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SEISMIC RISK ANALYSIS OF DATA COMMUNICATION NETWORKS: A FEASIBILITY STUDY

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ABSTRACT

The seismic risk assessment of spatially distributed infrastructures systems is gaining increasing research relevance. To date, data communication networks are less investigated than other networks, yet evidently important. This study focuses on framing the simulation-based probabilistic seismic risk analysis of data communication infrastructures systems and testing its feasibility in a real case study; i.e., the interuniversity data network of the Campania region (southern Italy), which develops for 280 km in a region that ranks among the highest seismically-hazardous in Italy. The framework includes: (i) the probabilistic characterization of seismic input in terms of transient and permanent ground deformation hazard; (ii) the framing of the vulnerability of the network's components; (iii) a preliminary performance analysis of the network. The paper illustrates the multi-disciplinary needs and the challenges of the seismic analysis of data networks, and provides the implementation of the probabilistic simulation approach, possibly useful for further, more advanced, studies on the same topic.

Keywords: civil infrastructure systems; performance-based earthquake engineering.

1. INTRODUCTION

Civil engineering research is dealing, among topics of largest interest nowadays, with risk and resilience to natural hazards of systems and assets serving the communities of the region where they are deployed. In fact, when it comes to earthquake engineering, there is a significant deal of research focusing on risk assessment of utility distribution systems, as gas or electric networks (e.g., Esposito et al. 2015; Cavalieri et al. 2014), and transportation networks (e.g., Argyroudis et al. 2015). These studies attempt to extend the probabilistic paradigm of performance-based earthquake engineering or PBEE (Cornell and Krawinkler 2000), originally developed for buildings (i.e., point-like structures), to spatially distributed infrastructures systems. PBEE entails the probabilistic characterization of (1) the seismic hazard, (2) the system's vulnerability, and (3) the consequences of the seismic damage to the structure/system of interest (i.e., the losses). Each of these three items presents scientific and practical challenges, when dealing with distributed infrastructures systems that motivate the mentioned research effort. Moreover, even in the broader PBEE framework adapted to spatial systems, each infrastructure requires specific calibration of the hazard, vulnerability, and loss models that reflect the peculiarities of the physical assets and of the consequences of seismic damages to them. The final aim is to compute the expected annual performance loss, for seismic causes, of the system, to be able to check its tolerability and eventually direct risk mitigation resources. Telecommunication networks (i.e., landline-voice, wireless-cellular, and data communication networks) can be certainly framed in the

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context of utility systems, and among those of largest importance for the immediate post-event emergency management and community resilience. On the other hand, these systems seem relatively less studied (in the earthquake engineering community) with respect to those mentioned above, although a few attempts exist (e.g., Leelardcharoen, 2011). It has also to be mentioned that the documented behavior in recent damaging events is quite well described. To give some examples, the moment magnitude (M_w) 6.5 San Fernando earthquake in 1971 had equipment failed in a central office. The M_w 8 Mexico City earthquake in 1985 had collapsed three floors of a communications building (Tang 2008). In both the M_w 7.1 September 4th 2010 and M_w 6.3 February 22nd 2011 New Zealand events, there were a variety of damages in the nodes and links of the telecommunication network: damage to underground facilities, mainly due to liquefaction ground failures, was the main causes to the service outages (TCLEE 2012). From a systemic point of view, instead, telecommunication networks have been performing well during the short-term post-earthquake phase (TCLEE 2011; Tang 2014). In the 2011 M_w 9.0 Tohoku earthquake, the overall system performance, including recovery and emergency response, was considered satisfactory, particularly for the data communication network. In this case, the damages experienced on the telephone network, mainly in central offices close to the coast, were mostly due to the tsunami and power outage (TCLEE 2011). But there are other examples where earthquakes had a great impact on the performance of data communication networks; e.g., the M_w 7 Taiwan earthquake, in 2006, reduced China's Internet access capacity by 74% for several minutes due to fiber cables cut. Such a capacity was progressively recovered in the following minutes due to automatic traffic reroute and in the following hours thanks to manual traffic reroute (Kitamura et al. 2007), helping the resilience of the community.

From the scientific literature on data- (or computer-) communication it emerges that assessing the effects of earthquakes on telecommunication networks, especially the data communication networks, is an emerging topic, presenting inherent difficulty due to nature of these networks and due to the mechanisms they employ to recover from failures. Studies, focused on the evaluation of the post-event performance of these systems, showed how natural events can cause severe service network disruption. Cetinkaya and Sterbenz (2013) presented a general classification of network failures, in which they consider large-scale disasters, including earthquakes. Fukuda et al. (2011) analyzed the impact of a recent earthquake in Japan on a national network. They observed that, even though some physical links were damaged, the network connectivity was maintained thanks to physical and internet protocol (IP) level redundancy. The former is warranted by dual physical links that route along different geographical paths, whereas the latter is provided by redundant multiple loops in the network topology. Despite the work done, these studies do not include in their investigation the study of the physical effects of the earthquake on each component of the network.

