, which have been formulated since 2007 in the framework of Triggered and Induced Seismicity (TAIS) working group of the International Association of Seismology and Physics of the Earth's Interior (IASPEI). They have been conceptually developed by the working group WG10: Infrastructure of Georesources, acting within the EPOS integration program (https://www.epos-ip.org; Lasocki et al. 2014). A prototype of IS-EPOS platform was a result of "IS-EPOS Digital Research Space of Induced Seismicity for EPOS Purposes" (http://is-epos.eu/) a project carried out from 2013 to 2015. The platform undergoes further enrichments and developments in the framework of EPOS-IP (EPOS-Implementation Phase) European project in the years 2015–2019. IS-EPOS platform is a complex and innovative solution, the main feature of which is the uniqueness of the integrated RI comprising two main deliverables (Lasocki et al. 2014): (1) multidisciplinary datasets, called "anthropogenic hazard episodes" (AHE, Fig. 2) and

(2) problem-oriented, bespoke applications implementing state-of-the-art scientific solutions for AS research. Both deliverables are uniquely designed for the analysis of relations between anthropogenic activity, seismic response and resulting hazard. Additionally, applications can be used for the analysis of individual user data uploaded to the platform under standardized format. The content of the platform is supported by a broad and continuously updated document/material repository, including peer-reviewed articles, books, reports, images, maps, etc.

System architecture

Many diverse elements intertwine in the IS-EPOS platform: from online operating measuring equipment, through harmonization and standardization of collected data, archiving and sharing procedures, to ICT solutions which facilitate conducting virtual experiments on collected data and implementation of software applications. The architecture of IS-EPOS platform (Fig. 3) envisages its further development, including collaborative functionalities and a dedicated space to integrate the data acquired within research projects. At the same time, IS-EPOS is a service provided by AS community to EPOS, and therefore, it interoperates with other EPOS technical components.

All components of the integrated research infrastructure, either data, software applications or documents, can be accessed through the IS-EPOS portal (https://tcs.ah-epos.eu). Without registration, visitors are allowed to preview all 21 integrated episodes (by August 2018). However, it is strongly recommended to register and log in using personal credentials. The registration requests are subjected to authentication, authorization and accounting (AAA), and access is promptly granted. After logging into the portal, the user gains access to three blocks of functionality (Fig. 4): (1) integrated AHE, (2) application packs of implemented software, (3) various documents and supporting material available in the repository. A forum for interaction with other users is also available within the platform. All these blocks are thoroughly managed by quality control groups, ensuring proper workflow, interaction and functionality of the system. The software and documents are stored in dedicated repositories in the IS-EPOS platform hardware, while the data are located in data nodes (DN) cooperating online with the portal. DNs acquire from data providers the data grouped as an AHE. The data were collected and stored in commonly used standards and formats (e.g., dataless SEED—miniSEED for seismic data, GeoTIFF—TIFF for raster geodata and .mat files for catalogs or technological data). We highlight that the generic data format (GDF) and multi-dimensional data format (MDDF) files with standard formats were elaborated

Fig. 1 IS-EPOS platform home page (http://tcs.ah-epos.eu)

as smart structures within the SHale gas Exploration and Exploitation induced Risks project (SHEER) to store many different measurements, e.g., water quality, air quality or other industrial and geodata. These data formats are very widely used and easy to use for further processing. Detailed descriptions of the formats used can be found in Project Deliverables available on the Project webpage (http://www.sheerproject.eu/; Cielesta et al. 2018).

The staff of DN harmonizes and adjusts the upcoming data components to the required standards and prepares the metadata for the AHE. The standardized AHE is subjected to a thorough quality control in the corresponding block of

Fig. 2 The Wysin AHE integrated on IS-EPOS Platform

episode integration on the IS-EPOS platform. After positive verification, data and information associated with the episode is published into the IS-EPOS platform to be accessible by the users. The communication and data transfer between DNs and the portal are based on metadatabase of IS-EPOS platform, which describes in detail the data resources of DNs. Therefore, at user's request, the suitable data package is copied from DN to the platform's temporary memory and becomes accessible by the user for further processing. On termination of user's session, the copied data are removed from the temporary memory.

