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TOWARDS MORE EARTHQUAKE-RESILIENT URBAN SOCIETIES THROUGH A MULTI-SENSOR-BASED INFORMATION SYSTEM

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Abstract

TURNkey (*Towards more Earthquake-Resilient Urban Societies through a Multi-Sensor-Based Information System enabling Earthquake Forecasting, Early Warning and Rapid Response Actions*) is a European project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821046. The project aims to make significant advances in the fields of Operational Earthquake Forecasting (OEF), Earthquake Early Warning (EEW) and the Rapid Response to Earthquakes (RRE), particularly when applying these systems in practice in Europe. The project will develop a flexible, extendable, robust and easy-to-use OEF/EEW/RRE system based on low-cost multi-sensor units and a cloud-based computer platform, which can be distributed as a fully-operational TURNkey product to public authorities (including search-and-rescue teams) and private companies (including operators of critical infrastructure). These developments will contribute to improved seismic resilience before, during and after a damaging earthquake and hence a reduction in losses. The project's outcomes will be demonstrated in six European Testbeds (TBs) with different hazard, vulnerability and exposure characteristics, spatial extents and monitoring networks as well as in two roaming TBs, one based on crowdsourcing and one for temporary installations. The six geographically-focused TBs are: the city of Bucharest (Romania), the Pyrenees mountain range (France), the towns of Hveragerdi and Husavik (Iceland), the cities of Patras and Aigio (Greece), the maritime port of Gioia Tauro (Southern Italy), and the Groningen province (Netherlands), which is affected by induced seismicity. The TURNkey consortium comprises a strong multi-disciplinary team of experts from 21 partner institutions in 10 European countries. The TURNkey project will be supported by major public and private stakeholders and will be advised and reviewed by a group of international experts. This paper presents a general overview of the project, briefly discussing the methodology employed in its different work packages and highlighting some of the innovative solutions proposed by TURNkey. Preliminary results to date are also presented, discussing how various implementation challenges are being addressed in practice, with special focus on selected Testbeds.

Keywords: Earthquake Early Warning, Rapid Response to Earthquakes, Operational Earthquake Forecasting

1. Introduction

European continent has a long history of large earthquake events that led to a number of fatalities, injuries, and caused significant economic losses. From 2006 to 2015, the continent experienced 21 earthquake-related disasters that resulted in 1,049 fatalities, more than 18 billion Euros in economic losses, and affected 284,000 people [1]. Although there is increasing risk awareness and perception towards seismic threats among the public and policy makers in many European countries, there is still a direct need to help mitigate the related risks by making the best possible use of the potential of earthquake forecasting and early warning as well as responding rapidly after an earthquake. One example of when a warning may have helped reducing deaths was the central Italy earthquake (M_w 6.3) on 6 April 2009, which devastated the city of L'Aquila, Italy, and the surrounding area. Less than 3 hours before, a M_L 4.0 event occurred at the same location, which was later interpreted as a foreshock of the devastating mainshock. Similarly, the Emilia (Italy) 20th May 2012 earthquake (Mw 6.1) was preceded by a M_L 4.1 earthquake about 3 hours before – spotting this as a foreshock may have reduced the death toll. The open question remains why these smaller events could not have been used to forecast the following larger events, and which tools, methods and observations (data) were lacking at that time.