The scope of the study reported in this paper is to investigate the application of the performance-based seismic risk assessment adapted to spatially distributed infrastructures systems to data communication networks. For the scope of the study, a real case is addressed, that is the recently established RIMIC (*Rete di Interconnessione Multiservizio Interuniversitaria Campana*), in southern Italy. It links the universities in the Campania region and is connected, via one of its points of presence, to the nationwide GARR (*Gruppo per l'Armonizzazione delle Reti della Ricerca*) backbone. The optical fibers of RIMIC are mostly buried and the POPs are located in university buildings. RIMIC has several sub-networks, however, for simplicity only the main loop, featuring four POPs, is considered herein. It deploys over more than 280 km, running in areas susceptible to ground failure and also close to the seismically active Irpinia (southern Apennines) area, which in 1980 originated a Mw 6.9 earthquake, the most damaging in the contemporary era in Italy. In this study, the seismic risk assessment consists of evaluating the expected loss of traffic due to earthquakes, also considering the traffic demand change after an earthquake, in the PBEE context. Because the study can be novel in this sense, its result are preliminary, and the identification of the modeling needs to carry out a more complete/definitive analysis for this kind of systems has to be considered as the primary outcome of this study.

The remainder of the paper is structured such that the peculiarities of data communication networks and communication mechanisms are described in order to understand how these networks work in normal operation status as well as during a failure. Subsequently, the general process of the performance-based seismic risk analysis for data networks is described. In the second part of the paper, the RIMIC test case is described from a physical and logical point of view. The seismological, geological and geotechnical features of the region where the system is located, are described. Then, the vulnerability models adopted are discussed, as well as the algorithms to compute the performance loss in the case of a seismic event. All these components are tied together and the seismic risk assessment for RIMIC is carried out.

2. DATA COMMUNICATION NETWORKS

A data communication network can provide connectivity between individual networks (i.e., telecommunication companies, multiple service providers and end nodes) at various levels through a complex and hierarchical interconnection of nodes and links. As shown in Figure 1 (left), computers at the border of the network (also called end hosts; i.e., devices used by human beings, servers, data centers, machines performing automated tasks, and, in general, all the entities that use the network for data communication with other entities) are connected through a series of intermediate devices (mainly switches and routers) that route, re-route, and in general, manage the traffic. From a physical point of view, the typical structure of a communication network is composed of a number point-like facilities (i.e., the intermediate devices) and distributed links (mainly fiber optics or copper cables) either buried and/or running on aerial lines. The intermediate devices usually reside inside the so-called points of presence (POPs) that represent the principal points of concentration and distribution of connectivity of the network. POPs are usually located in building facilities that provide appropriate services (electricity, air conditioning, alarm systems, fire protection, etc.) to ensure continuous operation of the devices of POPs and the proper installation of suitable racks to house such devices. Each rack contains optical adds/drop multiplexer, switches, routers, and, in general, all the devices needed to handle the traffic of the end users.

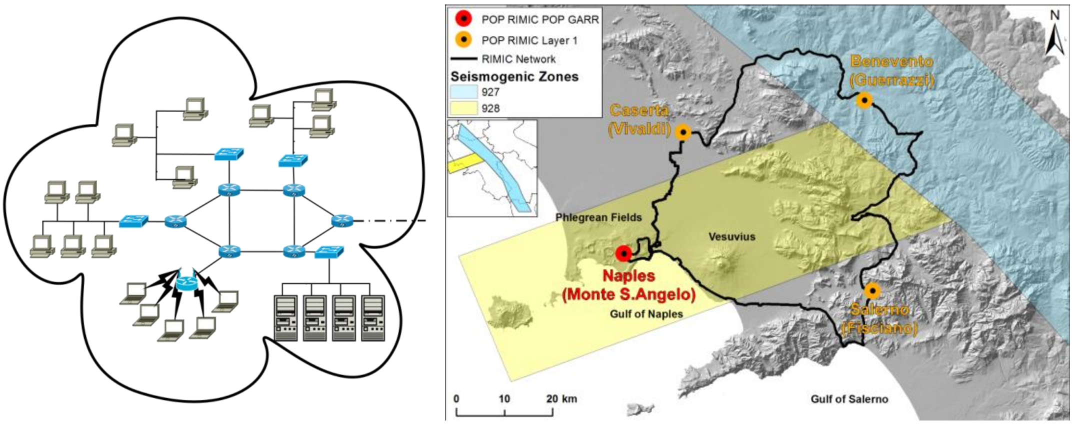

Figure 1. Example of data communication network (left) and the main loop of the RIMIC network (right)

Large networks are often organized in a hierarchy, where the highest level forms a backbone for the other levels. Today, each level of a geographical network is typically organized as a loop, where at least two cables connect each POP to other two POPs of the same level. This is to ensure that all the POPs have different paths available, which is an important redundancy requirement, especially for the main loops. POPs of lower layers are then possibly connected to at least one POP of the higher layer and to another POP of the same level.