Each registered and affiliated user is granted with a personal workspace which obtains a digital space assigned and organized individually by the user. Within this workspace all data selected by the user, processing logs and all processing results are stored. Any calculation performed using applications or data provided by IS-EPOS platform is placed here. Moreover, there is a possibility to upload external datasets to the platform workspace as far as they are adjusted to the data formats supported by the platform. The organization of user workspaces in IS–EPOS platform is based upon the InSilicoLab framework (Kocot et al. 2014), which provides core

Fig. 3 Topology of IS-EPOS platform. *DN* data node, *QC block* Quality Control block, *AH Episode* anthropogenic hazard episode, solid and dotted arrows represent already implemented and future interactions, respectively
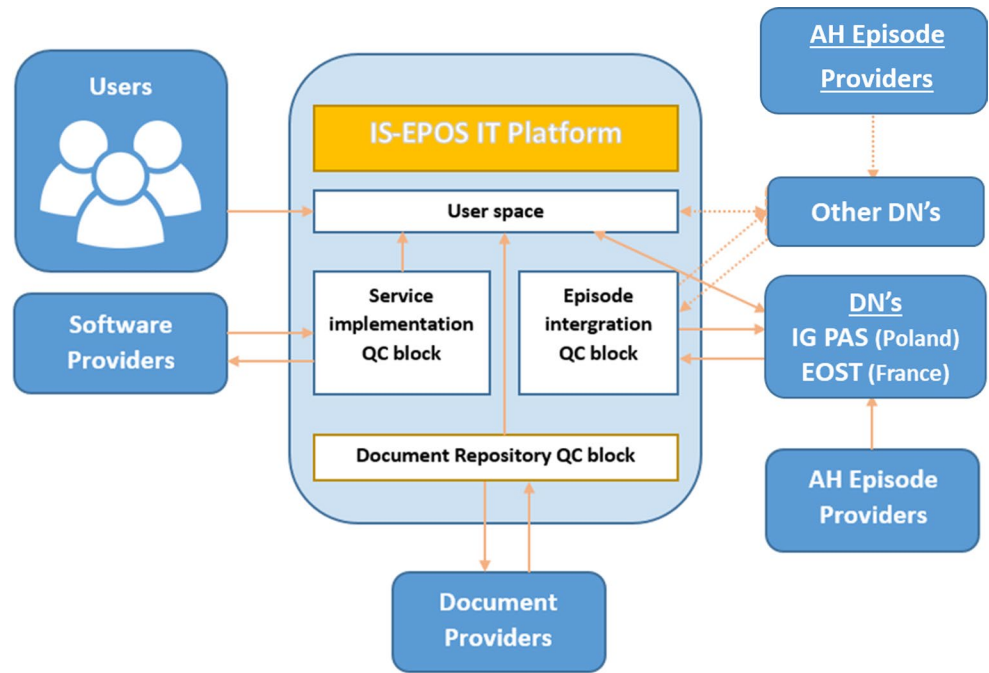
Fig. 4 Scheme of research infrastructure integrated within IS-EPOS e-platform (Modified after Cielesta et al. 2018)
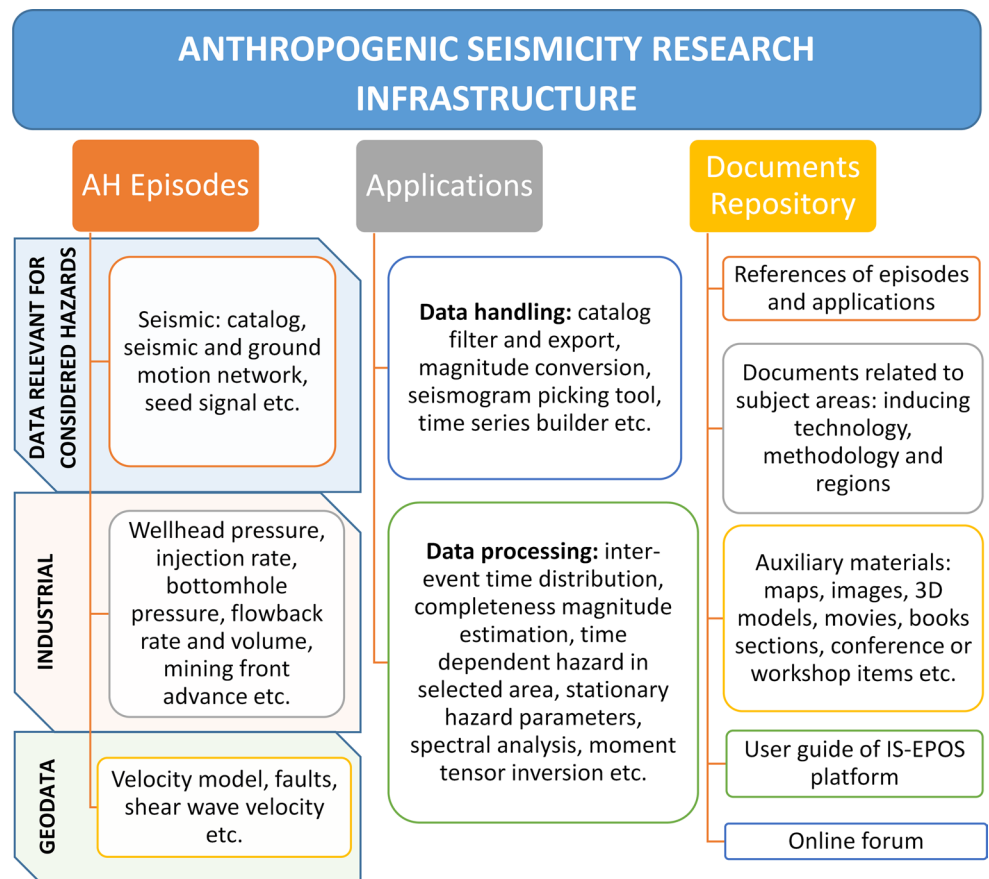
components that implement the workspace interface and realize the integration with advanced distributed computing infrastructures. Thanks to this integration, the platform applications can be executed on any infrastructure—cloud services, high performance computing (HPC) clusters or even single servers or personal computers. The InSilicoLab

