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THE IMPACT OF TURNkey SEISMIC MONITORING NETWORK IN BUCHAREST

Ștefan Florin BĂLAN, Bogdan Felix APOSTOL, Alexandru ȚIGĂNESCU

National Institute of R-D for Earth Physics, 12 Calugareni Street, Magurele, Romania

Corresponding author email: sbalan@infp.ro

Abstract

The paper presents the seismic monitoring network of the TURNKey Project (Towards more Earthquake-resilient Urban Societies through a Multi-sensor-based Information System enabling Earthquake Forecasting, Early Warning and Rapid Response Actions) in Bucharest. TURNkey aims to contribute to the mitigation of earthquake risks through European and global scientific collaborations. To reach its objectives the project brings together a strong multi-disciplinary team of experts (geophysicists/seismologists, geologists, engineers, disaster risk managers and sociologists) from 21 partner institutions covering 10 European countries. "Testbed 1" (Bucharest) is described in the paper, with its five monitored locations and the deployed seismic sensors and GNSS. The choice of monitored buildings is based upon the characteristics of the design code used in their construction. The paper considers the possible influence of local conditions at the sites of the monitored buildings.

Key words*: GNSS, seismic sensor, seismic network, testbed, TURNkey.*

INTRODUCTION

TURNkey is a European project under development over a three-year period being part of the Horizon 2020 programme. Through its general objective, that is to contribute to earthquake risk mitigation, the project will have an important application in reducing future economic and social losses in Europe.

TURNkey has brought together a strong multi-disciplinary team of experts (geophysicists/ seismologists, geologists, engineers, disaster risk managers and sociologists) from 21 partner institutions covering 10 European countries.

The focus of the project is to close the gap between the theoretical systems and their practical applications in Europe and to assist stakeholders in different risk mitigation actions before, during, and after a damaging earthquake.

An operational earthquake appraisal is accomplished by using available earthquake-hazard data and information for the regions of interest under continuously monitoring process with appropriate instrumentation. Rapid response to earthquakes is pursued by informing relevant stakeholders about the most probable damage scenarios in near-real time and by estimating direct and indirect losses, i.e. generated by main shock or aftershocks. An extended and near future high potential for implementing applications pertain to an earthquake near-real time damage warning-related procedure that an earthquake happened, establishing its ground motion levels and buildings response characteristics of spectral or dynamical-type.

Therefore, one of the main outputs of the project is a versatile and cost-efficient TURNkey multi-sensor unit consisting of seismic (vibration) sensors optimized for easy-data access and processing. The technology is implemented and under testing in six earthquake-prone areas in Europe, collectively referred to as the European Testbeds (TBs). The new low-cost multi-sensor units are installed in six physical TBs with the following aims: to densify/enhance existing sensor networks; to build-up new permanent sensor networks; to establish a mobile temporary sensor network (in disaster situations, for aftershock monitoring).

In the paper is described the impact of these procedures in Bucharest city, named as Testbed 1 (TB1). Another output is the TURNkey platform itself consisting in a multi-sensor-based earthquake information system, facilitating Rapid Response actions and enabling Early Warning. Two-way communication allows the platform to be more effective. Persons receiving the warnings will be able to provide immediate feedback to the platform.

TURNkey NETWORK

The TURNkey network in Bucharest (TB1) consists of 15 seismic sensors and 5 GNSS (Global Navigation Satellite Systems) installed on 5 (initial no. of constructions to be monitored) +1(only with GNSS) buildings. The seismic sensors are Raspberry Shake RS4D, (Figure 1), a 3 component orthogonally placed sensor accelerometer and 1 vertical geophone, and multi-sensor connectivity in the project. Basically, the sensors are small (100x120x50 mm), light (0.35 kg) and easy to install (plug-and-go installation), (Specifications for: Raspberry Shake RS4D, 2018). The TURNkey GNSS sensors (Figures 2 and 3), are connected to the RS4Ds and transmit raw GNSS and telemetry data in real-time to the server through the RS4D (Prototype dual-frequency GNSS receivers, 2019). The multi-sensor unit is a connection hub for other instruments and uses a single communication module that compresses the data and transmits in a consistent data format. Every sensor is connected to the internet where it sends signals in a continuous mode to the TURNkey Platform.