2.1 Communication Mechanisms

In the following, a short overview of the basics of data communication networks is provided. The information exchanged between the end-hosts (e.g., a web page, an image, or a voice flow) is fragmented in a number of pieces called packets. Each of these packets is then transmitted through the network, where each of the intermediate devices does packet switching; i.e., receives the packet first, it then inspects some part of the packet content (e.g., to find the intended destination), and finally forwards it through a specific link to a certain next intermediate device or to the destination end host.

All such packets constitute the so-called network traffic, which is therefore flowing on the links of the network, handled by the intermediate devices, and coming from and going to all the possible end hosts in the network. All the hosts of these network (end host and intermediate devices) use a very simple protocol to exchange data; i.e., the IP (internet protocol). This protocol is connectionless and best effort, in the sense that it tries to deliver each new packet produced by the application at its final destination using the route available in that particular moment. However, it does not guarantee or even assume that packets are actually received by the destination. Upper-layer protocols working on top of the IP are in charge of verifying if the packets have been received by the destination and to retransmit them in case of loss. On the other hand, intermediate devices have several links of different kinds (fiber optics, copper cables, wireless links, etc.) and several possible paths among them and perform an important function on packets, generally called routing. Basically, on packet arrival from a certain source on a certain link, they have to decide where to forward these packets, in order for them to arrive at their final destination. To do this, they construct the so-called routing tables; i.e., tables containing the outgoing link to be used for each possible destination. These tables are constructed by each device at start-up and continuously updated using the so called routing protocols, which are based on the exchange of specific information among them.

2.2 Failure Recovery

Failure recovery mechanisms can be of two main classes, depending on the layer of the protocol stack they operate at: IP- and physical-layer. IP-layer mechanisms (also called routing-layer or network mechanisms), are realized by routing-algorithms performed by the intermediate devices (the routers in particular). These devices, in case of link and node failures, may be able to automatically find a new path towards the destination through a process called re-routing. The time required for the IP-layer mechanisms to reach the new stable configuration and to deliver previously lost packets can be in the order of several minutes because network-layer devices require to exchange several messages in order to find the new paths. The actual time depends on several factors such as the internal state of the routing protocol, the topology and configuration of the network, the complexity of the network, the available paths that survived the failure, the routing protocol, etc. Physical-layer mechanisms operate differently. In case two or more links (e.g., more optical fibers from within the same cable) connect the same two physical layer devices, and one link (the primary) breaks, another one can automatically be used by such devices without being noticed by and/or informing all the other devices. These mechanisms may recover from failures in a much shorter time with respect to the IP-layer ones. However, these mechanisms can be of help only if a part of, but not all, the cables connecting the devices experiencing the failure is broken.

3. PERFORMANCE-BASED SEISMIC RISK ANALYSIS

This section describes first, the general process to characterize the seismic hazard acting on the components of a data communication network. Then, the characterization of seismic vulnerability of each component and the performance of the network as a whole is reviewed, highlighting the principal differences and limitations with respect to single-site systems and the other (more investigated so far) networks, such as gas, water, and electric power networks.

3.1 Seismic Hazard

A data communication network is a spatially distributed system made of different components regionally-distributed. This means that the seismic hazard of the region where the network is located has to be evaluated jointly for all the locations of the system's components. Besides the characterization of the seismic source in terms of earthquake occurrence, geometry, fault mechanism and the probabilistic distribution of magnitude and location of each seismic event, the seismic hazard characterization of an infrastructure system requires the joint evaluation of different ground motion intensity measures (IMs) that serve as input for the vulnerability models of each component of the network. This last aspect represents the key difference with respect to seismic risk analysis of point-like facilities: the seismic hazard has to be represented in terms of random fields accounting for the statistical dependencies between different ground motion parameters. The last aspect to consider in the characterization of the seismic hazard of data networks is that, the presence of buried components (i.e., cables) may (generally) require the consideration of permanent ground deformation (PGD) hazard triggered by the transient ground shaking hazard, such as landslides, liquefaction and fault displacements. The relative impact of induced PGD hazards on buried elements depends on several factors among which: the morphologic, geological, and geotechnical conditions of the subsoil as well as the deformation capacity of the vulnerable elements. In general, co-seismic fault displacement is evaluated by means of semi-empirical relations that correlate displacement to the magnitude of the earthquake, while for liquefaction and seismically-induced landslide hazard many models relate the permanent displacement, and the probability of occurrence, to transient ground motion parameters (typically the peak ground acceleration, PGA). Among the different approaches proposed in literature, the simple approach of HAZUS (FEMA 2004), represents a base-level scale-compatible application of geotechnical hazard characterization in the context of probabilistic seismic risk analysis of spatially distributed systems (e.g., Esposito et al. 2015) since it requires limited information about the geotechnical characterization of the region. However, although this is an issue commonly considered in the case of gas and water networks characterized by buried pipelines, data cables are more deformable than pipes, then the characterization of damages induced by PGD hazards should account for this.