processing model relies on a set of the so-called workers, which performs the computations and return the results to the gateway facing the user. The InSilicoLab core services are able to manage many simultaneous computations with different granularities (from tasks computed in seconds or minutes to calculations taking hours or days). The applications can also be run in a pipeline; in that case, the results of previous applications are used as input to the subsequent ones.

IS-EPOS overview

Registration, accessibility

The platform provides to the users an access to various sets of data, visualization tools, scientific applications and documentation at different levels. A trade-off between the part of resources available for all users and the part available only for the affiliated ones is maintained. This is done not only in an effort to secure the infrastructure from being intentionally or unintentionally abused, but also to provide the adequate access needed for research. According to this policy, the classes of users, infrastructures and functions are distinguished. An open access to a portion of integrated data and implemented applications of IS-EPOS platform is granted for all users—only registration is required. The users who have defined only their credentials (affiliation without any project linking) without providing any other information form the users class "public registered" (PR). A user of class "Researcher" (R) is the one authorized by an IS-EPOS platform management on the basis of provided affiliation. The user obtaining the Researcher level gets access to all open data and applications. In addition, an R user is able to work in the framework of his/her project(s) established on the platform, to form a working group and to share projects, data and data products with other users.

The platform ensures also the opportunity for cooperative work for the consortium of an external project. The consortium may deposit the data of its project in a selected data node and get an access to this data as well as to all platform facilities through IS-EPOS portal. Thanks to that the consortium will be able to process the data by means of applications implemented on IS-EPOS platform and make use of all platform facilities. Since project data is often embargoed until the end of the project, the accessibility to the data of external project via the platform may be restricted to the project consortium members only. This matter is addressed by specific agreements between platform and external project managements. Even when not fully accessible, the episodes of the project are visible on the platform for all users, as is the basic information about this project. Such an approach increases visibility and outreach of the project. This strategy

was used regarding SHEER project—the database has been just released. This has also put in force regarding EPOS-IP project, Science for Clean Energy (S4CE) project, and Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) project, all funded from the European Union's Horizon 2020 research and innovation programme.

Anthropogenic hazard episodes (AHE)

An AHE is a multidisciplinary dataset, comprehensively characterizing a specified anthropogenic seismicity case associated with exploration and exploitation of georesources. The AHE consists of a time-correlated collection of geophysical data representing the anthropogenic seismic process, data representing the operational activity related to this process and all other relevant geodata describing the environment of the activity.