Figure 1. Photo of an installed RS4D sensor setup

The GNSS data are processed in order to compute almost-real time estimations of the 3D displacements of the sensors and to provide long-term displacements measures with up to 1 mm repeatability (RMS), using a cost-effective multi-frequency calibrated GNSS antenna. The location of the sites with short description of the buildings and position of instruments are described in Table 1 and shown in Figure 4.

Figure 2. Photo of a GNSS antenna on a roof

Figure 3. Multi-frequency GNSS receiver fixed on the wall

The seismic sensors are deployed in 5 buildings in Bucharest city in the locations S1-S5, whereas 4 GNSS sensors are in S1-S4 locations and the fifth's is placed on a tower building (IFA building roof, S6) in Magurele, a locality in the near vicinity of Bucharest, considered as belonging to the metropolitan area of the capital.

All GNSS are connected to the Raspberry Shake RS4D and from here to the internet where they send signals in a continuous mode.

Next we will discuss the reasons and criterion for choosing these buildings. Bucharest is the capital of Romania and considered as the second-most earthquake-endangered metropolis in Europe.

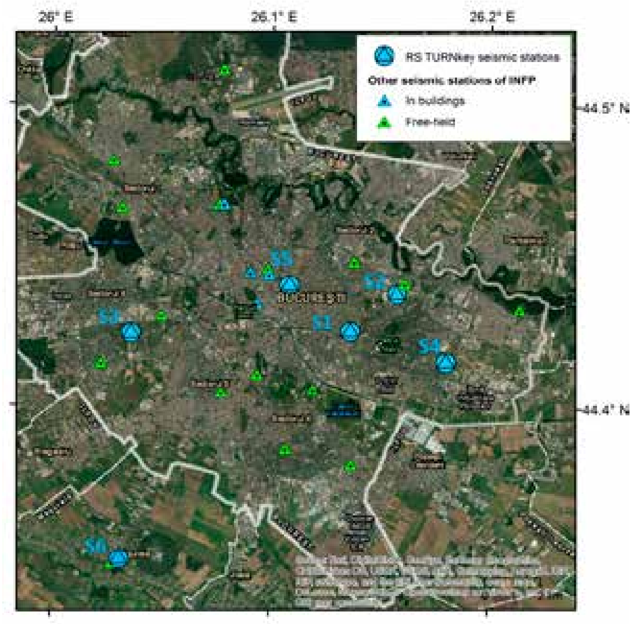

Figure 4. Location of TURNkey stations in Bucharest

Table 1. Description of the monitored buildings and position of instruments

No. site/ location	No. of floors	No. of instruments TURNkey	Location of instruments	Structure	Year of construction	Observation
S1/ near Baba Novac Blvd.	$B^1 + GF^2 + 1F^3$	2	1) basement 2) attic	masonry with wooden floors	<1940	1 GNSS on the roof
S2/near National Arena	B+GF+8F	3	1) 1th floor 2) 5th floor 3) 8th floor	reinforced concrete and panels.	1982	1 GNSS on the roof
S3/ Drumul Taberei (near the park)	B + GF + 10F	3	1) G floor 2) 5-th floor 3) 9-th floor	reinforced concrete; frame and panels	1964-1965	1 GNSS on the roof
S4/Titan	B + GF +10F	3	1) G floor 2) 5th floor 3) 10th floor	reinforced concrete, large panels;	1972	1 GNSS on the roof
S5/ near Biserica Armenească	-3B + GF +11F	4	1) 3th floor 2) G floor 3) 5th floor 4) 11th floor	reinforced concrete - frames	2008	
S6/ IFA Tower building	$B+GF+M^4+10F$		1) *B floor 2) *6 floor 3) *10 floor	reinforced concrete – shear walls	1974, retrofitted after 1990	1 GNSS on the roof

Legend: B^1- Basement; GF^2 - Ground Floor; F^3 - Floor; M^4 - Entresol; * - recordings with professional seismic sensors from INCDFP.