As part of the continuous efforts within Europe aimed at contributing to earthquake risk reduction, the European Union's Horizon 2020 research and innovation programme has recently funded a project called TURNkey (Towards more Earthquake-Resilient Urban Societies through a Multi-Sensor-Based Information System enabling Earthquake Forecasting, Early Warning and Rapid Response Actions) which has its goal to contribute in reducing future economic and social losses and mitigating the direct and indirect consequences of earthquakes in Europe. The consortium of the TURNKey project comprises a strong multi-disciplinary team of experts from 21 partner institutions in 10 European countries, and supported by major public and private stakeholders. The TURNkey project has as objectives to make progress in: Operational Earthquake Forecasting (OEF), also called time-dependent hazard assessment, Earthquake Early Warning (EEW), and its use both in real-time (during an event) and in near real-time, when rapidly responding to earthquake impacts (RRE); as well as in Information and Communication Technology (ICT) that allow effective two-way emergency communication between citizens and stakeholders, and Instrumentation Technology, that allows for much more cost-effective monitoring of earthquake ground motion and structural response to earthquakes. The potential benefits of these systems to society and individuals have been clearly identified [2], specifically in terms of RRE measures for more resilient societies. Such benefits range from the preservation of life, through improved public safety, to organisational preparedness to respond to and recover from an earthquake. The project's purpose is to develop the TURNkey FWCR (Forecasting – Early Warning – Consequence Prediction – Response) platform, a multi-sensor-based earthquake information system, facilitating Earthquake Forecasting and enabling Early Warning and Rapid Response actions, and a versatile and cost-efficient TURNkey multi-sensor unit consisting of seismic (vibration) sensors optimized for EEW and GNSS receivers suitable for various monitoring tasks (structural health monitoring, monitoring of rockfalls, rock/landslides, avalanches, tsunamis) and installation possibilities (free field vs building/infrastructure, field vs urban deployment). TURNkey will be demonstrated in six earthquake-prone areas in Europe, including areas affected by induced seismicity, collectively referred to as the European Testbeds (TB-1 to TB-6, Figure 1), a Worldwide TB-7, and a mobile European EEW unit for aftershocks TB-8. TURNkey's purpose will be attained by exploiting synergies among key actors, exploring data from existing sensor networks, and building on the infrastructure developed in various European TBs, fostering international collaboration, and affiliating with past and ongoing initiatives beneficial for/of interest to the project's success. To maximise the benefits of OEF, EEW and RRE systems the TURNkey project will explicitly ensure a full understanding of: 1) system performance standards (from design, through operation to impacts on resilience); 2) end-user trust in the reliability of the system; 3) the training needs of individuals; and 4) requirements of public and private end-users. The project builds on the developments over the last decade of small, accurate and low-cost hardware for geophysical monitoring, along with the great increase in data-transmission capacity of telecommunication systems and the deployment and great improvements of wireless long-range networks. The project builds on a firm scientific foundation in natural and physical sciences, probability and statistics, engineering, and social sciences, all combined to provide effective disaster risk management. This paper presents a general overview on the different aspects of the project, briefly discussing the methodologies employed and highlighting some of the innovative solutions proposed by TURNkey. Preliminary results to date are also presented, discussing how various implementation challenges are being addressed.

Fig. 1 – Distribution of TURNkey's project consortium partners (white dots) and the locations of the six geographically-based TURNkey Testbeds (TB-1 to TB-6, ellipses), plotted on the SHARE European Seismic Hazard [3]

2. Review current OEF/EEW/RRE systems and their applications for more earthquake-resilient urban societies

A review of literature [4, 5, 6, 7, 8] mapped the perceived benefits of EEW/OEF/RRE systems against key drivers of community resilience [9]. For EEW/OEF systems the perceived benefits from a community resilience perspective include: improved personal safety and mental preparedness/public health as well as a greater understanding amongst the general public and business organisations of the actions they can take to prepare for (training, better informed disaster management planning including loss estimates and early emergency service mobilisation, utility/asset control) and recovery from (post-event asset monitoring/damage prediction, and damage prediction/evacuation zones, and business continuity and resilience planning) an earthquake event. In addition, EEW/OEF can support a build-back-better approach to disaster risk reduction through improved national and local government planning (building codes, land zoning, and reconstruction planning) and better-informed insurance industry and capital markets. Whilst there are clear benefits of EEW and OEF systems to support improved community resilience, realising these benefits is not without difficulties. EEW/OEF systems must be scientifically robust and reliable and carefully designed to reflect the different needs of end-users (trigger thresholds, the regulatory framework in which they operate, relate to specific failure modes, integrate with both upstream and downstream processes). In particular systems need to present warnings and forecasts, including prediction and modelling uncertainties, in a transparent, timely and policy neutral way that reflects different attitudes to risk and uses language that is meaningful to non-technical stakeholders. Warnings and forecasts must also be accompanied by specific, coordinated, adaptation/mitigation guidance if the benefits of warnings/forecasts are to have a positive impact on community resilience.