IS-EPOS platform integrates currently metadata along with data description of 21 AHEs for anonymous users. Twelve AHEs among them are available for registered users, and the remaining episodes within EPOS IP and S4CE projects have restricted access. These episodes concern anthropogenic seismicity linked to underground mining in Finland, France and Poland, hydroelectric energy production (reservoir impoundment) in Italy, Poland and Vietnam, conventional and unconventional hydrocarbon extraction in Italy, Netherlands, Poland, UK and USA, underground gas storage in France as well as geothermal energy production in Germany and USA. Some AHEs include seismic data recorded continuously by download interfaces, and others are processed in the form of triggered signals and seismic catalogs. Network and sensor data do not necessarily refer to specific seismic networks, but may also contain any other sensor used in the industry to monitor the technological processes, for example, pressure sensors, thermometers and strainmeters. Technological data of episodes include injection rates, production rates, amount of ore exploited, advance of the mining front, level of water reservoirs, well pressure, panel geometry, flowback volumes/pressures/rates, wellhead pressures, etc. Auxiliary data such as shorelines, geological maps and faults projections are also available.

Seven of the above-mentioned episodes are associated with SHEER project. Since May 2018, these episodes are also available to PR users. These episodes concern specifically seismicity induced by hydraulic fracturing, geothermal energy production and conventional gas exploitation. The SHEER database harmonize data from different fields (geophysical, geochemical, geological, technological, etc.), and innovatively create and provide access to a unique and advanced database of case studies of environmental impact indicators associated with shale

gas exploitation and exploration. The data sources within SHEER project are categorized as:

- datasets from shale gas operation sites (Lubocino—Poland, Wysin—Poland and Preese Hall—UK);
- conventional oil and gas production sites (Groningen—The Netherlands and Oklahoma—USA); and
- sites where stimulation for geothermal energy production and geothermal experiments took place (Gross Schoenebeck—Germany and The Geysers—USA).

Moreover, at least 16 more episodes related to conventional hydrocarbon extraction, reservoir treatment, underground mining and geothermal energy production are during the process of integration within EPOS IP project. These AHEs will be gradually integrated and eventually opened to PR users in October 2019.

The heterogeneous multi-disciplinary data (seismic, displacement, geomechanical data, production data, etc.) are transformed to unified structures developed within IS-EPOS project, to form integrated and validated datasets. The TCS-AH integrated data is described by the metadata, stored and provided by DNs to the IS-EPOS platform. This structure offers homogenized and standardized datasets, allowing users to perform more efficient research. Moreover, every episode has its unique DOI allowing for proper citation of the resources. Dedicated visualization tools for multidisciplinary data that constitute an episode are also implemented. These tools are capable to aggregate and combine different data types and facilitate specific visualization possibilities (e.g., combination of seismic and technological information).

Applications

IS-EPOS platform grants access to particular applications dealing with specific scientific problems, designed in the area of anthropogenic hazards. The platform enables research studies using the applications and the supporting visualization tools. A significant portion of these applications has been developed within IS-EPOS project (part of software is free and can be redistributed and/or modified under the terms of the GNU General Public License as published by the Free Software Foundation, either version 3 of the License or any later version—http://www.gnu.org/licenses/).

The available applications in IS-EPOS are divided on the basis of their outputs into data handling and data processing, each of them containing applications grouped into thematic packages. Data handling applications comprise algorithms and tools for data format transformation, data filtering, conversion and visualization (Rudziński et al. 2017). On the other hand, data processing applications sustain advanced methodologies for AS data analysis. All of these applications are available to the R users and can be used for experimental analyses as soon as they are transferred to the personal user workspace. The products derived after the application performance (data, results, tables, figures, etc.) can be either further used as an input to other applications or downloaded by the user in various format types (e.g., .mat, .xlsx, .png, .jpeg, .pdf, .svg, .txt).

The data processing applications are categorized in groups for easier selection of a certain application: source parameters estimation (source localization/re-localization, moment tensor inversion, earthquake spectral analysis—Fig. 5); collective properties of seismicity (inter-event time distribution, completeness magnitude estimation, source-size distribution functions); probabilistic seismic hazard analysis (including hazard parameters estimation such as exceedance probability, maximum credible magnitude, mean return period, in either stationary or time-dependent mode); technology-seismicity interaction (correlation analysis, seismic hazard in stationary and moving geometry technology); stress field modeling (stress inversion from focal mechanisms, fracture network modeling). All of these applications consist of software packages and visualization facilities, applied to selected data subsets that a user has pre-defined and uploaded to the personal workspace. The user has therefore the possibility to proceed to either episode-oriented research (application of various methodologies focusing on a particular episode) or method-oriented research (perform a certain methodology at several datasets in order to compare results with each other and test the efficiency of selected approaches). Links and documents describing in detail the technical and scientific background of all the integrated applications can be found in the document repository.

