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PREVENT – AN INTEGRATED MULTI-SENSOR SYSTEM FOR SEISMIC MONITORING OF CIVIL STRUCTURES

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Abstract. The PREVENT project's main objective is to systemize the research outcomes and the computational capabilities in order to develop, implement and test an integrated dynamic platform for civil structures monitoring. The present paper focuses on the description of the instrumentation setup, dataflow, the platform architecture and preliminary results for the most recent Vrancea intermediate-depth earthquakes. The expected outcomes of the project will consist of the first high-quality database recorded on structures and will provide a valuable tool to the research community, earthquake engineering community, authorities and stakeholders as well as to teachers and students, for educational purposes.

Key words: seismic monitoring, multi-sensor platform, civil structures.

1. INTRODUCTION

Deterioration and degradation of structures are critical, since structural failure can involve large economical losses and can endanger the life-safety of occupants. In order to address this issue and to be able to implement rational management policies, strategies and practices, structural damage detection at the earliest possible time has become a worldwide research subject [1] from early 2000s. The dynamic response of structures to earthquakes is controlled by various factors, among which the most important are the amplitude and frequency content of the input motion, the dynamic characteristics of structures, the interaction of structural and non-structural elements and the soil-structure interaction. The process of tracking the evolution of the structure's integrity over time is often referred to as "Structural Health Monitoring" (SHM). Vibration-based seismic monitoring hinges on the fact that the dynamic parameters of the structure are related to its rigidity, thus any damage occurring in the structure (either by earthquakes or other hazard) will induce a change in its dynamic characteristics. However, not only the changes in rigidity can induce variations of the modal parameters. Previous studies have shown that small variations of the dynamic parameters can be induced by the atmospheric conditions, for instance temperature, heavy rainfall, wind, soil saturation [2–5].

Romania is a country with a high level of seismic hazard and the main endangered area in the perspective of a future strong earthquake is Bucharest area [6]. With a building stock of more than 131000 assets, 44% of them being constructed before 1963 (2011 National Census), the earthquake and ambient vibration data recorded on buildings can provide very useful information for engineering community to assess their structural integrity and also for authorities, in case of emergency after a strong earthquake [7]. To support this, INFP has made great efforts in recent years to enhance seismic monitoring of buildings. At present, INFP is monitoring 10 buildings, seven in Bucharest, one in Magurele, one in Focsani, in Vrancea epicentral area and one in Eforie, close to the Black Sea. All stations record continuously the vibrations at a sampling rate of 100 Hz and the data is sent in real-time to the INFP National Data Center, in Magurele where SeisComP runs and provide data acquisition, data quality control, real-time data exchange, network status monitoring and basic rapid data processing [8, 9].

Following this challenge, a new framework including a web-based platform for seismic monitoring of structures has been proposed. The PREVENT (Open system for integrated civil structures monitoring) project's main objective is to develop and test a sustainable online service platform capable of generating applicative products based on seismological research and sensor monitoring, enhancing the safety and security of urban environment against earthquake disasters (with considered potential for adding other types of hazards). The beneficiaries of this platform are numerous: building administrators, authorities (as a helpful tool for the decision-making process), research community and earthquake engineering community, as a basis for inter-disciplinary studies and practical applications, students and teachers as a modern educational tool for hands-on activities related to data manipulation and processing [10]. The overall ambition of PREVENT is that the developed platform becomes a standard recognized by stakeholders and thus emerge as an "indispensable partner" in different risk mitigation actions before, during, and after a damaging earthquake, enabling through its success the expansion toward other types of natural hazards where new monitoring technologies can make a difference.

The current paper presents the overall concept and architecture of the interactive platform, a case-study site along with some preliminary results and the next steps to be implemented for achieving the PREVENT's ultimate aim, *i.e.* reaching the Technology Readiness Level (TRL) 4 – validation in laboratory environment of the PREVENT system capability.

2. CONCEPT AND ARCHITECTURE

The PREVENT platform is thought to be dynamic, continuously fed and updated with new data and open, in the sense of providing the possibility of bringing and integrating new parameters and data that would become useful in the future, from researchers, property owners, local authorities and the general public. The platform

will increase the capacity of INFP to generate laboratory validated solutions for a new service and to offer it to stakeholders. Another aim is to develop computer algorithms based on observed data for computing and monitoring engineering demand parameters (EDP), checking for the exceedance and issuing alerts accordingly. The platform will also help create the first database in Romania to offer quality raw and uniformly processed data recorded in buildings.

As presented in Fig. 1, the platform will include several layers, the main ones consisting of data acquisition/archiving, data processing tool and the presentation module.

