Seismic Risk Simulations of a Water Distribution Network in Southern Italy

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Abstract. Critical Infrastructure Protection (CIP) is at the heart of the European and International Agenda. Such issue should be handled also with adequate methodologies and tools to carry out effective prevention and protection of the assets (technological, industrial, strategic) from impacts arising from natural disasters that can harm them and reduce the continuity of services delivered. In this general framework, the RAFAEL Project aims at integrating ad hoc technologies into a comprehensive Decision Support System called CIPCast, which has been implemented to support risk analysis and emergency management in the case of natural hazardous events. A specific module is devoted to the earthquake simulation (CIPCast-ES). The Castel San Giorgio water distribution network (located in Campania Region, Southern Italy) was selected to analyse the seismic risk by simulating four earthquake relevant events, occurred in the past in the area of study. Thus, four different scenarios were produced and, for each of them, two types of results were obtained for each pipe element of the water network, expressed respectively in terms of probability of failure and damage status.

Keywords: Seismic risk · Simulation · Water network · Critical infrastructure protection · CIPCast · DSS

1 Introduction

1.1 The Critical Infrastructure Protection (CIP)

Critical Infrastructure Protection (CIP) is at the heart of the European and International Agenda since several years. Recent data [1] show an increase in the number of disasters affecting Critical Infrastructures (CI), capable of producing huge damage and draining important financial resources. These events, furthermore, can have high costs in terms of casualties. The use of more advanced tools and technologies to promote the preparedness and, consequently, the reduction of global damage (especially in terms of human

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casualties as well as short- and long-term economic losses) is a strategy that cannot and should not be overlooked.

As far as CIP is concerned, the European Union has since long identified its own line of intervention. The Directive 2008/114/EC of the Council of the EU has identified the importance of protection of a number of infrastructural assets. As stated by the art. 2 of such Directive, a critical infrastructure is defined as *"an element, a system or part of this located in the Member States that is essential for the maintenance of the vital functions of society, health, safety and the economic and social well-being of citizens whose damage or destruction would have a significant impact in a Member State due to the impossibility of maintaining these functions"*. The Directive was subsequently transposed in Italy through the Legislative Decree 65/2011. Finally, the recent proposal (COM/2020/829 final) for a new EU Directive on the "Resilience of Critical Entities" (Directive "RCE", update of Directive 114/2008/EC) will impose on the Member States a stronger governance of the management of the security of CI assets.

Once defined at a legal and institutional level, the CIP problem should also be handled from the technological point of view, by supporting Public Administration and Operators to carry out effective prevention and protection of the assets (technological, industrial, strategic) from impacts arising from natural disasters and other events that can harm them and reduce the continuity of services delivered.

In particular, CI Systems include not only utility networks such as energy, water, telecommunications and transportation systems, but also discrete critical facilities such as hospitals, schools, ports and airports among others. As analysed in several studies [2–4], these infrastructures have become increasingly complex and interdependent.

A typical example of interdependency is that of CI water on CI electricity: there are numerous devices that require the power supply for the relative functioning of the water service. However, the severity and extent of the effects that critical situations in electrical CI can cause in strongly interconnected systems, such as those dedicated to the water service provision, are not yet understood [2]. A methodology to assess the impacts on a water network coming from failures occurred on the power network has been presented by [5, 6]. From such studies it is possible to deduce that the impact assessment is strongly dependent on the characteristics of the water system, on the data availability and – above all – on the CI level of interdependency. These features make the problem hard to be well-defined.

On the other hand, such aspect has induced a high level of vulnerability to a series of natural or non-natural events, which can cause damage or destruction [7, 8]. For an effective protection of the CI, thus, the development of new approaches and methodologies is needed, in order to reduce the vulnerabilities, mitigate the risks and face new threats to which these complex systems, essential for the everyday life, are exposed. There is a large number of studies that illustrates the effects of natural phenomena on CI systems. In particular, the effects that earthquakes have on infrastructures were widely studied in the literature [9–16].