Data handling applications include a seismogram picking tool (Fig. 6), signal and waveform download tools, catalog filtering, catalog and other data export (from Generic MATLAB Data format to.xlsx format), a time series builder, SEED to SAC converter, ground motion parameters tool and magnitude conversion to diverse magnitude scales. Visualization applications are also available within IS-EPOS including several generic graphical tools implemented in the platform. These tools can be used to illustrate, e.g., the evolution of seismic activity together with the production/technological processes related to each AHE. Various plotting options are provided (zooming, different plotting styles and scaling, rotation, etc.), allowing the users to investigate potential patterns and links between seismicity and technology. Depending on the inducing technology of the episode and the available data, additional visualization tools are offered such as: correlations of seismic parameters to production parameters, lower hemisphere projection of

Fig. 5 Amplitude spectra from S-waves picked on two horizontal components of a seismic station, as derived by the 'Spectral Analysis' application. The Snoke (1987) fitting is illustrated as well. (see Rudziński et al. 2017 for examples)
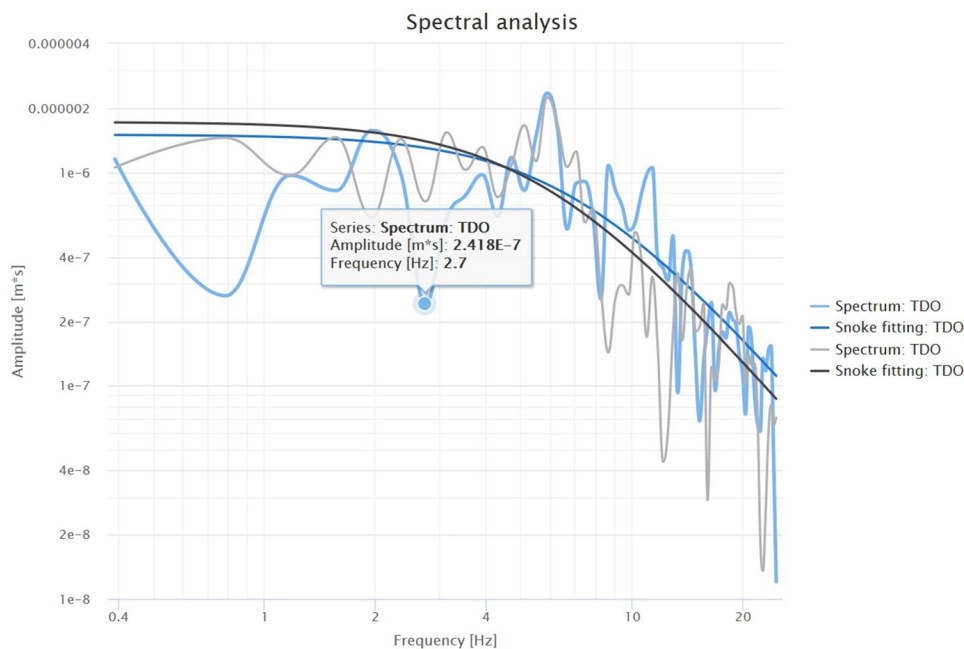
focal mechanisms, histograms and 3D graphs and animations. Such tools facilitate the realization of an analysis by both visual inspection and interactive selection of parameters (Fig. 7). IS-EPOS platform offers to the users a variety of parameters and data selection options (typing values, interactive selection from tables, graphs, lists, calendars and maps) in order to be more efficient and user friendly. Moreover, input data limitations and constrains are reported to the user for ensuring the proper application performance.

Additional applications (assigned to existing or new packages) are under development and scheduled to be progressively integrated in IS-EPOS platform and will be fully functional by October 2019. At the same time, the already existing applications are under continuous improvement and quality control, including the entry of new features in some packages.

Document repository

The IS-EPOS platform integrates within its repository numerous items of different types (more than 800 by August 2018) with ~ 570 of them being peer-reviewed studies published in international scientific journals. Among the other types of materials stored in the repository are books and book chapters, peer-reviewed and unreviewed reports, various materials from conferences and workshops (e.g., posters and presentations), theses, videos, maps, images, etc. Taking into account copyright policies most of the documents in the IS-EPOS document repository are only references with link to the editor/publication website; nevertheless, some of the items are available for direct download. The classification of

the documents inside the repository takes into consideration multiple aspects and provides to the user an opportunity to search for a specific document according to various criteria (methodology, regions, inducing technology type, authors, publication date/type, etc.).