Operational Earthquake Forecasting (OEF) involves the dissemination of authoritative information about time-dependent earthquake probabilities over time scales of hours to decades, to inform the decisions that people and organisations make to mitigate seismic risk [10]. The USGS initiated OEF efforts in the 1980s [11], with foreshock alerts as part of the Parkfield Earthquake Prediction Experiment [12], two earthquake advisories issued in conjunction with the State of California before the Loma Prieta earthquake [13], and aftershock and foreshock alerts based on the model, which estimates earthquake probabilities based on empirical Omori–Utsu and Gutenberg–Richter statistics [14]. The Short-Term Earthquake Probability (STEP) model added spatial information and hazard to the Reasenberg and Jones model [15]. On the other hand, Long-term forecasts, which are applicable from decades to centuries, represent the OEF first line of defence for mitigating earthquake risk, primarily by informing building codes [16]. Also, Omori–Utsu based statistical clustering models have demonstrable reliability and skill concerning short-term triggering and therefore provide a rational basis for short-term OEFs [16]. However, the primary challenge to usefulness is that triggering models usually estimate a low probability for damaging earthquakes [13]. Probability gains may be as high as factors of 1000, but the overall likelihood of triggering damaging events will typically be less than a few per cent [16]. The exceptions are during aftershock sequences of very severe (M >7) earthquakes when this probability can climb above 10%. Such low-to-moderate probabilities will constitute useful information if the potential consequences of large triggered events are high [17]. Decisions to undertake mitigation actions based on OEF information depend on the balance between costs and benefits, which are specific to the risk at hand [16]. Because these decisions are contingent on a host of economic, political, and psychological considerations that lie beyond the science of hazard analysis, scientific information about future earthquake activity should be developed independently of any specific risk assessment or mitigation effort [16].

Earthquake early warning (EEW) systems provide real-time information about ongoing earthquakes, enabling individuals, communities, governments, businesses and others located at distance to take timely action to reduce the probability of harm or loss before the earthquake-induced ground shaking reaches them. Examples of potential losses mitigated by EEW systems include injuries and infrastructure downtime. Today, EEW systems are operating in the USA, Japan, Mexico, Romania, Turkey, Taiwan, South Korea, China, and India. They are also being tested for use in Italy, Switzerland, Chile, Israel, Nicaragua, Spain, Slovenia and Austria, Greece, New Zealand and Iceland, as well as in Costa Rica and El Salvador [18]. It is encouraging for developers of EEW systems to note that they are generally viewed as positive measures by relevant stakeholders. A recent review study by [19] highlights that most of the cutting-edge innovations in current EEW applications concern the seismological aspects of the system. For this reason, we concentrate specifically on the decision-making component of EEW systems in this sub-section. While definitions of early warning explicitly refer to its potential to mitigate damage/loss/harm, decisions to trigger EEW alerts are not currently made with risk-related metrics. The closest proxies for risk used are the ground-motion amplitude and macroseismic intensity measures, which both capture the effects of ground shaking. However, the considered threshold values in terms of those parameters are not calibrated based on explicit damage/loss analysis and mainly rely on engineering judgement. More generally, there are a number of limitations associated with decision-making based on this type of metric. Firstly, there is an explicit assumption that a given level of ground shaking will result in a specific degree of damage. In reality however, the relationship between ground shaking and damage at a target site is highly uncertain [20]. In addition, regional EEW-system decision making based on ground shaking does not account for varying levels of fragility across the affected area, i.e. the fact that damage probability and severity for a given level of ground motion is not the same across different types of structure/infrastructure/systems. Failure to account for uncertainty in damage may lead to a miscalculation in false (or missed) alarm potential. Another notable limitation of ground shaking-related decision metrics is their failure to explicitly consider losses, which are additionally uncertain with respect to damage [21]. Accounting for losses as well as damage would therefore further amplify the potential miscalculation of false alarms from ground shaking. Distinction between losses is also important for optimal decision-making. For example, a business owner may be more interested in measuring the value of an alert based on its ability to mitigate building downtime (business interruption) than the cost of repair after an event; ground shaking decision-based metrics are not useful in this instance. Finally, descriptions of an event in terms of magnitude/ground motion/macroseismic intensity are difficult for the public to understand [18]. Confusion in the meaning of an alert makes the public less likely to take preventative action [22], which decreases the value of a warning. To maximise the benefits of alerts, they should be paired with robust messaging, which is best achieved using risk-orientated decision metrics (e.g., consequences).

Rapid Response to Earthquake (RRE) systems aim at providing an accurate picture of an earthquake's impact, in the shortest time possible after the event. Following an initial sizing of the earthquake event, emergency responders and crisis managers quickly expect an account of the most damaged areas along with estimated casualties, at precise locations (e.g., at the level of city districts or building blocks), in order to coordinate rescue efforts in an efficient manner. Most current RRE systems rely on the derivation of shake-maps and on the application of rapid damage and loss assessment tools. Shake-maps refer to updated ground-motion maps that make the most of the available post-earthquake information (i.e., earthquake parameters, ground-motion records, macroseismic testimonies), in order to constrain uncertainties on expected ground-motion levels [23] (i.e., to be published a few minutes following the event). In Europe, several shake-map services are operating at national level [24]: they usually follow the USGS ShakeMap® v3.5 algorithm, which is based on a weighted interpolation procedure between the observations and the grid points [25]. A detailed literature review of current shake-map services has highlighted several noteworthy points and issues:

- An approximate knowledge of the faulting mechanism or of the fault geometry within a few minutes may lead to large near-field uncertainties, which should be covered by considering, for instance extreme configurations of fault extents.
- Another issue lies in the characterization of site amplification factors: by default, most shake-map systems use a model based on topographic slope, with very little guarantee that it provides accurate results for the area of interest.
- The integration of macroseismic testimonies is not systematic in all shake-map systems, with various ways or collecting and interpreting the data (i.e., different types of online forms). The duration required to collect meaningful data and to translate it into macroseismic values constitutes a challenge for their use in near real-time applications. The use of additional data inputs for shake-maps (e.g., from mobile apps or social media) is worth investigating, in order to cover the time gap before the arrival of more accurate macroseismic intensities (i.e., after several minutes).
- In terms of shake-map algorithms, the version 4.0 of ShakeMap® offers substantial improvements over the version 3.5. The weighted interpolation algorithm, which is based on the definition of "radii of influence" that are difficult to quantify in practice, is replaced by a matrix-based procedure that relies on the multi-variate normal (MVN) distribution [26].

Finally, additional comments and recommendations can be made on existing rapid loss assessment tools:

- Some systems, such as PAGER [27], aim at providing a picture of the potential impact at the level of the whole earthquake event. This scale is useful for rapidly sizing the disaster and for deciding at which level (e.g., regional, national, international) crisis management operations need to operate; however, much more detailed information at local level is needed very quickly. Therefore, systems that estimate damage and losses at a more detailed resolution (e.g., SeisDaRo [28], ELER [29]) constitute the strict minimum to meet these operational needs. As a result, the coupling between a shake-map system and a rapid loss assessment tool (at least at city district level) is necessary.
- Most rapid loss assessment systems on predicting damage to common buildings and on estimating fatalities, while few of them look at infrastructure components or critical facilities: especially, none of the current systems are considering the effect of failed components on the global performance of the infrastructure, which has a great influence on the crisis management operations (e.g., inaccessible roads, power outage, disrupted water supply).

The limits and potential applications of current state-of-the-art EEW systems will be tested in Europe considering a number of candidates EEW algorithms, including PRESTo, Virtual Seismologist and ElarmS. In the specific, the feasibility of EEW with be assessed considering two different approaches. The first one

#UCL contribution. The second one aims at evaluating the performance of the identified EEW algorithms at the TBs, considering both real recordings and broadband synthetic seismograms computed by the UCSB code [30].

3. Stakeholders needs/requirements and citizens expectations

The TURNkey project will use a participatory action research methodology [30] to guide the design, development and testing of the TURNkey platform. PAR is a well-established research methodology applied to socio-technical systems where context needs to be considered alongside scientific enquiry in the development of problem-solving technologies. In the TURNkey project, a team of researchers and practitioners/stakeholders (collectively the PAR research team) will work together, to examine the issues associated with the design, development, implementation and operation of the TURNkey platform. The PAR approach will use theory to drive changes in practice in support of the project end-goal: to improve societies reliance to earthquake disasters. Through a series of iteration cycles (Planning; Implementation; Reflection; Review) the impact of theory will be assessed (degree to which is achieves its end-goal) and refined until the end-goal is achieved or the journey is abandoned. PAR-Cycle 1 has begun with the creation of the PAR research team drawn from representatives of WP3, 4, 5 and 6 and from the stakeholder groups in the 6 Testbed regions. The PAR research team has reviewed the theory pertinent to the development of EEW/OEF/RRE tools from their perspective and is in the process of defining a series of use-cases for key stakeholder groups (citizens, emergency responders/civic protection, critical infrastructure providers, and business organisations) which will inform the development of the TURNkey FWCR Platform.