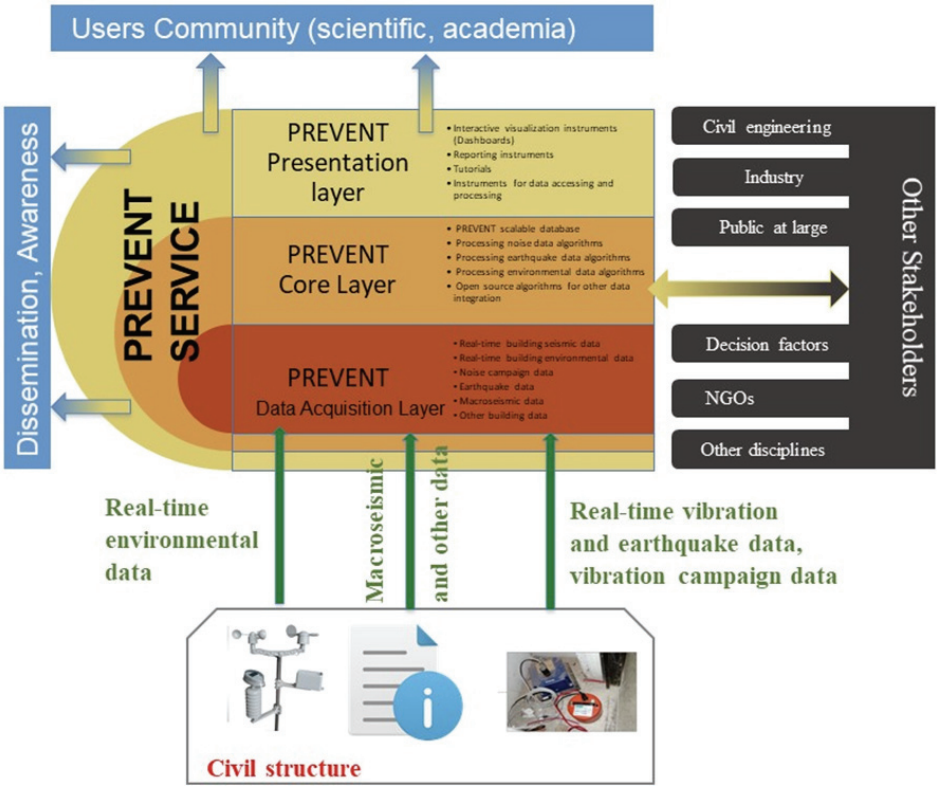

Fig. 1 – The general concept of the PREVENT service.

The first layer will enable data collecting and archiving. For the real-time seismic data, a seedlink server is used which is a part of SeisComP software [11]. For other data types (*i.e.* environmental), either real-time or measurement campaigns, specific open-source solutions will be implemented. A key element of this layer is represented by the data standardization procedure. All the data will be archived and saved in a uniform manner [12], to ensure compatibility between different data-sets and easier manipulation.

The core of the platform will be represented by the data processing tool. A first quality check will be performed in terms of data availability, followed by absolute and relative amplitude checks for different channels, in order to remove or flag the possible outliers in the dataset, values that are not properly collected due to either technical or human errors. Based on open-source interactive solutions (mainly Python, Jupyter Notebooks, ObsPy [13]), specific processing tools for earthquake engineering parameters will be implemented and tested on the data collected from structures. This module will allow the evaluation and track of the building's dynamic parameters (fundamental frequency, damping ratio) and report any abnormal values. More specific engineering demand parameters will also be computed, for seismic events of interest: acceleration, velocity, displacement time-histories, peak values, spectral values, inter-story drift, Arias Intensity or Housner Intensity. The platform will be designed to be scalable, thus more information (building information, reports, photos or additional data) and processing algorithms can be accommodated afterwards, improving the platform's efficiency. The environmental parameters (air temperature, relative humidity, wind speed, precipitation) recorded by the meteorological station will serve as a basis for correlation with different fine variations of the fundamental frequency. The acceleration response spectra computed at the base of the structure will also be verified for exceedance with respect to the building design spectra and specific alarms can be issued accordingly [14]. The presentation layer will include different outputs, in terms of real-time data, a dashboard with dynamic interface, rapid reporting based on raw/processed data and user-based access level. Although there are many options for Structural Health Monitoring, the analysis in (near) real-time poses great challenges regarding data acquisition, efficient processing algorithms, harmonized data flow, error identification or result representation and interpretation; there is still a lack of an end-to-end solution and previous attempts for implementation of a platform using real-data from seismic sensors (such as SHARD or the Antelope with the Bighorn module) proved to have significant limitations, mainly due to multiple module dependencies and code flexibility. The PREVENT platform is thought to separate modules responsible for different tasks, keeping SeisComP for data acquisition (since it proves to be a reliable and free service for this task, with easy possibility of connection with almost any type of seismic sensor) and creating a computational-efficient database model framework separate in terms of conversion, raw Big Data storage, interrogation, algorithm processing, data handling and representation.