Additionally, a platform user guide is available in the document repository in order to provide a brief but comprehensive description of the portal functions and applications together with instructions for navigating into the platform (https://tcs.ah-epos.eu/eprints/). The user guide describes the different functions available on the platform by examples and by demonstration movies. A quick-start guide providing an overview of the platform and the basic navigation procedures and functionalities is also available and recommended for new users.

Conclusions and future perspectives

IS-EPOS was created as a Science Gateway—a web-based platform offering to AS researchers a portal for accessing and analyzing data related to anthropogenic seismicity. The system architecture consists of data and metadata repositories, which are filled and managed by the services of data acquisition and integration. On the other hand, these depositories also consist of the computing infrastructure that enables performing calculations on relevant data. IS-EPOS platform has been operating since January 2016 as a prototype of TCS-AH within the EPOS. It is continuously upgraded and updated in order to provide to the AS community virtual access to multidisciplinary and complex data, fully
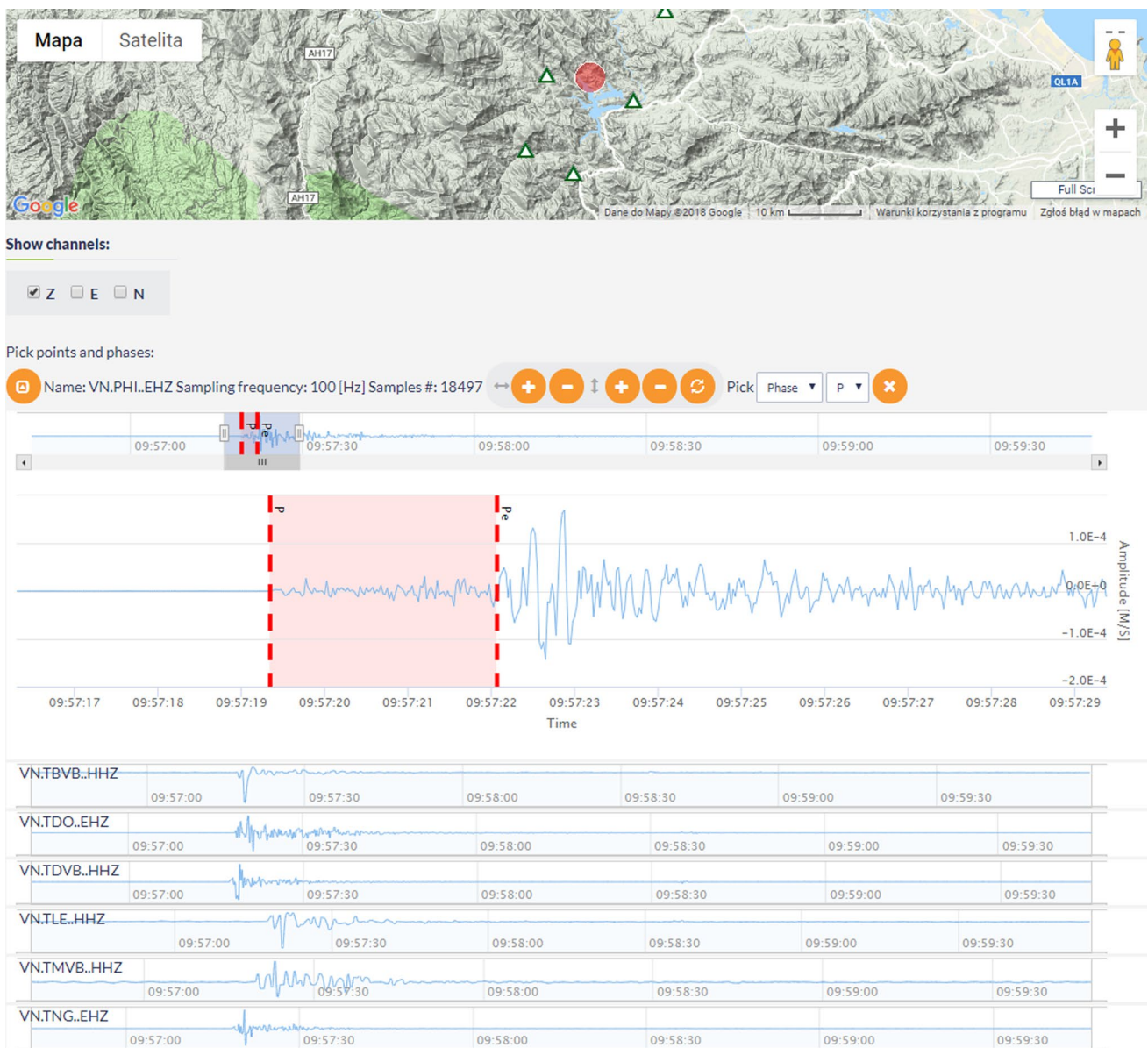
Fig. 6 P-wave phase picking example in the 'seismogram picking tool'

functional scientific applications and visualization tools supplemented by an electronic library. By August 2018, more than 700 users from over 100 institutions and companies in about 30 countries worldwide have registered.