3.2 Seismic Vulnerability

To estimate seismic damage of each component of a distributed network given ground shaking or ground deformation hazard, IMs have to be related to effects by means models; e.g., *fragility* functions. In particular, for point-like systems, these relations typically provide the probability of reaching or exceeding some damage state (DS) given the intensity. This applies to the aboveground components of networks, while for buried elements such as pipelines, fragility models usually consist of a seismic-intensity-dependent rate, providing the number of damages (e.g., leaks or breaks) per unit-length.

As detailed above, the typical physical structure of a data communication network is made of distributed elements (i.e., cables) and a number of point-like facilities (intermediate devices). In geographical networks, point-like facilities reside inside the so-called POPs, usually located in buildings and housed in racks. At the lowest refinement level, the vulnerability characterization of POPs may be performed analyzing the seismic behavior of the hosting facility (i.e., buildings) and the equipment inside (i.e., presence of anchored or unanchored subcomponents; or electrical components, connection type, etc.). Starting from a seismic characterization of the hosting building and the sub-components characterizing the point-like component, a fault tree analysis may be applied in order to identify which sub-component is critical with respect to seismic fragility (see section 5). Regarding the distributed-elements, cables are usually made of fiber optics or copper and they can be either buried and/or running on aerial lines. Damages observed in past seismic events shows that buried cables are mostly sensitive to permanent ground deformation induced by liquefaction, landslide and co-seismic rupture. However, although the seismic behavior of both unburied and buried data cables has been well described in post-earthquake reports (TCLEE 2012), to authors’ knowledge, no fragility curves specific for data cables have been proposed in literature, although attempts exist for electric networks (Kongar et al. 2017).

3.3 Systemic Performance

Performance evaluation of infrastructure systems reflects their spatially distributed and functionally interconnected nature, which needs specific indicators (Franchin and Cavalieri 2013; Esposito et al. 2015). The identification and description of the relation/interactions between the components of each system (intra-dependencies) and inter-relations between the systems (inter-dependencies) is a fundamental step for the evaluation of the state of the system (i.e., the performance) as a function of the states of its components and of other systems. The quantitative measure of the performance of the whole system is usually given by performance indicators (PIs). Performance indicators depend on the type of analysis that is performed on the network. In particular, two types of system evaluation may be considered: (i) connectivity analysis, which is related to the existence of a path connecting sources to demand nodes, and (ii) capacity analysis, which consists in assessing capacitive flows from sources to end nodes based on the damages. In the case of data networks, capacity analysis requires the knowledge of the amount of traffic flowing through the network. Such amount of traffic is dependent on the number and kind of users, applications, and end hosts. It is also strongly dependent on the characteristics of the network in terms of capacity to actually transport such traffic to its intended destination. Therefore, the traffic on the network before and after the event can be used as a performance parameter to evaluate the effect of the earthquake on the network. To do this, the traffic matrix of the network before the event has to be considered first, it contains the volume of traffic exchanged by any two nodes in the network. Having such matrix before the event, what changes in the network after the event has to be studied. In particular, after the event, any two nodes can still be able to exchange traffic or not, based on whether a path connecting them is still available or not.

4. THE REGIONAL INTER-UNIVERSITY DATA NETWORK RIMIC

4.1 Logical Description

The network under study is a new infrastructure recently deployed in the Campania Region of Italy as part of a publicly financed project called *Rete di Interconnessione Multiservizio Interuniversitaria Campana*. The project has created a high-speed and high-redundancy network connecting the universities, research centers, and public institutions of the region, as well as the interconnection and upgrading of existing Metropolitan Area Networks (MAN). It covers the entire territory of Campania. Physically, the network is configured as a ring system: the first ring (or loop) has regional coverage to which additional rings are connected. RIMIC has several sub-networks, however, for simplicity only the main loop (Figure 1, right) is considered in this study. It is meant to be a backbone interconnecting the main POPs. The secondary loops as well as other networks and MAN infrastructure are then attached to these main POPs. Regardless of the hierarchical level of membership, all POPs also perform aggregation of connections of end hosts. In particular, these hosts can be connected in two different modes: (1) directly connected to the nearest POP via optical fiber; (2) connected through urban and/or regional networks connected to the POP. The hierarchical structure of the network ensures high availability: the nodes of the main loop have at least one path geographically diversified. Such dual path connection is meant to manage network failures by dynamically re-directing traffic on the alternative route. In addition to that, network devices inside POPs are inherently redundant, decoupling the transmission components of the different optical fibers so as to cope with failures of such components. The network has physical- and IP-layer recovery mechanisms. First, each physical link is realized through different couples of optics fibers and physical-layer mechanisms are then adopted to automatically reroute traffic on the backup fiber in case of failure of the primary one. Moreover, the loop structure allows redundancy, and thus protection, also in case POPs or paths connecting POPs fail (e.g., rupture of the entire cable containing all the optical fibers). In this case, automatic and dynamic rerouting is performed. In the analysis presented in this paper, the network is considered able to instantaneously reroute traffic on the available links or paths. This means that no traffic is lost in case of single link failures due to the loop topology.