A series of focus groups, in-depth interviews and workshops are being conducted with representatives of the four stakeholder groups across the 6 Testbeds to enhance the project teams understanding of links between EEW/OEF/RRE systems and community resilience to earthquake events in Europe. The focus groups/in-depth interviews are exploring current practice across Europe to establish what works and what doesn't from an earthquake disaster risk reduction perspective and identify any issues/gaps that could be filled by the TURNkey FWRC Platform. In relation to the latter, reactions are being sought to the TURNkey proposition solution including identifying drivers and barriers to usage, exploring communication protocols and channels, and the integration of the TURNkey FWRC with existing systems and processes. The results from the focus groups, interviews and workshops will be presented to the TURNkey FWCR development team in the form of end-user use-cases that identify the requirements (technical and operational) of the TURNkey FWRC Platform. Once the first iteration of the TURNkey FWRC Platform has been developed its performance against the use-cases will be assessed through a second PAR-Cycle (focus groups, interviews and workshops) and revised use-cases will be developed to address any areas of underperformance. A third PAR-Cycle will follow before the final prototype TURNkey Platform specification id developed.

4. Methodologies for OEF/EEW/RRE information system

4.1 Concept of Operational Earthquake Forecasting (OEF) system

A flexible and extendable procedure for OEF is being developed for the TURNkey platform that takes into account the short-term changes in the seismic hazard and the uncertainties associated with these changes. These uncertainties will be captured through logic trees expressing the degrees of belief in a particular observed change being associated with a change in the likelihood of a large earthquake. The procedure is based on methods for time-dependent seismic hazard assessment that can account for short-term changes in seismicity rates (parameters of magnitude-frequency relationships) evidenced by geophysical and geochemical parameters (geodetic deformations at a regional and local level, local strain measurements, borehole water levels, radon emissions and chemical content of borehole water) that have been associated in previous studies with changes in the likelihood of a future large earthquake. The assessed time-dependent seismic hazard will be expressed in terms of an earthquake forecast (with its associated probability and uncertainty) for use in the other work packages and by the Testbeds. The developed framework will be demonstrated using data from at least one of the Testbeds and the size of the possible changes in the likelihood of a large earthquake assessed. A particular focus is OEF in the context of aftershocks and TB-8. A key objective will be to make the developed procedure flexible and extendable so that future developments on earthquake forecast can easily be integrated into the TURNkey framework.

4.2 Concept of Earthquake Early Warning (EEW) system

The discussion above suggests that there is a strong need to develop next-generation EEW systems that significantly advance the state-of-the-art in EEW decision-support as proposed in TURNkey. These systems should trigger alerts based on interpretable probabilistic risk-based estimates that are optimised for the needs of the end users and are understandable to the public, so that they can take clear preventative actions to mitigate the impact of the event. Fragility and vulnerability/damage-to-loss models for target structure/infrastructure components from earthquake engineering analysis should be incorporated to translate ground motion amplitudes to estimates of damage and loss. For well-informed decision-making on EEW triggering, we propose that next-generation EEW systems be developed based on a robust end-to-end theoretical framework that explicitly tracks uncertainties at each stage of the EEW process, such as the performance-based earthquake early warning (PBEEW) [31]. This framework utilizes the concept of real-time probabilistic seismic hazard analysis (RTPSHA), where the probability distribution of an intensity measure is conditioned on real-time seismic measurements that are related to the probability distributions of the source parameters. (Note that RTPSHA could easily be adapted to include additional conditional information, such as updated estimates of source parameters from operational earthquake forecasting calculations). This type of probabilistic approach is rarely used in current EEW applications. RTPSHA is mathematically extended to a performance-based framework, to also quantify expected dollar losses in terms of the source-dependent real-time seismic measurements.

We also propose combining PBEEW with the multi-criteria decision-making (MCDM) framework of [32]. This would improve the dollar loss-based decision-making procedure of PBEEW, as it would enable explicit consideration of an end-user's preferences (via weights assigned to various criteria) and would remove the requirement for criteria to be exclusively expressed in monetary terms. Within the proposed framework, more advanced resilience-orientated decision-making could be facilitated by deriving indicator values directly from IMs following the limit-state approach of [33], which developed fragility functions that link ground motion intensity straight to post earthquake functionality and recovery consequences. These resilience-based metrics have been successfully applied to support post-earthquake decision-making in previous studies [33]. A key limitation of existing damage- and loss-focused studies related to EEW is their narrow focus on one target site (and generally one target structure) of interest. However, system-level consequences are also important to consider for EEW applications to network-based components. For example, the thresh- old for triggering an alert to shut down a vehicular bridge should explicitly account for an indicator that measures the resulting decrease in functionality across the entire road network. Thus (where relevant), next- generation EEW systems should incorporate decision-making tools that capture interdependencies in losses. This could be achieved using mathematical tools developed for seismic engineering-related network analyses [35]. As a significant advancement over current EEW approaches, next-generation EEW systems should con- sider more advanced IMs (e.g., spectral-shape-based IM or inelastic spectral acceleration values at a range of prescribed periods) when calculating predicted earthquake ground motion for RTPSHA and consequent loss estimates. This would notably enhance EEW suitability to risk-based engineering applications, as these IMs are much better correlated with structural response/damage/loss than those typically considered for EEW. For example, it would enable interaction between EEW systems and structural control mechanisms that could rapidly alter the behavior of a building in response to the forecasted spectral acceleration at the structure's fundamental period, which may reduce the structural vulnerability (and resulting losses). This would be particularly beneficial in critical buildings required to be operational for emergency management immediately after an event (such as hospitals and fire stations).