IS-EPOS has been designed in a way which supports and promotes its further development by the means of both AH episodes and applications. The platform is already involved in four Horizon 2020 projects (SHEER, EPOS-IP, SERA and S4CE) and one national project co-financed by the European Union from the European Regional Development Fund (EPOS-PL). Within SHEER project, seven AH episodes connected with hydraulic fracturing, geothermal energy production and gas exploitation activities are integrated on

IS-EPOS platform and are available to registered users since May 2018. Over sixteen additional AH episodes and more than ten new data processing application packs are planned to be integrated within EPOS-IP project until October 2019. Within SERA and S4CE projects, IS-EPOS platform will serve as a virtual access tool to integrated anthropogenic hazards data and it will be strongly developed in terms of IT solutions facilitating platform usage. Under the framework of some of these projects, non-seismic anthropogenic hazard data (e.g., air quality, groundwater chemistry) are about to be integrated as well. Within EPOS-PL, project to Multi-disciplinary Episodes from Upper Silesia, Poland, will be

Fig. 7 Snapshot from input parameter selection for 'Time-Dependent Seismic in Selected Area' application. First, the events are filtered by inter-actively selecting a circular, rectangular or polygonal area. Then, the user further filters the data by selecting the parameters shown below the map (e.g., temporal and magnitude range)
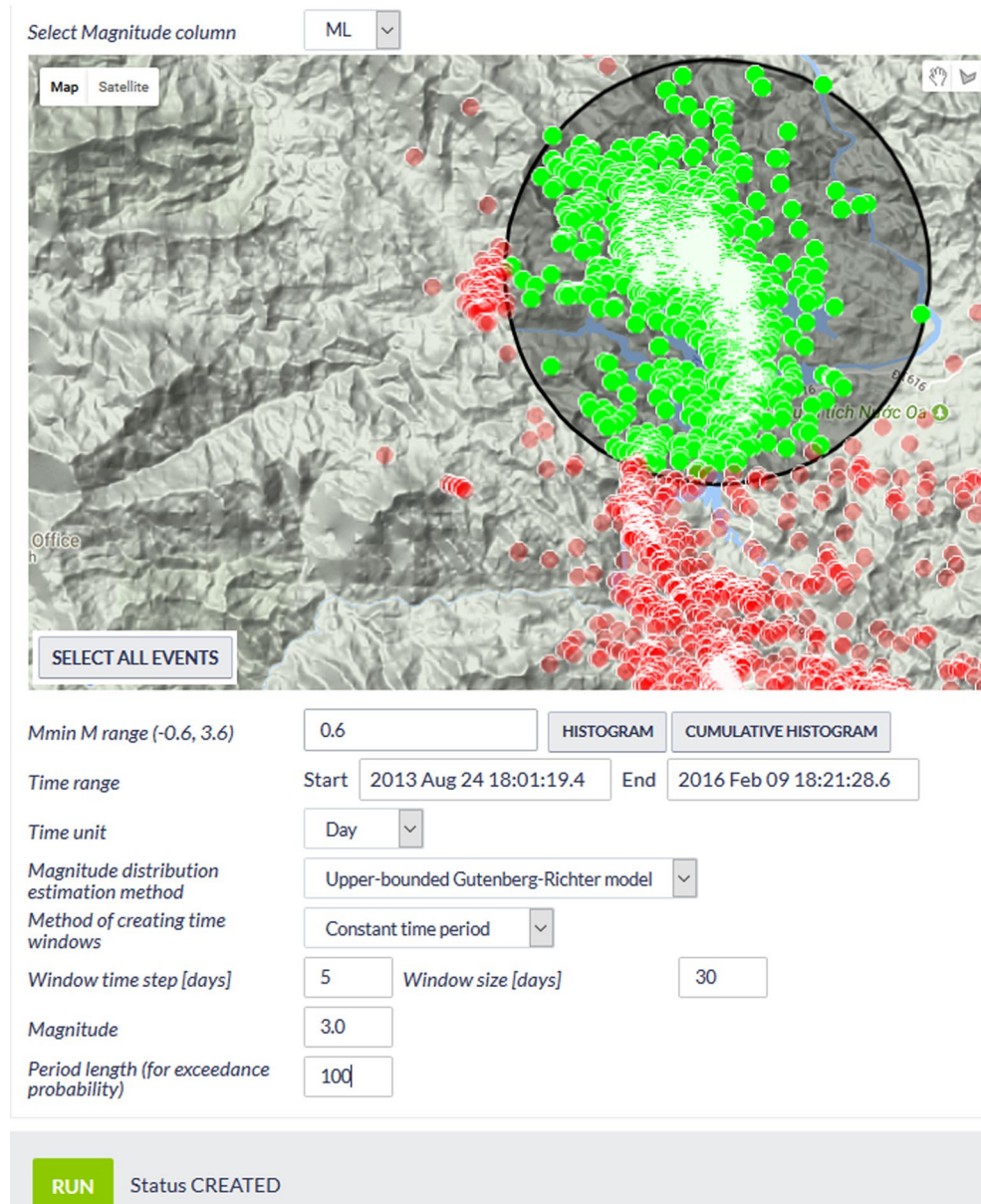
integrated, incorporating various geodata such as seismic, global navigation satellite system (GNSS) and gravimetric data.