Vrancea intermediate - earthquakes, characterized by focal depth between 90—200 km, are affecting large areas. Magnitude and local site (amplification) characteristics are decisive factors of how earthquakes are affecting the constructions in seismic areas.

The largest recent destructive earthquake recorded from the Vrancea region was on March 4, 1977, with a moment magnitude M_w=7.4, at 94 km focal depth. The epicentre was located at a distance of around 160 km from Bucharest area and significant structural damage were produced to the building stock of the city and its surroundings (Berg et al., 1980; Sandi et al., 2007). The loss assessment initiatives such as HAZUS-MH (USA, FEMA 2015) and RISK-UE (Milutinovic and Trendafiloski, 2003; Lungu et al., 2007) that considered the possible (earthquake) scenarios had to include the size and location of earthquakes together with the specificity of the local geology. Bucharest's building stock significantly changed after 1977 year (and certainly after 1989 as well). There is a wide distribution of buildings on various seismic design codes. Though there were accomplished activities in instrumenting and collecting data for the most representative buildings typologies, still it is very difficult to provide a damage or loss model for Bucharest and to derive earthquake scenarios likely to be generated by the Vrancea earthquake zone.

The variations of the ground motion parameters, the large variety of constructions materials, and high vulnerability buildings make seismic risk mitigation a difficult task. Thus, disaster prevention and mitigation of earthquake effects is an issue of highest priority for Bucharest and its population. Under these circumstances a program of monitoring some representative buildings was carried out during last years (Balan et al., 2019). The aim was to evaluate and analyse the response of the specific structures located in the Bucharest area.

Several buildings are monitored by National Institute of Research-Development for Earth Physics, and the TURNkey project added six instrumented buildings with a total of 15 multi-sensor units and 5 GNSS. The selected buildings are typical representatives of structures build under different seismic codes from 1930's to 1990's and for which the seismic vulnerability is different.

One first criterion for choosing buildings are the similarity in type (geometric conformation) and design, therefore outputs about their behaviour could be used for many others. The second criterion is based on the lessons that have to be learnt from the last century when strong earthquakes destroyed many buildings because there were not appropriate seismic codes in force in Romania at that time. The earthquake of 1940 (November 10, M_w = 7.7) led to the collapse of Carlton apartment block in Bucharest (the tallest reinforced building at that time in Bucharest) and almost entire cities (e.g., Panciu city near the source) were destroyed in a large proportion in the Vrancea epicentral region, with hundreds of people dead in the whole country. After this strong seismic movement of 1940 and after World War II ended, begun a constant preoccupation, among designers, about seismic codes which went through different stages of improvements along the years.

Thus, the following normative acts were elaborated in Romania:

- 1952 - STAS 2923-1952 comprising a seismic zoning map;
- P13-63, "Condition for the design of civil and industrial constructions in seismic regions" came into force on July 18, 1963, being carried out in accordance with the "Basic rules for the design of constructions in seismic regions" drawn up under CAER; - P13-70, "Norm for the design of civil and industrial constructions in the seismic regions", December 1970; Seismic zonation map STAS 2923-1963;
- P100-78, "Normative for the antiseismic design of social, cultural, agro-zootechnical and industrial buildings" with experimental application;
- P100-81, the above normative with seismic zoning map STAS 11100 / 1-77; map with 7 areas of different degrees of seismic zonation are specified;
- P100-91 and P100-92 with their own seismic zoning maps; there are 6 degrees of zonation;
- P100-1/2006, "Design provisions for buildings – Part I" in Seismic Design Code with its own zoning map;
- P100-1/2013, "Design provisions for buildings – Part I" in Seismic Design Code with an improved zoning map.

