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SEISMIC PERFORMANCE OF A SYSTEM OF INTERDEPENDENT LIFELINE AND INFRASTRUCTURE COMPONENTS

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Abstract: The aim of this research is to develop a generic procedure for the assessment of the serviceability of a system (single system or system of systems) if one or more interacting components of the system are damaged by an earthquake. The system serviceability (functionality) is evaluated starting from the expected degree of damage of the single components (direct physical damage estimated using appropriate fragility functions) and accounting for their functional interaction (functional system architecture and single or by-directional interactions among components). Through the evaluation of the components' non-functionality, the overall serviceability of the system is assessed, possibly in the form of a "system serviceability curve", for different levels of seismic input intensity. Aleatory and epistemic uncertainties are treated using a Bayesian inference. The applicability of the proposed approach is established through an illustrative example. It is shown that the methodology is quite general and applicable to real systems with diverse degrees of complexity and knowledge of system and components details.

1. INTRODUCTION

In the framework of a comprehensive risk analysis and management of interacting lifeline and infrastructure systems, their seismic performance should be considered in a rigorous and unified way. This could only be achieved through the assessment of the systems' functionality, considering the complexity of structures and the interdependencies among systems and their components.

Several approaches are available to help describe the relations existing between system's components. Some of these are: Graph theory, Fault-tree analysis (FTA), Event-tree analysis (ETA), Series system in parallel (SSP), Agent-based models and Complex Adaptive Systems (Amin 2001, Little 2002, Brown et al. 2004, Bernhardt and McNeil 2004, Tolone et al. 2004). The probabilistic evaluation of the performance of the system (PNET) can be carried out employing the methods of System Reliability Analysis. These include expansion methods, such as FORM/SORM or the response surface technique (Ditlevsen and Madsen 1996), as well as the Monte Carlo simulation methods (Rubinstein 1981). Depending on the nature of uncertainty and the aptitude to determine them, the probabilistic approach may be replaced or enhanced by possibilistic approaches based on Fuzzy Logics, so-called Fuzzy Networks. Also, non-simulation methods have recently seen interesting advances, e.g. in the form of Matrix System Reliability Analysis (Song and Der Kiureghian 2003, Der Kiureghian and Song 2008).

Moving to a higher level, several researchers have proposed different types of interdependency (interactions between different critical infrastructures) simulation models (Kameda 2000, Giannini and Vanzi 2000, Rinaldi et al. 2001, Peerendoom et al. 2001, Amin 2001, Haimes and Jiang 2001, Little 2002, Li and He 2002, Tang et al. 2004, Yao et al. 2004, Brown et al. 2004, Bernhardt and McNeil 2004, Santos and Haimes 2004). Only few methodologies have incorporated interdependencies in the seismic risk analysis of lifelines (Nojima and Kameda 1991, Scawthorn 1992, Eidinger 1993, Shinozuka et al. 1993, Shinozuka and Tanaka 1996, Menoni 2001, Duenas-Osorio et al. 2007, Tang and Wen 2008).

Furthermore, very few studies can be found in the literature dealing with the highest level problem of multiple systems interaction in the case of seismic vulnerability and loss estimates (Duenas-Osorio et al. 2007, Kim et al. 2007). They have still an exploratory character and are based on rather extreme simplifications, being limited to the analysis of at most two systems. Network analysis and graph theory are usually adopted. The Bayesian approach is often used for network analysis. The systems' serviceability is also analyzed using flow or connectivity analysis. Some recent studies have been focused on the proposal of a methodology to evaluate the associated losses of interacting lifeline elements for various strong motion intensities and the estimation of complex fragility curves of interdependent components (Kakderi et al. 2007, Kakderi et al. 2008, Alexoudi et al. 2008a, b).

There is a need for the development of a rigorous methodology for the assessment of systems functionality, considering the complexity of structures and the interdependencies among systems and their components. The ultimate goal is the formulation of a system function that allows the evaluation of the state of the system as a function of the states of its components. The availability of such a function is a prerequisite for the evaluation of the system performance.