The study described in the present paper focuses on the seismic risk and the impacts of earthquakes on a Water Distribution Network (WDN). To this end, an interactive simulation model was developed to simulate different seismic events, actually occurred in the past within the area of study, assessing the damage levels virtually obtained. Such

model was implemented in a Decision Support System (DSS) platform (developed in the framework of the RAFAEL Project, described in Sect. 1.2) and was applied to an actual metropolitan WDN operating in the Southern Italy (Sect. 1.4) to evaluate various damage scenarios in consequence of each simulated earthquake.

1.2 The Context of Application: The RAFAEL Project

The study and the related applicative case presented in this paper have been carried out in the framework of the RAFAEL Project (*"system for Risk Analysis and Forecast for critical infrastructure in ApenninEs dorsaL regions"*, PNR 2015–2020, co-funded by the Italian Ministry of University and Research, Grant no. ARS01_00305, scheduled to end in November 2021, https://www.progetto-rafael.it/). As part of the technological developments undertaken over the last few years, the Project aims at integrating ad hoc technologies, developed within its activities, into a comprehensive DSS platform [17] (namely CIPCast and described in the next Section), which will become the reference platform to provide services to companies and to the Public Administration through the constitution of EISAC.IT programme (www.eisac.it) that will carry out its operational deployment in Italy. RAFAEL deals with the management of numerous CI assessing the relevant damage deriving from natural disastrous events, and evaluating the impact on the services and the consequences on the population and on the infrastructural system. Among its objectives, the RAFAEL project is going to extend the current CIPCast capabilities, by implementing new analytical and simulation tools to further improve the CIP tasks.

1.3 The CIPCast Platform

CIPCast is a DSS platform, which has been conceived for supporting risk analysis and emergency management in the case of natural hazardous events [17]. It includes and manages more than 400 geospatial data layers for spatial analysis, protection of CI and increasing urban/infrastructures resilience. CIPCast can run in operational mode (on a 24/7 basis, as an alert system) and in an off-line mode by simulating events. In the first case, CIPCast gets external data from many different sources (e.g. seismic network, meteo/hydrological models), to establish the current conditions [18]. Then, it produces an expected "damage scenario" for each element of the monitored CI, depending on the type of event expected (and its intensity), considering the specific vulnerabilities of infrastructure elements (pipes, substations, etc.). In the simulating mode CIPCast can be exploited as a stress tester enabling to set-up synthetic natural hazards (e.g. earthquakes) and assessing the resulting chain of events [19, 20]. Moreover, CIPCast can be also exploited as an interactive application for supporting multi-criteria decision processes [21]. All the services are accessible by means of the geographical interface of CIPCast, a WebGIS application that can be used as graphical front-end of data and information provided and/or produced.

The specific module devoted to the earthquake simulation and risk analysis is called CIPCast-ES (Earthquake Simulator). It has been exploited to carry out the simulations performed during the case study here presented.

1.4 The Case Study

The Castel San Giorgio water distribution network (WDN) was the CI chosen within the RAFEL project in order to define and simulate the seismic risk scenarios. The network (Fig. 1) is located in the Campania Region (Italy) and serves a population of about 14,000 inhabitants, over an area of approximately 13 km^2. It distributes approximately 60 l/s daily from three wells, which guarantee the entire water supply, through a network of around 60 km of pipelines. More information about the characteristics of the WDN can be found in [6].

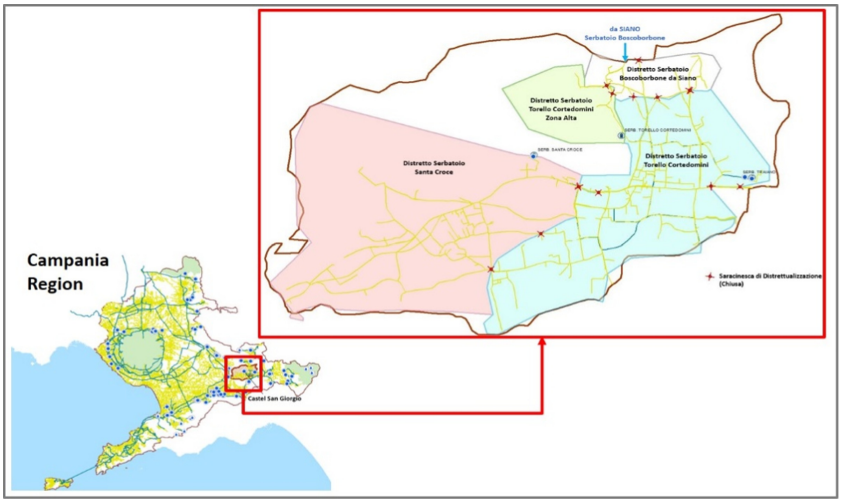


Fig. 1. Study area location: Castel San Giorgio municipality water distribution network