Therefore, the buildings were chosen to fit a certain specific code in force at the time of design and to analyse their behaviour for at least a medium seismic movement in the period of monitoring, started at August 2020. For the time being there was no seismic movement with M_w > 5.5 generated by the Vrancea seismic source to be recorded. However, the instruments and workflow can be implemented and tested in advance and the approach already demonstrated its readiness and functionality. The additional data from the RS4D sensors and from the TURNkey project in overall, will contribute to the studies of building structural (dynamic) response with application in risk estimation.

The strongest earthquakes the TURNkey network experienced during monitored time period were of medium intensity with the following characteristics: 1) April 9, 2021 M_w=4.2, time: 21:36:47 (local time), 78 km focal depth, 156 km epicentral distance in Bucharest, maximum recorded PGA by Romanian Seismic Network 4.4 cm/s^2 and 2) May 25, 2021, M_w= 4.3, time: 00:30:37 (May 26 local time), 131 km focal depth, 126 km epicentral distance in Bucharest, maximum recorded PGA by Romanian Seismic Network 6.6 cm/s^2.

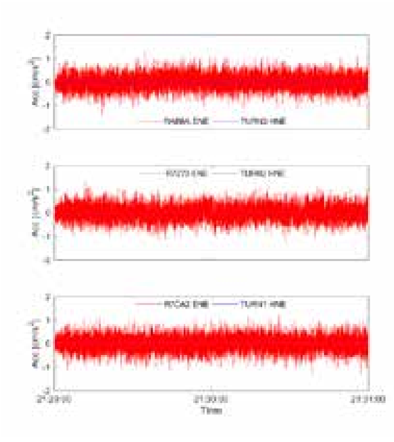

Figure 4. Pre-earthquake May 25, 2021 ambient noise on TURNKey sites S4 and S6.

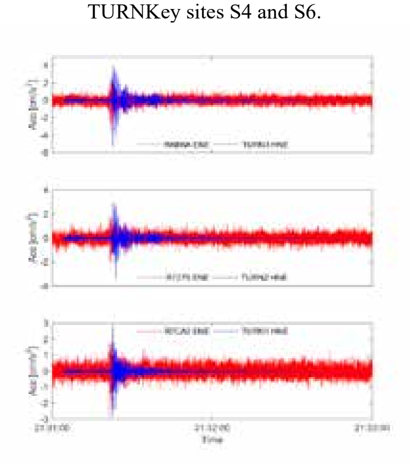

Figure 5. Recordings of earthquake of May 25, 2021 on TURNkey sites S4 and S6

In the following it will be presented some recordings from the TURNkey seismic sensors in the buildings from Table 1.
In Figure 4 can be seen a comparison of the pre-earthquake ambient noise level of the May 25, 2021 earthquake for the professional sensors mounted in S6 (in blue) and RS4D acceleration channels on East-West direction (in red) in S4, for the basement (TURN 1-B/S6, GF/S4), intermediate floor (TURN 2- 6 floor/S6, 5 floor/S4), and top floor (TURN 3 – 10 floor/S6, 10 floor/S4).
In Figure 5 is acceleration recordings channels (red) for earthquake of May 25, 2021 at site S4, compared with S6 building professional sensors (blue) on E-W direction. Displayed sensors are placed at basement (TURN 1- B/S6, GF/S4), intermediate floor (TURN 2-6 floor/S6, 5 floor/S4), and top floor (TURN 3-10 floor/S6, 10 floor/S4).