Herein, a generic procedure is developed for the assessment of the serviceability of a system, if one or more interacting components of the system are damaged by an earthquake. With the word system, we consider either a single system composed by many interacting components (e.g., one lifeline) or a system of systems (e.g., a set of lifelines and infrastructures), where interaction among components and systems are accounted for. The various types of uncertainties (aleatory and epistemic) are treated with the use a Bayesian inference.

The method introduces a formal and schematic way to account for several innovations in the systemic vulnerability field, such as, different levels of damages, their uncertain link to different levels of functionality, the uncertain configuration of each sub-system, the epistemic uncertainties related to each probability value, the summarization of single functionalities through a normalized performance index of the whole system. All these issues are developed in a generic and coherent framework. However, given the modularity of the methodology, each one of such innovations may be adapted to be applied as single module in the previously presented methodology. In any case, the proposed methodology is quite general and it is applicable, eventually with several further assumptions and/or simplifications, to real systems with diverse degrees of complexity and knowledge of system and components details.

2. SERVICEABILITY MODEL – UNCERTAINTIES AND INTERDEPENDENCIES

The modular procedure to assess the system serviceability proposed by Selva et al. (2011) is adopted. The procedure starts from the Physical Damages (PD) of each component of the system, as assessed through its specific fragility curves. Then, the PDs of all components are translated into their Physical Non-Functionality (PNF), that is, the impossibility of the component to provide its service (supply) to the other components of the system due to the experienced damages. Interactions among the functionality of the components, i.e., their interdependencies, are accounted for assessing the Actual Non-Functionality (ANF) of components and/or sub-systems, i.e., the impossibility to provide services not only because of physical damages (PNF), but also because of the lack of external supplies that are necessary to it. Note that the ANF can be referred to either single "physical" components or "sub-systems", for which a global ANF is modeled starting from the PNF of the "representative" components. Finally, the overall Serviceability of the System (Ss) is assessed, by analyzing the ANF of the "real components" and/or of the "representative sub-systems" that provide the system's final service(s).

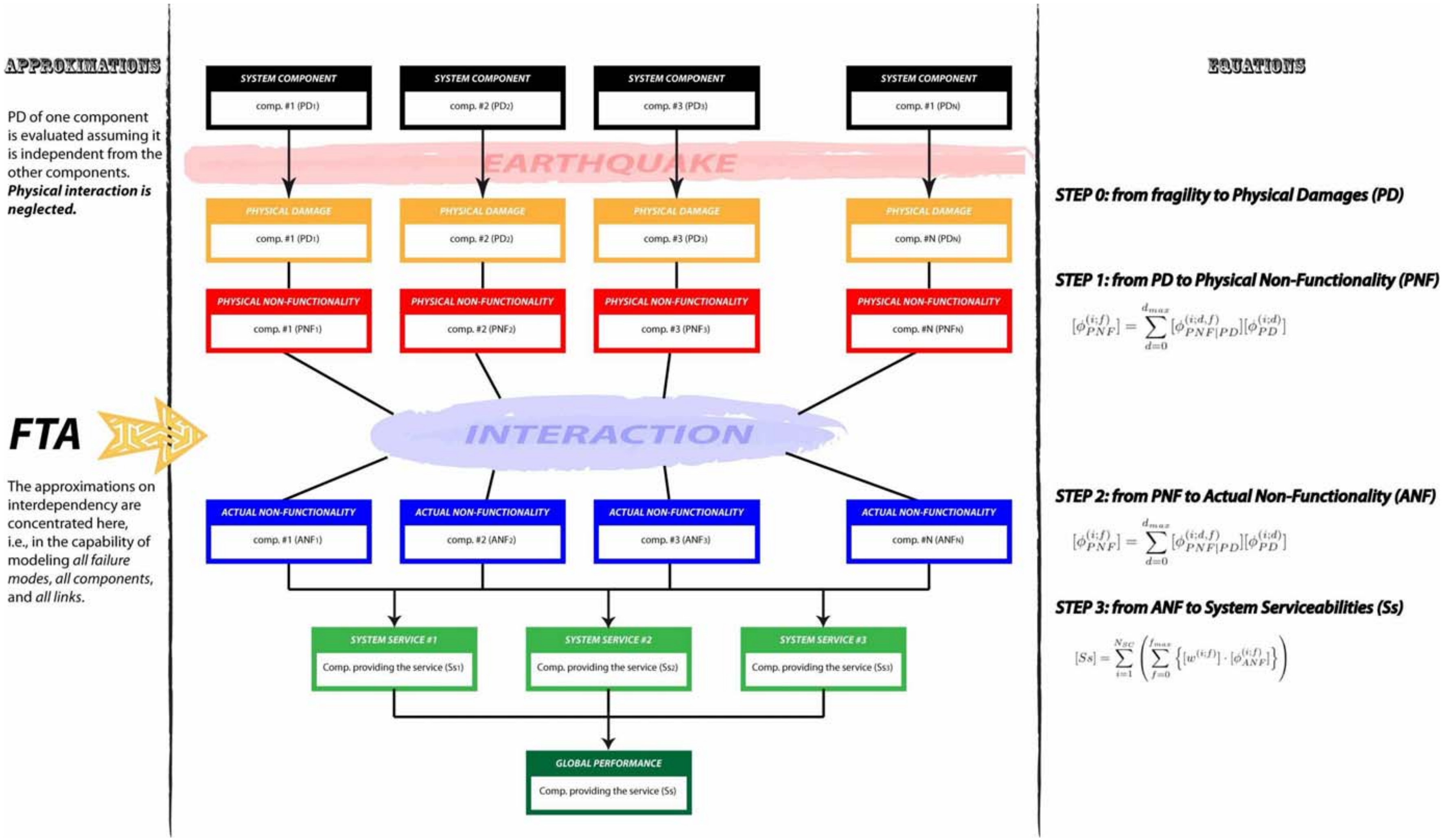
The procedure is schematically reported in Figure 1, and it can be summarized as following:

- STEP 0: FC (Fragility curve of a component) → PD (Physical Damages of the component).
- STEP 1: PD → PNF (Physical Non-Functionality of the component due to physical damages).
- STEP 2: PNFs → ANF (Actual Non-Functionality of a component or a sub-system, given the interaction among components).
- STEP 3: ANFs → Ss (overall Serviceability of a System).

The method aims at accounting for all the uncertainties involved in the serviceability assessment. In particular, it explicitly deals with (i) the epistemic uncertainties related to all probability assessments (e.g. Woo 1999), (ii) the uncertainties related to loss estimation and quantitative risk probability assessment [uncertainty related to seismic hazard, response and vulnerability of structures, probability of damage or collapse and the damage/ collapse to loss relationships (e.g. Spence 2007)], and (iii) the problems related to the partial knowledge of systems, in particular regarding missing components and/or links (e.g. Pitilakis et al. 2005). This goal is achieved by combining several strategies.

First, the process is schematized in several consequent events, making the model more readable (and testable) and allowing the use of conditional probabilities (Marzocchi et al. 2010, Grezio et al. 2009). Second, all parameters and values of the model (including probability estimations) are evaluated in a Bayesian perspective, that is, through probability density functions (pdf) (e.g. Gelman et al. 1995). All the probability density functions are then combined together by the extensive use of Monte Carlo simulations. Third, since several "sub-systems" (e.g., networks) cannot be completely known and/or change quickly through time, they are modeled starting from their general characteristics, without assuming specific configurations. In this case, groups of "representative" components are modeled jointly, so that the range of applicability of the method is by far increased, but also the sensibility of the results to missing or not known elements/ links is minimized.

Other important aspects of this model are the fact that it allows (i) to account for the interdependency among different components of the same system (e.g. Kakderi et al. 2007, Duenas-Osorio et al. 2007, Alexoudi et al. 2008 a or b) (ii) to assess and merge the different levels of both "physical damage" and "non-functionality" that each component may experience (Kim et al. 2007, Menoni et al. 2002), (iii) to circularly apply the procedure from single systems to higher level system of systems.



PD of one component is evaluated assuming it is independent from the other components. ***Physical interaction is neglected.***

The approximations on interdependency are concentrated here, i.e., in the capability of modeling *all failure modes*, *all components*, and *all links*.