4.2 Physical Description

As mentioned before, the case study is composed by four main nodes (POPs) one of which (i.e., the Naples' POP) is connected to the ultra-broadband national network (GARR, the broadband network connecting universities and research institutes in Italy). The four POPs are located in building facilities providing appropriate services and housing the racks for the devices. The racks are anchored and housed in the four buildings at the ground floor. The main characteristics of the four buildings and the corresponding vulnerability class according to HAZUS (FEMA 2004) taxonomy are summarized section 5. The four POPs are connected by a ring of about 280 km of optical fibers mainly housed along roads (urban and extra urban), railroads and in some parts along bridges decking systems and tunnels that create a linkage in both transportation and telecommunication networks. Fiber optic cable lines are buried at about 1 m and have a diameter of 50 mm. They are composed of a central strength member. Central strength members are needed to provide the stiffness to keep the cable from buckling and protect the individual fiber optical cables from breaking during the installation. The individual fiber tubes are stranded around the central member into a compact and circular cable core. Around the cable cores there is an aluminum polyethylene laminate filled with a compound that protect the individual cables from water ingress. The cable core is then covered with a double polyethylene sheath that enhances cable crush resistance, impact resistance and moisture proofing.

4.3 Seismotectonic and Geological Setting

The network crosses a wide area along relevant expressways passing for the main cities of Campania region (i.e., Naples, Caserta, Benevento, Avellino, Salerno). It lies on different geological formations, eventually characterized by the presence of a groundwater level in the shallower layers, which can affect the seismic site response analysis and the occurrence of landslides and liquefaction phenomena.
Figure 2a shows the RIMIC track, which intersects eighteen geolithological complexes, mainly located in plains and riverine contexts and only in few cases along slopes. The shallower layers (2-3 m depth) are constituted by pyroclastic materials, debris, paleosoils and infillings, but for the scale of this study (1:100.000), only the geological bedrock was considered. The concrete rigid structures (tunnels and bridges), on which the network can be located were neglected too. The case study is mainly interested by two seismogenic areal sources as shown in Figure 2b. The two zones are the 927 and the 928 according to the Meletti et al. (2008) seismic model of Italy (used for the official seismic hazard map of the country). Data characterizing the two seismic zones are given in section 5.

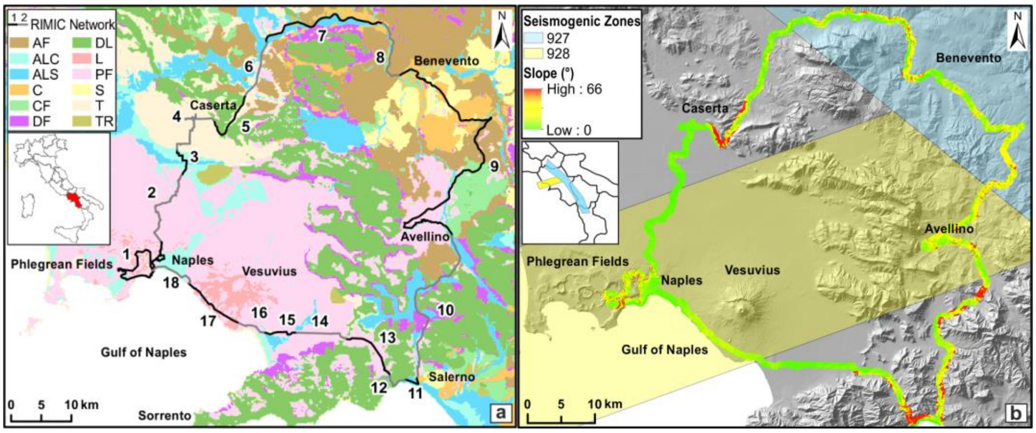

Figure 2 (a) The outcropping lithological formation map; black and grey line is the RIMIC network, which intersects eighteen homogeneous lithological sectors; CF) clay and AF) arenaceous formations; DL) dolostone and limestone; C) conglomerate; S) sand; L) lava; ALC) alluvial and lacustrine clay; ALS) alluvial sand; DF) debris and fan deposits; T) tuff; PF) pyroclastic fall; TR) travertine; (b) slope angle map with seismogenic zones