CHARACTERISTICS OF THE NETWORK SITES

The influence of the local soil geological conditions manifests itself in amplification for certain spots of the ground motion amplitude. Many urban areas hit by strong earthquakes that suffered considerable damage have certain specificity in local soil conditions, as Michoacan in 1985, Loma Prieta in 1989, Northridge in 1994 and Kobe in 1995 (Anderson et al., 1986; Bard et al., 1988; Beresnev et al., 1998; Celebi et al., 2017; Aguirre and Irikura, 1997; Boore, 1989). In the case of Bucharest city this specificity consists in the cohesion less Pleistocene-Holocene geological complex. The Romanian capital is built on alluvial soil underlain by soft weak consolidated rocks of Quaternary deposits. The proximity between the vibration period that characterizes the sedimentary layers and the building fundamental period may have an important role in endangering the safety of buildings during strong seismic movements. Obviously one may take into account the old buildings designed without any antiseismic norms and those with construction errors. For these the highest damages were recorded and almost all of collapses were due to their lack in design regulations or cumulative damage due to earthquakes / WWII bombing.
In the aftermath of the strong 1977 Vrancea event a campaign was launched for computing the particular period of oscillation for different sites in Bucharest area. The results show values between 0.9 s and 1.6 s (Mandrescu, 1978). In the next decade the studies have continued making use of the increasing number of geotechnical projects, several tens of deep

geological boreholes allowing to interpolate predominant period results covering the entire area of the city, the values varying between 0.9s and 1.9s, from south to north (Mandrescu et al., 2004). Similar results were obtained by applying the H/V ratio technique for ambient noise and small and moderate earthquakes (Bonjer et al., 1999).

Other information offered by geotechnical experiments or geophysical procedures were the shear soil velocity that allowed to apply the well-known formula $T_S = 4H/V_S$ (where T_S is the period, H is the depth, and Vs is the shear wave velocity) in delivering results about fundamental period. The shear wave velocity of 650 m/s is roughly chosen for the seismological (or geophysical) bedrock limit, where its value exhibits a jump toward higher values (Mandrescu, 2007). Other authors, applying different methods, recently, assign ~544 m/s (Bala et al., 2009), or between 477-628 m/s (Marmureanu et al., 2013 and references therein, Manea et al., 2016).

The five sites of the considered structures with seismic sensors are disposed from the west of Dambovita river (one) toward eastern part of the city (four). According to Mandrescu et al., 2004, the fundamental period encountered in these areas are roughly between 1.4 s and 1.5 s from South to North.

The local conditions in terms of V_{S30} for all five sites are in the range of 280-310 m/s which are specific for these layers of soft alluvial soils. Even the values for V_{S50} do not exceed values of ~320 m/s. According to EURCODE 8 this range implies a C-type soil for the considered areas. In fact the whole town has this soil conditions, these characteristics being withdrawn from all the studies and experiments carried out over time.

The average value for the shear-wave velocity considered as representative for the first seven layers of Quaternary sediments deposit for the seismological studies can be taken about 400 m/s. This information is used also for nonlinear behaviour studies which are suitable in the Bucharest subsoil context for intermediate-strong Vrancea earthquakes.

During the 1977 earthquake the majority of the collapsed buildings were in the centre of the city, where the considered intensity on MSK scale was VII-VIII. Almost all of these buildings were erected between the two world wars without adequate seismic design protection.

New empirical relationships were developed, between observed macroseismic intensity and strong ground motion parameters (e.g., peak ground acceleration and velocity) for the Vrancea subcrustal earthquakes (Constantin et al., 2021a). This approach can be used for the rapid assessment of ground motion level and damages in the interest areas. For this, different types of data were employed; including macroseismic database resulted after the re-evaluation of the effects produced by the strong Vrancea earthquakes (e.g., 1977 seismic event) (Constantin et al., 2021b). For example, in order to determine the seismic intensities, besides observation originated from the field surveys made immediately after the earthquake of 1977, macroseismic questionnaires were distributed in the damaged area, including city of Bucharest (2000 questionnaires only there). This way, information were gathered, regarding the effects on structures and on the environment. The outcome of the re-evaluation process consists in assigning the maximum observed intensity as IX-X (on MSK scale) and the final intensity for Bucharest being VIII-IX on the same scale at this earthquake (Pantea and Constantin, 2013).