Two types of beneficiaries were identified: user-only, which will include the general public, emergency services and decision-makers and building administrators as well as user-contributors. The latter includes researchers, students and professors, civil and earthquake engineers, who can also contribute with their own data to the platform, run the analysis tool and retrieve the desired results. For students and teachers mainly, the platform will serve as a practical interface for educational purposes.

3. CASE-STUDY

Within the project, one building from Magurele (Institute of Atomic Physics – IFA) is monitored using different types of sensors. The data will be processed within the platform and the achievements and results will be promoted in order to reflect the platform capabilities and ensure the creation and expansion of a future monitored building network. In addition, other research reports and data relevant to the topic (such as soil profiles, ambient noise measurements, amplification curves etc.) will be included in the platform, in order to aid in removing knowledge barriers.

The building was selected based on its previous instrumentation history and its specific importance for Magurele [15–18]. It represents a typology of structures that have been affected by the 1977 earthquake and was retrofitted afterwards, in the beginning of the 90s, in order to ensure its future serviceability. In the current application, seven low-cost Raspberry Shake sensors (accelerometers and seismometers) were installed, in addition to the existing three professional sensors, already monitoring the building since December 2013 (Fig. 2).

Fig. 2 – Pictures taken during the installation of the new instrumentation in the IFA building.
Left – a low-cost 3D Raspberry Shake sensor collocated with an existing professional accelerometer.
Right – a low-cost 4D Raspberry Shake sensor installed alone in a new location.

The instrumentation setup is presented in Fig. 3. With red arrows are represented the professional three-component accelerometers (TSA-100S), located at the basement level, 6th floor and 10th floor. These sensors and one digitizer were installed in 2013. The data archive consists of more than six years of continuous recordings, including more than 80 earthquakes with moment magnitude larger than 3.8, analyzed by Tiganescu *et al.* in 2021 [18]. An extensive instrumentation program has been initiated in 2020, in conjunction with the start of the PREVENT project. The green arrows in Fig. 3 represent the newly installed instruments and consist of Raspberry Shake sensors. The RS3D sensor model is a three-component velocity sensor (geophones) while the RS4D sensor model consists of three-component microelectromechanical systems (MEMS) accelerometers and a vertical geophone.

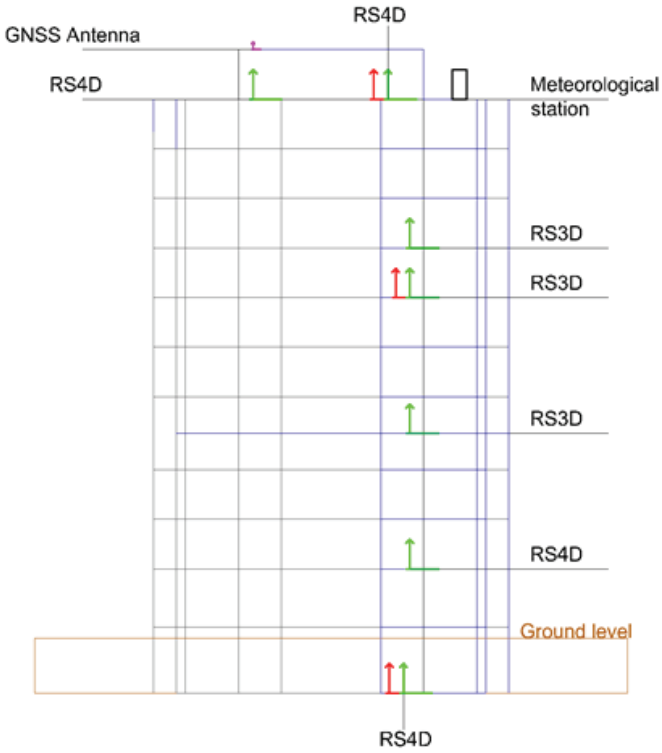

Fig. 3 – IFA building instrumentation setup.

In addition to the seismic sensors, a GNSS receiver and antenna were installed in the framework of the TURNkey project (www.earthquake-turnkey.eu), and by the end of 2021 Summer a meteorological station will be installed on the top of the structure. All this permanent instrumentation will allow researchers and building owners to have a better assessment of the building's behavior with time, either as a response to ambient vibrations or earthquake motion. For real-time data acquisition and archiving the SeisComP software is used, for the sensors installed in the IFA building. The IFA building dataflow within the PREVENT platform is presented in Fig. 4.