5. ANALYSIS

The scope of the present study is to apply the performance-based seismic risk assessment, adapted to data communication networks (discussed in section 3) to the case study of the main loop of RIMIC network (described in section 4). The network performance was assessed evaluating the amount of traffic that is correctly transferred through the network to the POPs, considering the traffic demand change after an earthquake. Both transient ground deformation (TGD) and permanent ground deformation (PGD) hazards were accounted for. Fiber cables and POPs were considered the vulnerable elements, and the risk assessment was performed in terms of one capacity-level PI.
The simulation was performed implementing the application network in the object-oriented framework for infrastructure modeling and simulation (OOFIMS, https://sites.google.com/a/uniroma1.it/oofims/) software (Franchin and Cavalieri 2013) for the seismic risk assessment of interconnected

infrastructural systems (the software was enhanced, on purpose, with the tele-communication class). Although remaining on the methodological side, this section describes the steps of the (Monte Carlo) simulation-based assessment, as well as the models to carry out the simulation, based on the approach proposed in Esposito et al. (2015) and considering all the aspects discussed in section 3. In fact, each simulation represents a seismic event and the following impact on the performance of the RIMIC network.

5.1 Simulation of Seismic Input

The computation of the seismic input in each run of the simulation is mainly characterized by four phases: i) simulation of a random event on the considered seismic sources; ii) computation of the ground motion for the region where the network is located; iii) amplification of the ground motion due to local site conditions; iv) computation of the ground failure displacement induced by liquefaction and landslide; see Esposito et al. (2015) for procedural details.
In each run, the seismic event is simulated in terms of earthquake location and magnitude considering two seismic sources of Figure 2b. Data characterizing the two seismic zones and needed for the simulation of the events on the seismic sources were taken from Barani et al. (2009). The magnitude of each event is computed considering an exponential truncated Gutenberg-Richter distribution (Gutenberg and Richter, 1944), while the location of the earthquakes was assumed as uniformly distributed over each source zone. The ground motion at the bedrock is then computed. The earthquake IM considered in the analysis is the PGA because of the fragility curves used for the vulnerability analysis (see next section). The PGA field at the bedrock for each scenario was evaluated using the Bommer et al. (2012) ground motion prediction equation (GMPE) on a regular grid of points discretizing the region covered by the network. The model formulated by Esposito and Iervolino (2011) for PGA was used to account for correlation of intra-event residuals. Moreover, GMPE-based amplification factors were considered to account for local site conditions and to transform the PGA at the bedrock in the PGA at the surface $\left(PGA_S\right)$, that is TGD. To this aim a geological analysis of the region was performed and the average shear-wave velocity between 0 and 30-meters depth (Vs30) was associated to each site of the network based on a 1:100.000 scale ISPRA geological maps (http://www.isprambiente.gov.it/); Forte et al. (2017). Regarding the ground failure (i.e., PGD hazard), the potential earthquake-induced events which may occur in each simulated event are: rock falls and debris flows along high angle calcareous slopes (southern sector of Figure 2a); reactivation of slow slope movements in the clayey hills domains (northern and eastern sector) and sandy silt soils liquefaction in the intermountain basins (northern) and alluvial plains (western sector). Therefore, the landslide and the liquefaction potential of the region, where the network deployed, was evaluated, according to the HAZUS (FEMA, 2004) procedure (co-seismic surface ruptures was neglected). In particular, a landslide susceptibility map was obtained for the purpose of this study, based on the geological groups, slope angles, and ground-water conditions of the study area. At both sided of the network a buffer polygon of fuve-hundred meters was considered. The slope angle map (Figure 2b) was generated by a digital elevation model of the studied area with a grid resolution of 20 m (SINAnet – ISPRA - http://www.mais.sinanet.isprambiente.it). For each lithological class, wet (considering groundwater table at ten meters of depth) or dry conditions were assigned. By overlying the slope angle, groundwater and lithology class maps, it was possible to draw a map of the landslide susceptibility which was finally transformed into the critical acceleration map, k_c, shown in Figure 3a, adopting the simplified method by Wilson and Keefer (1985). In each simulated earthquake, permanent displacements occur or not in a susceptible deposit, in those cases in which PGA_S exceeds k_c. In particular, to each susceptibility category, a percentage of map area having a landslide susceptible deposit, starting from the values proposed by Wieczoreck et al. (1985) is associated. Then, such values are used as probabilities of observing landsliding at a site, given that PGA_S at the site exceeds k_c (Weatherill et al. 2014). The resulting displacement induced by landslide is finally calculated via the Saygili and Rathje (2008) empirical model. Regarding the liquefaction potential map, in the liquefaction-prone areas, basing on the groundwater table depth, the presence and the thickness of wet sand soils and the historical liquefaction events, a liquefaction susceptibility degree

was assigned (moderate, high, and very high) according to HAZUS procedure (Figure 3b). Each liquefaction susceptibility category (SC) has associated site specific liquefaction coefficients, given in the HAZUS manual, and derived from the empirical models of Liao et al. (1988), as well as correction factors that depend on the groundwater depths and the magnitude of the event (see Seed and Idriss 1982, for more details). The likelihood that an earthquake will be able to initiate the phenomenon is then evaluated for each SC as a function of these site-specific coefficients and correction factors. Given that liquefaction occurs at a particular location, the amount of PGD (i.e., displacement) due to lateral spreading and due to settlement, are calculated following Seed and Idriss (1982) and Tokimatsu and Seed (1987), respectively.