4.3 Concept of Rapid Response to Earthquakes (RRE) system

The proposed RRE system articulates around an automated execution of successive modules, from the detection of the earthquake, to the derivation of shake-maps and to the estimation of damages and losses at the level of a city district or a building block. Multiple types of sensor data and observations are considered in order to constrain uncertainties and to generate accurate loss estimate as quickly as possible: (a) RaspberryShake-4D (RS-4D) sensors are deployed in complement of existing seismic networks in the area of interest, so that higher resolution shake-maps may be computed; (b) The exploitation of social media data (e.g., Twitter feeds) will be investigated in order to obtain an approximate extent of the felt area, before online macroseismic intensities start pouring in; (c) RS-4D coupled with GNSS instruments may be deployed in critical facilities, in order to perform real-time structural health monitoring and to provide an estimate of the likelihood of damage right after the earthquake; (d) Mobile apps (e.g., Earthquake Network Project, www.earthquakenetwork.it) may be used in order to estimate the location of people in real-time, thus updating building occupancy models and further calibrating the estimation of potential losses. For the generation of shake-maps, it is foreseen to use either the MVN distribution procedure [26] or the Bayesian updating approach for the inference of ground-motion fields [36]: both approaches have proven to be mathematically sound, with an accurate treatment of the uncertainty field. They are also able to integrate multiple types of observations and to treat different intensity measures while accounting for their cross-correlation. Uncertainties have to be propagated from the source characteristics up to the estimation of loss: this challenge will be addressed by considering Bayesian Network tools, which have the ability to manipulate uncertain variables and to update probabilistic distributions from observations (i.e., evidence).

5. Development of the cloud-based FWCR platform

The knowledge and the various methodologies, hazard and risk models that are being developed, as described above, will be compiled and integrated into a cloud-based FWCR (Forecasting – Early Warning – Consequence Prediction – Response) platform that can provide actionable output for identified stakeholders and assist them in different risk mitigation actions before, during, and after a damaging earthquake, i.e. to react at the earliest stage to reduce the direct and indirect (follow-up) impacts and consequences.

5.1 Development of OEF, EEW and RRE Engines

OEF, EEW, and RRE engines are the event generating components of the FWCR platform. The development of these components will involve: (a) design, development and integration of modules for earthquake source monitoring and real-time/rapid ground-motion prediction (integration of seismic hazard prediction models/systems). The modules will be directly linked with the customized multi-sensor units that can continuously transmit seismic and GNSS data before, during and after an earthquake; (b) development and integration of modules for real-time and rapid earthquake consequences prediction to physical components in terms of damage, direct and indirect economic loss and affected populations. The modules will be linked with the generation of ShakeMaps based on observations from the customized multi-sensor units that can continuously transmit data from monitoring of physical components, and information from citizen accounts through online platforms and social media. (c) development and integration of modules for real-time and rapid alerts to technical stakeholders, SAR teams, rapid emergency response and safety communication to non-technical stakeholders and to the public. The modules will be linked with the predicted earthquake consequences.

5.2 Development of multi-sensor units-based module for real-time data transmission

The multi-sensor unit is based on the RaspberryShake 4D (raspberryshake.org) a low-cost seismograph with vertical velocity and triaxial (vertical, north, east) MEMS sensors. The unit will be improved by integrating CAPS, a multi-format acquisition system, supporting EEW data packets and and acting as data hub for collocated GNSS sensors. The RaspberryShake 4D includes a geophone with a flat response of ~2s to ~40Hz and MEMs supporting a wide range of applications from microseismic to structural health monitoring and strong-motion processing integrating seismic and GNSS data. The low-cost sensors allow to setup extraordinary dense networks being the ideal basis for the planned EEW engine. The high density of PGA measurements in combination with the smartphone-based and eyewitnesses observations give a valuable input for the RRE engine. The observations are transferred via QuakeLink streaming real-time earthquake information and observations to the OEF, EEW and RRE engines. The real- time data acquisition and earthquake detection/processing system is based on SeisComP, an opensource seismic real-time data processing and analysis framework.