2 Methodology

2.1 Overview

To assess the damage, considering the various approaches analysed and proposed in literature during the last years [16], the following steps were implemented and defined in CIPCast-ES (Fig. 2):

1. Classification of the infrastructure elements according to a defined taxonomy;
2. Simulation set-up: parameters input (e.g. epicentre, magnitude, etc.);
3. Hazard assessment: ground motion intensity measures elaboration;
4. Repair Rate (*RR*) assessment as a function of the hazard;
5. Probability of failure (P_f) assessment as a function of *RR* and pipe length;
6. Damage assessment, in order to assign a specific damage level/rate as a function of P_f to each CI element (e.g. a single pipe track).

Then, the CIPCast-ES module (Fig. 3) was exploited to set-up and run different earthquake simulations and, consequently, to produce the relative damage scenarios.

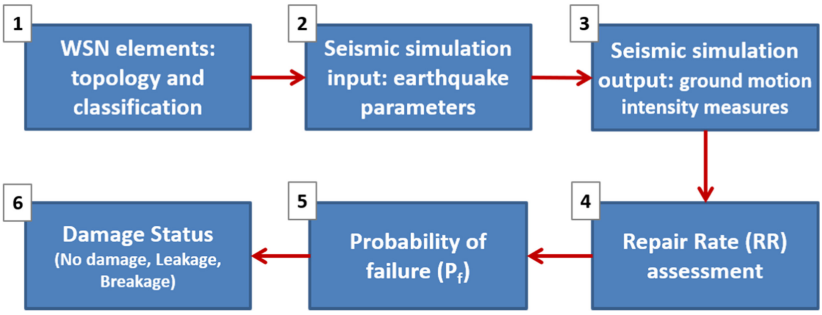


Fig. 2. CIPCast-ES: simulation workflow

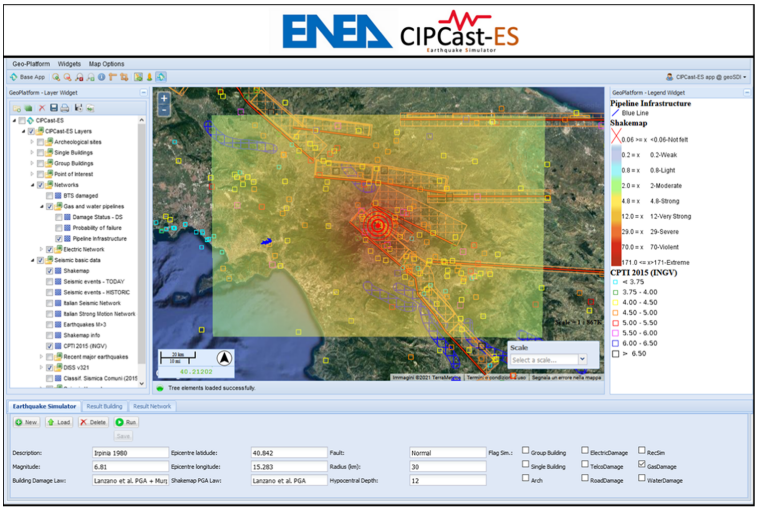


Fig. 3. CIPCast-ES interface: example of visualization of basic data (e.g. seismogenic sources, historical earthquake catalogue) and of the results obtained after a simulation (e.g. Shakemap in terms of peak ground acceleration, PGA)

2.2 Seismic Simulations and Scenarios

In the case-study related to the Castel San Giorgio WDN, once its elements (buried pipes) have been suitably classified and stored into the CIPCast Geodatabase, it has been possible to perform the simulations. The simulations were set-up through the CIPCast-ES user-friendly wizard. The following parameters has been provided as inputs of the application: epicentre coordinates (in latitude and longitude), hypocentre depth (in km) and magnitude. To this end, four past occurred events were selected (their characteristics are reported in Table 1), as significant earthquakes in terms of magnitude and/or proximity to the geographical area where the Castel San Giorgio WDN is located.