RESULTS AND DISCUSSIONS

The entire ground motion types of displacements, from slow movements (with GNSS sensors) to earthquakes (with seismic sensors), including noise are measured by this network, closing data gaps with the other networks in Bucharest.

The recorded data (seismic sensors and GNSS) on every testbed in the project is transmitted to TURNkey - FWCR (Forecasting - Early Warning - Consequence Prediction - Response) platform, a multi-sensor-based earthquake information system, facilitating Earthquake Forecasting, enabling Early Warning and Rapid Response actions. It has a two-way communication that will allow the platform to be more effective; persons receiving the warnings will be able to provide immediate feedback to the platform. The platform is analysing in real time all data from the 6 testbeds, fulfilling the targets mentioned above.

The TURNkey platform is using data from all testbeds for further testing, development and evaluation by researchers and stakeholders. One important accomplishment of the central system consists in an increased flexibility and applicability.

The activities involved in this project give the possibility to assess the buildings behaviour during and immediately after an earthquake. Therefore a rapid response is evaluated and the output can be implemented in general procedures that can be applied within and in conjunction with the project. The characteristics of each testbed (in terms of seismicity, sensor locations and locations of the elements at risk) were considered in the developed procedures so that they will be as useful as possible for the project. The wide range of characteristics of the TBs (Bucharest/Romania; Pyrenees mountain range/France; Municipality of Hveragerði, Municipality of Norðurþing, Húsavík/ Iceland; Patras and Aegio/Greece; Maritime ports in Gioia Tauro/Italy; Groningen province/ Netherlands) will also mean that the developments will be applicable widely beyond the project.

During the monitoring period (August 2020 - present), the TURNkey network recorded medium-low earthquakes (crustal and intermediate-depth), with local-magnitudes from 3.7 to 4.7. As can be seen in Figure 5 the sensors RS4D needs stronger seismic movements to get out of the sensor self-noise and the signal to be better observed.

For the selected recordings it cannot be distinguished a specific influence of local conditions, although for higher level of seismic movement over the city area or stronger magnitudes the site response can be affected by these features (Cioflan et al., 2004).

CONCLUSIONS

The testbeds including TB1 (Bucharest) manage to develop and validate a robust multi-disciplinary research methodology for guiding impact analysis of the involved systems (EEW etc.) toward improvement of the community resilience to earthquakes across Europe. In this endeavour the application is implemented and proved for Bucharest city area.

The TURNkey network undergoes an appropriate integration of its data in the national seismic network thus improving local and regional seismic monitoring. It secures and demonstrates the real-time streaming of various geophysical markers in a consistent data format to the central (SeisComP) server through continuously feed parametric data from the testbeds to the TURNkey (FWCR) platform that enables a consistent approach to improved Earthquake Early Warning and Rapid Response to Earthquakes.

The infrastructure development facilitates future integration of multiple other geophysical markers, thus contributing towards Operational Earthquake Forecasting advances in the European testbeds.

The aims that had to be achieved through the project activities were the coordination and management of deploying instruments in a consistent and coordinated manner in the geographically-based European testbeds (TBs) and real-time data provisions for the development of the TURNkey Forecasting - Early Warning - Consequence Prediction - Response (FWCR) Platform.

In the case of an absence of strong-earthquake data it will be completed a virtual implementation of the TURNkey platform at testbeds for monitoring, processing, analysis and visualization purposes - for the platform development.

With the data from the network, in the near future will be achieved:

- Performance evaluation and validation of the TURNkey platform against end-user use-cases;
- Ensuring a sustained flow of information to other TBs as needed.

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