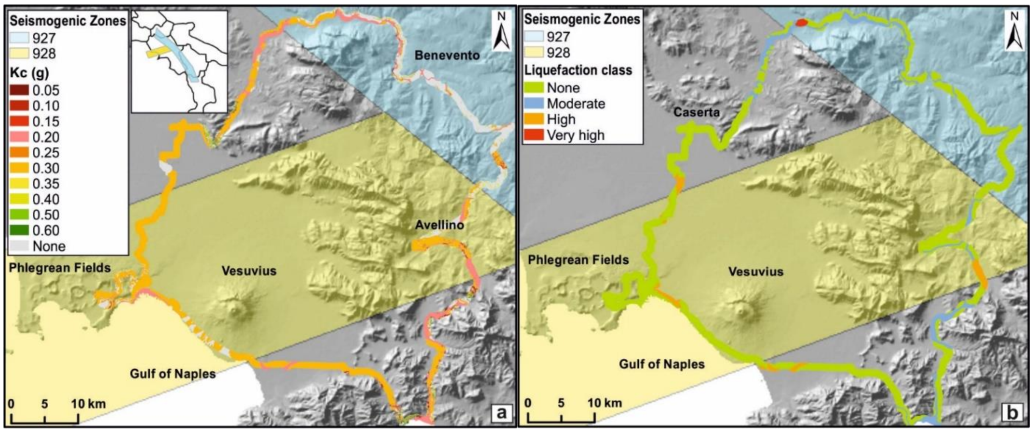

Figure 3. (a) Critical acceleration (k_c) map; (b) liquefaction susceptibility map

5.2 Damage Assessment

To estimate earthquake-induced damage in each simulation, IMs were related to system component damage via fragility models. To evaluate the seismic vulnerability of the nodes (i.e., POPs), a fault tree analysis was applied in order to identify which sub-component is critical with respect to seismic vulnerability. In this case, the functionality of the nodes depends on the seismic behavior of the building housing and on the response of the non-structural components; i.e., the racks. In particular, the complete loss of functionality of each POP (complete damage state; i.e., no data transmission) has been attributed to the building collapse (complete damage state) or sliding or overturning of the rack resulting in malfunction. The vulnerability of the rack has been characterized through the use of the fragility curves for acceleration-sensitive non-structural components developed by HAZUS (FEMA 2004) specific for each building class (see Table 1). In particular, the malfunctioning of the rack has been associated to the fragility curves developed by HAZUS for moderate damage state. The vulnerability of the building housing has been characterized through the use of lognormal fragility functions, in terms of PGA, available in literature as given in Table 1.

Table 1. Hazus (FEMA, 2004) class for the vulnerability characterization of the non-structural components (racks) characterizing each node of the network.

Description and coordinates	*Typology*	*Design*	*Rack Hazus Class*	*Damage state*	*Reference*
Univ. Naples Federico II [40.84, 14.19]	Reinforced Concrete (3-storey)	Moderate Code	C2L	Complet e	Tsionis et al. (2011)
Univ. Salerno [40.77, 14.79]	Reinforced Concrete (1-storey)	Moderate Code	C1L	Complet e	Tsionis et al. (2011)
Univ. Luigi Vanvitelli [41.06, 14.33]	Reinforced Concrete (3-storey)	Low Code	C3L	DS5	Kappos et al. (2003)
Univ. Sannio [41.13, 14,78]	Masonry (3-storey)	Pre-Code	URMM	DS5	Rota et al. (2008)

Regarding the optical fiber cables, expert-based (preliminary) vulnerability models have been adopted, because no models were found to be suitable for this study, and this represents a critical issue of this kind of studies. In particular, PGA_S and PGD were adopted as proxies to estimate the expected damages on the fiber cables that in past earthquakes were found to be relatively vulnerable in moderate-high seismic events and in case of triggering of liquefaction or landslides hazard (Alex Tang, American Society of Civil Engineers, *personal communication*). In particular, 10% of probability of failure of optical fibers, that corresponds to a total loss of functionality, is associated to two cases: (i) occurrence of permanent displacements induced by liquefaction or landslide or, (ii) peak ground acceleration values (at the site of interest), larger than a threshold value, which corresponds to the median value evaluated for each site through the Bommer et al. (2012) GMPE already mentioned, considering moderate-high magnitude and relatively close seismic events; i.e., $M = 6.6$ and source-to-site distance equal to 30 km.