Then, it has been selected the area of interest of the simulation, the CI typology to be processed amongst those available (water/gas pipelines, power network, buildings) and finally the GMPE (Ground Motion Prediction Equation) [22] to be used in order

Table 1. Earthquake event selected for the simulations (source: INGV, Italian National Institute for Geophysics and Volcanology, CPTI15 v3.0 - Parametric Catalogue of Italian Earthquakes)

Event	Date	Magnitude	Epicentre coordinates
Penisola Sorrentina	07.31.1561	5.56	40.68 N–14.71 E
Castel San Giorgio	04.27.1930	4.98	40.78 N–14,69 E
Irpinia-Basilicata	11.23.1980	6.81	40.84 N–15.28 E
Sant'Arcangelo T.	09.27.2012	4.2	41.18 N–14.92 E

to describe the ground shaking effects in terms of peak ground motion intensity measures. GMPEs or "attenuation" relationships, allow to model the ground shaking and its associated uncertainty at any given site or location, based on an earthquake magnitude, source-to-site distance, local soil conditions, fault mechanism, etc. Different GMPEs are currently implemented CIPCast-ES.

As proposed by FEMA [23] and by the A.L.A. Guidelines [24] and applied in many similar studies (see [15] for an overview), seismic damages to buried pipes can be expressed by the "Repair Rate" (*RR*) per unit length of pipe, that is the rate between the number of repairs and the length (in kilometres) of a pipe exposed to seismic hazard. This number is a function of pipe material, joint type, soil conditions and diameter size, and of ground shaking, expressed in terms of *PGA* (Peak Ground Acceleration) or *PGV* (Peak Ground Velocity, as used in the present analysis), or else ground failure expressed in terms of *PGD* (Permanent Ground Deformation). Then, to evaluate the *RR* for the WDN pipelines, referring to seismic wave propagation in terms of *PGV*, we have applied the Eq. (1) proposed by A.L.A. [24]:

$$RR = K_1 0.002416\, PGV \tag{1}$$

where K_1 is a coefficient that considers pipe material, joint type, soil type and conditions and diameter size (determined experimentally and reported in specific tables provided by A.L.A. [24]). *PGV* was evaluated using the GMPE proposed by Bindi et al. [25], which allowed to obtain the spatial distribution of the geometrical mean of the horizontal components of the *PGV*. Subsequently, from the *RR* (representing the number of leaks/breaks per pipe length) the failure probability of a single pipe was calculated according the Eq. (2) proposed (among the others) by [24] and [26]:

$$\overline{P_f} = 1 - e^{-RRL} \tag{2}$$

The failure probability of a single pipe is equal to one minus the probability of zero breaks along the pipe. In addition, a damage status was derived for each single pipe by means of the approach proposed by [27], which allows to classify the pipes according three different levels of damage: "No Damage", "Leakage" and "Breakage".

3 Results

By simulating in CIPCast-ES the four earthquake events selected (Table 1), four different seismic scenarios were obtained, according to the approach described in the previous Section. For each scenario, two types of results were produced for each pipe element of the Castel San Giorgio WDN: i) probability of failure; ii) damage status.