An example of a 4.7 M_L earthquake recorded by the sensors on May 25th is presented in Fig. 5. An advantage of the PREVENT platform is the easy integration and comparison with the data coming from the national Romanian Seismic Network, run and maintained by INFP. In Fig. 5 the raw data are presented, from all the building stations. This type of representations helps the user to identify the earthquake, to discriminate between different wave arrivals and also to assess the wave propagation within the structure.

Several previous studies have presented different methods for building data processing. Based on a sensitivity study, the platform will include specific processing algorithms and methods used for extracting the dynamic parameters of building, for

integration from acceleration to velocity and displacement, for computing the peak values and for rapid computation of engineering demand parameters.

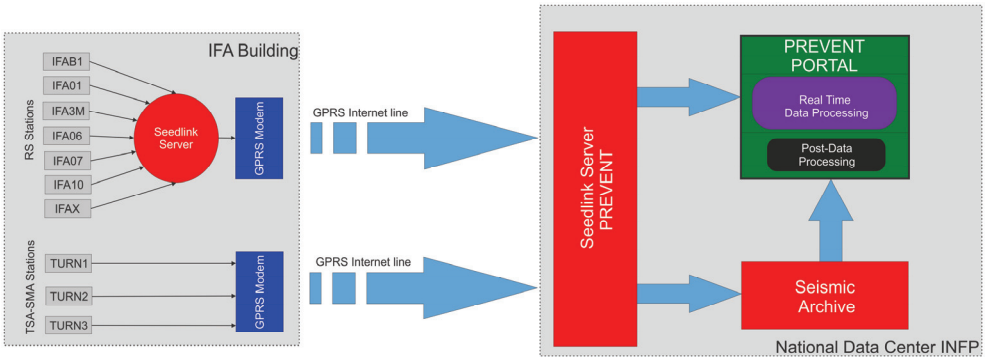

Fig. 4 – Seismic dataflow in real time using SeisComP.

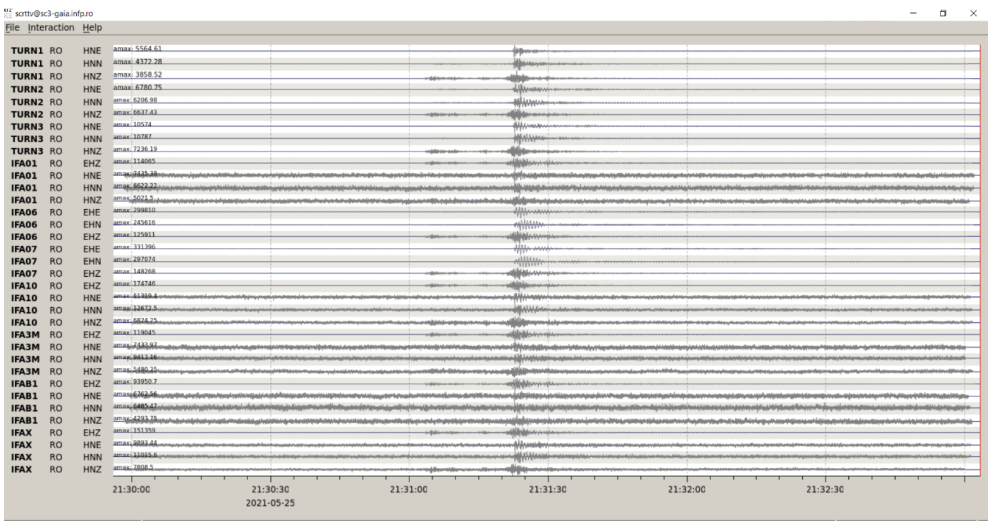

Fig. 5 – Data recordings from the May 25th earthquake, from all sensors and all components.

In addition to the automatic algorithm implementation, an open-source tool based on Jupyter Notebooks will be made available for general or specific users. An example is presented in Fig. 6. By integrating the ObsPy capabilities, the users will be able to customize and test the algorithms either on data available on the platform or on their own data. The acceleration time-history graph and also the spectrogram, some simple tools, can be easily computed and plotted using interactive scripts, as presented in Fig. 6. This tool will represent a powerful yet easy-to-grasp resource for the research/engineering community and also for students eager to use theoretical knowledge in practical applications.