5.3 Performance and risk assessment

The seismic performance of the network has been carried out in each run via a capacity analysis. To this aim the network (considered bi-directional) has been modeled as a graph characterized by a connectivity matrix and a traffic matrix. The traffic matrix contains the volumes of traffic exchanged by the nodes (per unit-time). The following figure shows the connectivity matrix and an example traffic matrix for a particular hour of the day.

	Napoli	Salerno	Benevento	Caserta
Napoli	1	1	0	1
Salerno	1	1	1	0
Benevento	0	1	1	1
Caserta	1	0	1	1

FROM \ TO	Napoli	Salerno	Benevento	Caserta
Napoli	0.7	0.1	0.1	0.1
Salerno	0.8	0	0.1	0.1
Benevento	0.8	0.1	0	0.1
Caserta	0.8	0.1	0.1	0

Figure 4. RIMIC connectivity (left) and traffic (right) matrices.

Each node is also connected with itself in the connectivity matrix. The traffic matrix adopted in this study is based on the following assumptions: nodes have equal behavior in terms of traffic in input and output to/from them with the only exception of the node in Naples that is also the gateway to the internet and therefore all the traffic will pass through it; each node sends 0.1 traffic units (TUs) towards the others and 0.7 TUs towards the internet (through Naples-POP); each node sends and receives no traffic towards itself, except Naples (i.e., traffic towards the internet). This matrix has been used as a baseline scaled according to the particular hour of the day. The sum of the sum of values the columns represents the total traffic delivered to destinations at a particular hour. After a seismic event, each link and node of the main loop is either considered still working or broken using the vulnerability models described above. The ratio of total traffic that cannot be delivered is then computed and saved; i.e., traffic lost, T_{lost} that is performance parameter. Doing this, it is implicitly assumed that all the links in the network are over-provisioned with respect to the traffic. This assumption is actually verified for the network under study because i) the links are all made of fiber optics with very high capacity (10/100Gpbs), and ii) the number of users is still low because the network has started working since few months. Moreover, it is also assumed that the failures can always be recovered through *physical-layer mechanisms* (as long as a fiber optics still exists between the nodes). In practice, there is no need to use the *network-layer mechanisms*.

6. RESULTS AND DISCUSSION

Five-thousands simulations (i.e., 5000 simulated earthquakes) were carried out to evaluate the statistics of the chosen PI $\left(T_{lost}\right)$. Figure 5 (left) shows the complementary cumulative distribution (CCDF) and relative frequency histograms of T_{lost}, given the occurrence of one event on one of the two seismic sources. Figure 5 (right) shows the annual rate , $\lambda_{TrafficLost}$, of exceedance of T_{lost}; it represents a measure of total seismic risk for the infrastructure. $\lambda_{TrafficLost}$ is obtained multiplying the CCDF of the chosen performance indicator, given the occurrence of one event, by the total annual rate of occurrence of earthquakes on the seismic sources. The given results are purely illustrative of the framework and require major efforts towards consolidation. This is mainly because of the lack of models for the seismic vulnerability assessment of the components of this kind of networks. The recognition of the need for such models should be considered the primary result of the study, which primarily aimed at a critical discussion of the strong multidisciplinary effort needed to carry out this kind of study in the framework of performance-based earthquake engineering.

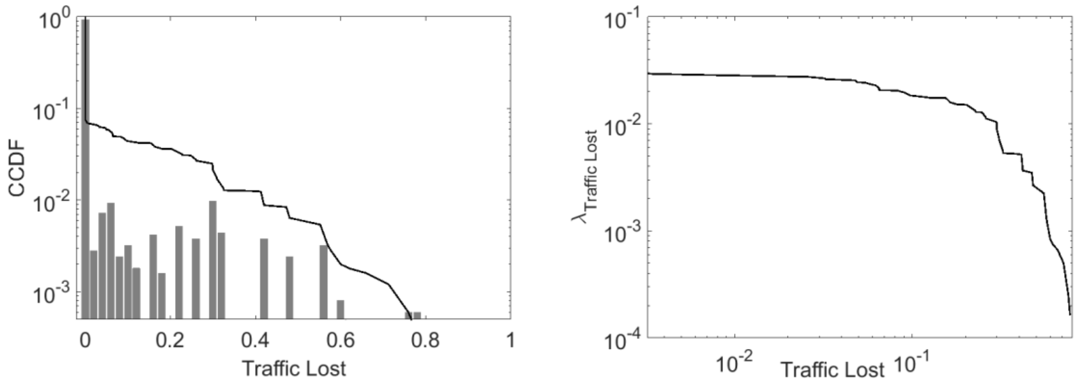

Figure 5. CCDF and frequency histogram (left) and annual rate of exceedance (right) of T_{lost}.

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