5.3 Development and integration of cloud end user module/interface

Even the best methodologies and scientific models stay useless until the findings and information are effectively passed to decision takers and converted into actionable outputs. To achieve this TURNkey provides cloud-based components like an efficient FWCR Integration Infrastructure and a multi-tenant FWCR End User Interface. The overall solution is built following the principles of an Event Driven Architecture (EDA), which focuses on the generation and handling of event notifications. This concept defines strongly flexible architectures, in which the elements generating event notifications do not need to know the receiver components. In addition to that, an EDA has not a deterministic response time for processing input events, but it is much faster adapting to changes. This paradigm makes possible to create near real-time responsive architectures. Few years ago, an innovation report by Gartner [37] foresaw that by 2020, event-sourced, real-time situational awareness will be a required characteristic for 80% of digital business solutions. And 80% of new business ecosystems will require support for smart processing of real-time events provided by the customers, users, and IoT networks. The FWCR Integration Infrastructure relies on the Microsoft Event Grid, a fast, highly resilient, and easily scalable PaaS component available on the Microsoft Azure cloud. FWCR event are notified according to the "publish once, use many" paradigm and the "publish-subscribe" pattern. Actually, TURNkey is an open platform where any authorized receiver (e.g. government agencies, private command & control rooms, etc...) will be able to subscribe FWCR events in the future and manage them as they want. Nevertheless, in order to realize a full featured end-to-end solution, TURNkey also provides a FWCR End User Interface in a multi-tenant manner. Every tenant is programmed to manage a set of assets and to perform specific tasks, according to specific procedures and checklists, following different priorities or timing. These tasks might be user actions or autonomous actions fulfilled by external system integrations. To achieve all these requirements, the FWCR End User Interface is implemented using latest Microsoft .Net technologies for web-based applications as well as common standards like RESTful WebAPI.

5.4 End-to-end validation of FWCR platform

The project will use a Participatory Action Research (PAR) methodology to guide the design, development and testing of the TURNkey FWCR platform. PAR is a well-established research methodology applied to socio-technical systems where context needs to be considered alongside scientific enquiry in the development of problem-solving technologies. A multi-disciplinary team of researchers, practitioners and stakeholders will work together to overcome problems with the design, development, implementation and operation of the TURNkey FWCR platform. The PAR approach will use theory, refined through a series of iteration cycles (Planning; Implementation; Reflection; Review), to drive changes in practice (through the development of the TURNkey FWCR platform) to support the project’s goal: to improve society’s resilience to earthquakes. All the validation and reviewing activities of each PAR cycle will be based on the selected Testbeds that are the core of TURNkey.

5.5 Testbeds for implementation, testing and validation

For the purpose of TURNkey’s development and demonstration of the results, six European Testbeds (TB) have been identified. They are: TB1: Bucharest, Romania; TB2: Pyrenees, France; TB3: Towns of Hveragerði and Húsavík, Iceland; TB4: City of Patras and Aegio region, Greece; TB5: Ports of Gioia Tauro, Italy; and TB6: Groningen, Netherlands. In addition, data from mobile applications will be gathered in all earthquake affected areas worldwide (virtual TB7) using the smartphone apps LastQuake and EarthquakeNetwork.it. Finally, a mobile EEW system for aftershock monitoring will be developed (mobile TB8).