STEP 0: from fragility to Physical Damages (PD)

STEP 1: from PD to Physical Non-Functionality (PNF)

$$[\phi_{PNF}^{(i;f)}] = \sum_{d=0}^{d_{max}} [\phi_{PNF|PD}^{(i;d,f)}][\phi_{PD}^{(i;d)}]$$

STEP 2: from PNF to Actual Non-Functionality (ANF)

$$[\phi_{PNF}^{(i;f)}] = \sum_{d=0}^{d_{max}} [\phi_{PNF|PD}^{(i;d,f)}][\phi_{PD}^{(i;d)}]$$

STEP 3: from ANF to System Serviceabilities (Ss)

$$[Ss] = \sum_{i=1}^{N_{SC}} \left(\sum_{f=0}^{f_{max}} \left\{ [w^{(i;f)}] \cdot [\phi_{ANF}^{(i;f)}] \right\} \right)$$

Figure 1. Framework of the proposed methodology (Selva et al. 2011).

3. ILLUSTRATIVE EXAMPLE

The goal of this application is to show a possible implementation of the model described above at various levels of seismic intensity, by considering the elements that contribute to provide service, accounting also for interaction with other infrastructure systems. Herein, two lifelines are examined, the water and electric power supply systems, with the final demand being the supply of potable water to the end users. The final serviceability is evaluated at two levels a) for all end users and b) for emergency use. The system is essentially divisible into three inter-dependent sub-systems: the electric power supply, the pumping and the pipe network sub-systems.

The whole system is assumed only partially known, and it is simulated through its main characteristics. The various sources of uncertainties are modeled following the Bayesian approach, so that all the uncertain parameters (including probabilities) are modeled through appropriate statistical distributions.

The seismic input is expressed in terms of PGA and it is made vary from 0 to 1 g. At each PGA level, the actual input for all elements is randomly sampled from a uniform distribution centered on the level and with a width 0.1 g. The analysis is then performed with 50 different sampled inputs, which simulate the variability of the seismic intensity at a local scale.

Three levels of application are performed, in order to capture all possible modes of inter and intra-dependencies and assess the altering mode of systems serviceability with an increasing level of induced interactions among components and systems. The three cases examined are the following:

Case 1: Water supply system comprised only of pipeline elements (study of interactions between the same components of one system). The Actual Non-Functionality (ANF) of the Pipeline Network (PN) depends only on its Physical Non-Functionality (PNF) (Figure 2A), as assessed through global properties of network (see below).

Case 2: Water supply system comprised of pipeline elements and one pumping station (study of interactions between different components in the same system). The Actual Non-Functionality (ANF) of the Pipeline Network (PN) depends on its PNF and the Actual Non-Functionality (ANF) of the Pumping Station (PST). In a row, the ANF of PST depends only on its PNF (Figure 2B).

Case 3: Water supply (pipelines and pumping station) and electric power system (electric substation) (study of interactions between systems). The Physical Non-Functionality (PNF) of the Pipeline Network (PN) depends on its PNF and the Actual Non-Functionality (ANF) of the Pumping Station (PST), as in Case 2. However, in this case the ANF of the PST depends on its PNF and the ANF of the Distribution Network (DS). Finally, the ANF of the DS depends on its PNF that depends on the PNF of the ETMS and a probability of transition that models the not perfect knowledge of the network (Figure 2C).