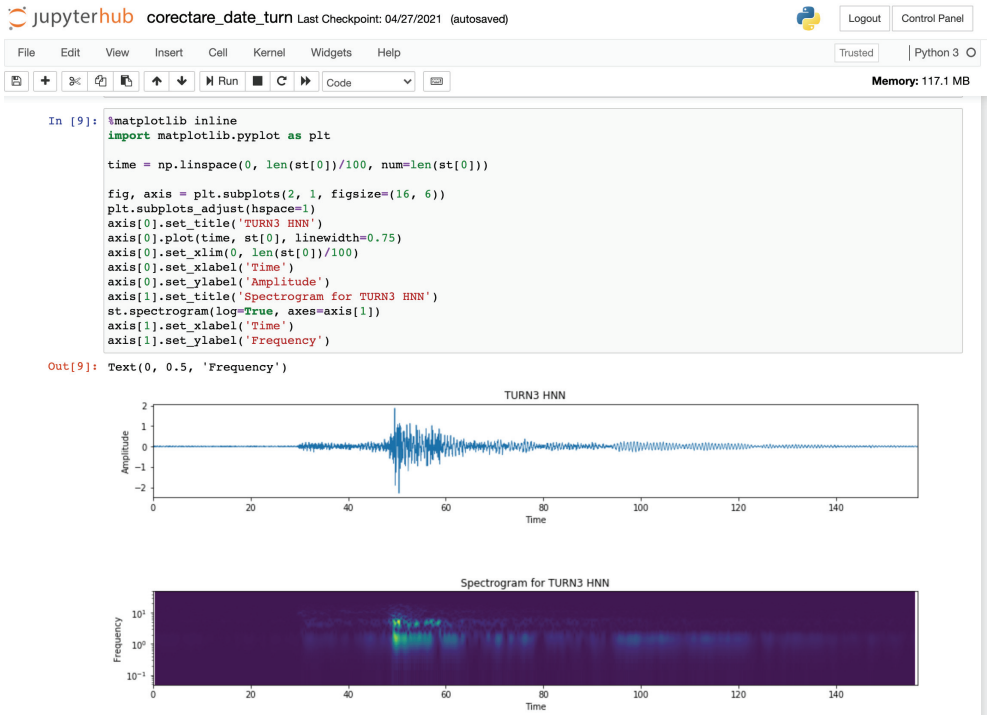

Fig. 6 – Example of interactive use of Jupyter Notebooks: Acceleration time-history and spectrogram for TURN3 station.

4. DISCUSSION AND CONCLUSION

Currently, the efforts of various institutions in Romania, including INFP, URBAN-INCERC and UTCB, in managing and using seismic networks and sensors for building monitoring are not synchronized and do not follow similar procedures [19]. The PREVENT Platform will create the means for harmonized processing and analysis of data, in accordance with international methodologies and standards. It will also create the means for bringing all data in the field of study together.

New technologies such as low-cost precise seismic sensors, Big Data real-time analysis or ICT dynamic interfaces are not yet well interconnected in order to show the general public their applicability in seismic risk reduction. The aim of the project is to make the proper links and create a product scientifically sound and also easy to use and understand by beneficiaries. One of the challenges will be uncertainty estimation (since state-of-the art algorithms in Structural Health Monitoring have their ranges of limitations) and the way it is accounted for in different studies. PREVENT will impact on Society, Economy, Environment, Knowledge and People and proposes a method to help in the prevention of these impacts through real-time

monitoring of civil structures for continuous assessment of their integrity. Although there are worldwide solutions for assessing and tracking the buildings' structural integrity, they have limitations mainly due to multiple module dependencies and code flexibility or they are focused on particular aspects.

By collocating professional sensors with low-cost sensors, the idea is to test the reliability of using different types of instruments and to compare the results, the thresholds, the frequency range of the recordings and their sensitivity [20]. For students and teachers, the platform will serve as a modern educational tool for hands-on activities related to seismic data manipulation and processing.

The PREVENT project will be complementary to the European Project TURNkey (Towards more Earthquake-resilient Urban Societies through a Multi-sensor-based Information System enabling Earthquake Forecasting, Early Warning and Rapid Response actions), a Horizon 2020 funded project that started in June 2019 and within which INFP is a partner. The aim of TURNkey is to develop a coherent strategy, at European level, for seismic monitoring and decision-making process in three main directions: Operational Earthquake Forecast (OEF), Earthquake Early Warning (EEW) and Rapid Response to Earthquakes (RRE). Bucharest is one of the six European testbeds within the project and 5 buildings are instrumented with accelerometers in the framework of the project. PREVENT will link the existing infrastructure and equipment installed in structures by INFP to the new TURNkey developments and will add value by deploying multidisciplinary sensors in structures and correlating the observations with seismic data.

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