In the geographical European TBs the most vital infrastructures of a modern society are the built environment, in particular the residential and office buildings, roads, bridges, ports, hospitals, dams, schools, trains, pipelines, industrial sites, levees, etc. For this purpose, the exposure data in the TBs will be collected and classified in a consistent manner on the basis of knowledge levels and embedded in the TURNkey FWCR platform. That enables a systematic comparison with exposure data collected in other European projects, such as SERA and the European Exposure database. The TB-population ranges from a few thousand to a few million people, and the area coverage from a few tens to many tens of thousands of square-km. Moreover, the maximum seismic hazard ranges from low hazard (e.g., TB1, TB6) to the highest known hazard in Europe (TB3, TB4, TB5). The type of seismic hazard also varies, from natural to manmade (TB6). In each TB multiple stakeholders contribute to the project by specifying their needs with respect to EEW, RRE and OEF based on their infrastructures and operations. Thus, the TBs have been designed to cover a wide variety of spatial extents, seismotectonic conditions, seismic hazard levels, and densities of population and vulnerable infrastructure, stakeholder types, as well as covering multiple existing sensor networks (SN) and in some cases existing OEF and/or EEW systems at various levels of operation. The sensor networks include the seismic and strong-motion networks and arrays, structural monitoring arrays, and geodetic networks (GPS). In addition, and for OEF purposes primarily, other geophysical markers from exising SNs will be streaming data, such as borehole sensors such as pressure gauges, strainmeters and geomagnetic and geochemical sensors, into the TURNkey FWCR platform. TURNkey will complement/extend the TBs' existing SNs with the TURNkey multi-sensor units to enhance each TBs capabilities for EEW, RRE and OEF, as identified by TB-coordinators and project partners. In TB1 the TURNkey multisensor units will be deployed in the most prevalent building types built during the periods of three different building codes to understand how design evolved over a period of 80 years and how different types of buildings are at risk. In TB2 the TURNkey multisensor units will be deployed focusing on the towns of Tarbes, Luchon and Lourdes, along with the 45 km-long high-speed train line between Perpignan and Figueras in order to improve coverage for the towns and transportation infrastructures. In TB3 the TURNkey multisensor units will be deployed to densify existing urban strong-motion arrays in the towns of Husavik and Hveragerdi at a high spatial resolution over variable soil types, and enhance the structural response of several important and tall building in both towns. In TB4 the TURNkey multisensor units will be distributed for the optimization of the network for EEW and RRE in the towns of Patras, Aegion, Kalavryta and Lidorikion and for structural monitoring in important buildings. In TB5 the TURNkey multisensor units will be installed in the port of Gioia Tauro to monitor key structures, and seismic movements of the channel. In TB-6 the already dense existing sensor networks will be augmented by the TURNkey multisensor units, placing them at strategic locations to optimize the network for EEW and RRE, focusing on linear infrastructures such as roads and railways, in particular bridges.

5.6 Testing reactions amongst first responders and citizens

Qualitative in-depth interviews and discussion groups will be held with first responders and citizens in three of the testbeds. These will be carried out in two phases with each phase feeding into the initial and later stages of the TURNkey FWCR Platform. The first phase of research will research first responders to understand current practice with regards to sourcing of information and communication with citizens during seismic events, as well as reactions to the a top-level description of the platform and any unmet needs that the platform may help address. It will also investigate citizen awareness of existing protocols and needs and expectations, in particular with regards to communication of information during the preparedness and response phases of an earthquake. The findings from this first wave of research will feed into the initial development of the platform to the end of taking the needs and expectations of both categories into consideration in the design of the solution. The second phase of research will be carried out further on in the project to determine whether a prototype/mock-up of the FWCR platform developed up to that point is line with the needs of first responders and will be able to support communications with citizens in a way that respects established protocols while safeguarding citizen and community safety and resilience.

7. Conclusion

TURNkey project (www.earthquake-turnkey.eu) has its goal to contribute in reducing future economic and social losses and mitigating the direct and indirect consequences of earthquakes in Europe. The project consortium comprises a strong multi-disciplinary team of experts from 21 partner institutions in 10 European countries, and supported by major public and private stakeholders. The project has as objectives to make progress in: Operational Earthquake Forecasting (OEF), Earthquake Early Warning (EEW), and its use both in real-time (during an event) and in near real-time, when rapidly responding to earthquake impacts (RRE); as well as in Information and Communication Technology (ICT) that allow effective two-way emergency communication between citizens and stakeholders, and Instrumentation Technology, that allows for much more cost-effective monitoring of earthquake ground motion and structural response to earthquakes. The project's purpose is develop the TURNkey FWCR computer platform, a low-cost multi-sensor units and a cloud-based earthquake information system, which can be distributed as a fully operational TURNkey product to public authorities (including search-and-rescue teams) and private companies (including operators of critical infrastructure). The cost-efficient multi-sensor units will consist of seismic (vibration) sensors optimized for EEW and GNSS receivers suitable for various monitoring tasks (structural health monitoring, monitoring of rockfalls, rock/landslides, avalanches, tsunamis) and installation possibilities (free field vs building/infrastructure, field vs urban deployment). The TURNkey FWCR platform will be distributed as a fully operational TURNkey product to public authorities (including search-and-rescue teams) and private companies (including operators of critical infrastructure). TURNkey will be demonstrated in six European Testbeds (TBs) with different hazard, vulnerability and exposure characteristics, spatial extents and monitoring networks as well as in two roaming TBs, one based on crowdsourcing and one for temporary installations.

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