IS-EPOS platform receives an open access tool for the experimentation and training of students and young scientists, who want to perform AS research. Several successful trainings and demonstrations for undergraduate as well as postgraduate students on AS and hazard have been carried out in Germany, Poland, Greece, Sweden and USA. It is important to strengthen that due to virtual access and DNs policy IS-EPOS platform can be easily utilized to share and promote the results of any scientific project on anthropogenic hazards and enrich the scientific community knowledge and research possibilities. Collaboration abilities are scheduled to be integrated in the upcoming platform version, enabling

team generation and sharing common projects, data, applications and results among the users. IS-EPOS thus promotes new opportunities to study and understand the dynamic and complex solid earth system response to human activities by integrating the use of data, data products, analysis models and online facilities. (Lasocki et al. 2017; Leptokaropoulos et al. 2017a). IS-EPOS has been already used to facilitate scientific research in recently published papers connected with anthropogenic as well as natural seismicity by utilizing data, applications and/or the interface and facilities of the platform (Wiszniowski et al. 2015; Kozłowska et al. 2016; Lizurek 2017; Rudziński and Dineva 2017; Gkarlaouni et al. 2017; Lizurek et al. 2017; Olszewska et al. 2017; Staszek et al. 2017; Leptokaropoulos et al. 2017b, 2018a, b; Lepto-karopoulos and Staszek 2018; Orlecka-Sikora et al. 2018).

The number of papers in which IS-EPOS e-platform is being cited is still increasing; current list of publications is available in the platform repository at http://tcs.ah-epos.eu/eprints/id/saved_search/4.

Appendix: Summary of abbreviations and acronyms

AAA	Authentication, authorization and accounting
AHE	Anthropogenic hazard episodes
AS	Anthropogenic seismicity
DN	Data node
EOST	Ecole et observatoire des sciences de la terre
EPOS	European plate observing system
EPOS-IP	European plate observing system—implementation phase (http://epos-ip.org/)
EPOS-PL	(https://epos-pl.eu/)
GDF	Generic data format
GNSS	Global navigation satellite system
HPC	High performance computing
IASPEI	International Association of Seismology and Physics of the Earth's Interior
ICT	Information and communication technologies
IG PAS	Institute of Geophysics Polish Academy of Sciences
IS-EPOS	Induced seismicity—European plate observing system (http://is-epos.eu/)
MDDF	Multi-dimensional data format
PR	Public registered (platform user)
QC	Quality control
R	Researcher (platform user)
RI	Research infrastructure
S4CE	Science for clean energy (http://science4cleanenergy.eu/)
SERA	Seismology and earthquake engineering research infrastructure alliance for Europe (http://www.sera-eu.org/en/home/)
SHEER	SHale gas exploration and exploitation induced risks (http://www.sheerproject.eu/)
TAIS	Triggered and induced seismicity working group
TCS-AH	Thematic core service—anthropogenic hazards (https://tcs.ah-epos.eu/)

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