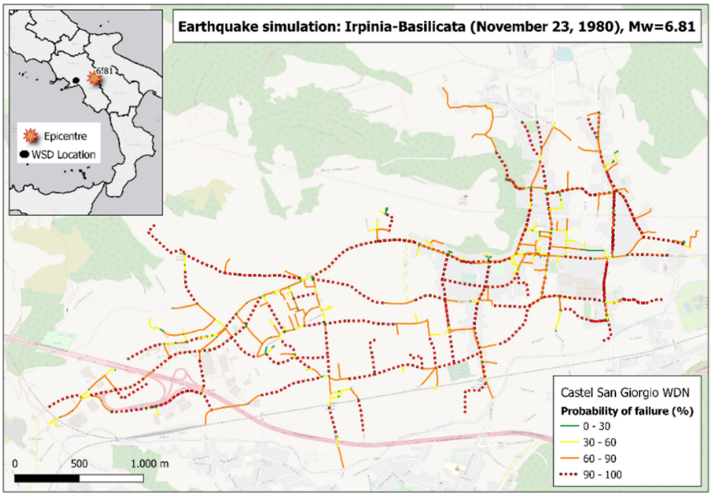


Fig. 4. Earthquake simulation: Irpinia-Basilicata 1980 (Mw = 6.81). Example of scenario produced in terms of probability of failure (in percentage)

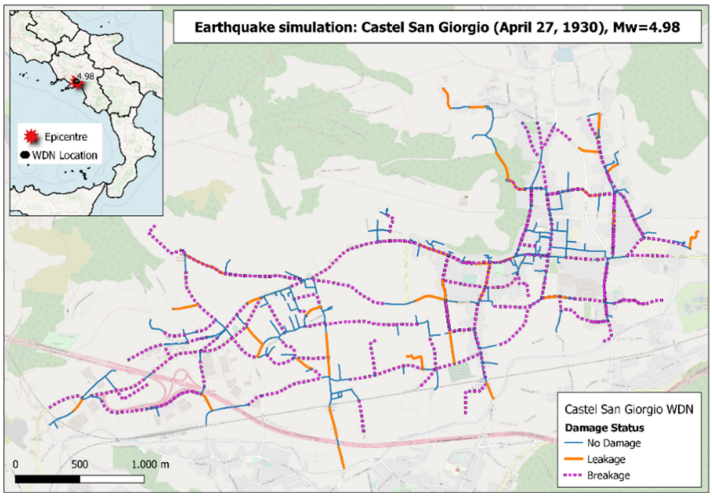


Fig. 5. Earthquake simulation: Irpinia-Basilicata 1980 (Mw = 6.81). Example of scenario produced in terms of damage status ("No Damage", "Leakage" and "Breakage")

As results of the above described simulations, in particular, Fig. 4 shows the probability of failure (expressed in percentage) for each branch of the Castel San Giorgio WDN, in consequence of the ground shaking (expressed in terms of *PGV*) obtained by simulating the Irpinia-Basilicata 1980 earthquake ($M_w = 6.81$, see Table 1). Moreover, still considering the same seismic event, in Fig. 5 is depicted the potential damage status obtained, expressed according to the above-mentioned three levels [27].

4 Conclusions and Future Developments

The activities carried out in the framework of RAFAEL Project aim at the development of methodologies and technological tools (such as the CIPCast platform) for the analysis, monitoring and risk assessment of CI. To this end, the earthquake simulator CIPCast-ES module has been exploited in the case study described in the present paper, focused on the Castel San Giorgio WDN, located in an area characterised by a high seismic hazard. Thus, it has been possible to perform a seismic risk analysis and produce different damage scenarios on the WDN, by simulating the impacts of four pasty occurred earthquakes.

The outputs of the simulation model can represent the inputs of hydraulic simulations, to be used for describing the hydraulic behaviour of the damaged WDN, in order to evaluate and suggest post-event actions for a prompt system recovery [28, 29]. Although this aspect is out of the scope of the present paper, it has been tackled in another task of the RAFAEL Project, as described in [5, 6]. Simulated scenarios can also be used to analyse cascading effects: for example, how the lack of energy (due to a failure on the power network) can further influence the operational level of the WDN [30].

Finally, some considerations about the on-going and the future developments. The CIPCast-ES workflow will be further improved by considering the approaches developed in similar studies, among others [13, 15, 31–34]. Contextually, other earthquakes occurred in the past will be reproduced in the simulator (e.g. the 2016–2017 Central Italy seismic sequence [35]): the outputs produced by CIPCast-ES will be compared with actual post-earthquake damage surveys and data. This will allow to calibrate the simulator and, consequently, to improve the reliability of the results produced.

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