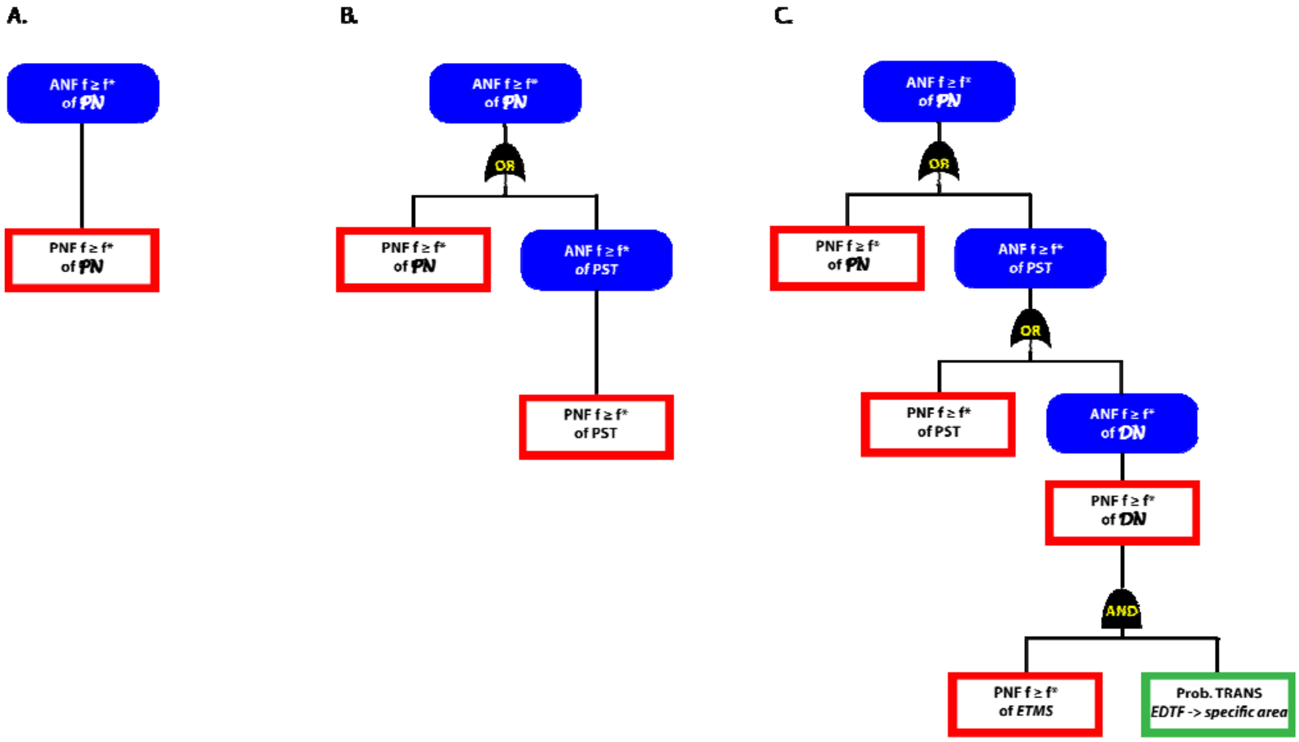


Figure 2. (A) FTA for Case 1 (water supply system- pipeline elements), (B) FTA for Case 2 (water supply system- pipeline elements and pumping station), and (C) FTA for Case 3 (water supply and electric power systems).

The Physical Non-Functionality of the Electric Substation (ETMS) and the Pumping Station (PST) is defined based on the 5 damage states fragility functions proposed in HAZUS (NIBS 2004) for medium voltage substations with anchored subcomponents and for medium /large pumping stations with anchored subcomponents respectively. A 5-d Dirichlet distribution is used to model the uncertainty with a quite high level of confidence (equivalent number of data Λ is set in both cases to 50). The best guess values at all degrees of functionality (f) for the Electric Substation and the Pumping Station are reported in Table 1. Since the Electric Substation (ETMS) is a representative element of the electric supply system (its non-functionality does not necessarily leads to the non-functionality the entire system) a "probability of transition" equal to 0.3 is considered in order to simulate the possibility that the failure of the ETMS is compensated by the rest of the network.

Table 1. Best guess values at all degrees of functionality (f) for the Electric Substation (ETMS) and the Pumping Station (PST).

	0 – complete functionality	1 - partial non-functionality	2 - complete non-functionality
0 (no damages)	1	0	0
1 (minor damages)	0.9	0.1	0
2 (moderate damages)	0	0.65	0.35
3 (extensive damages)	0	0	1
4 (complete damages)	0	0	1

The Pipeline Network sub-system (PN) is a complicated network of different types of pipe, subject to spatially varying seismic input. Their functionality is evaluated at the network level, instead of at the level of single elements based on the statistics of the Repair Rate per pipeline length (RR/km) of each one of the element. For the estimation of the RR/km, O'Rourke and Ayala fragility function is used as proposed in HAZUS (NIBS 2004) for wave propagation. A network composed by 1000 pipeline elements, nominally with a length of 30 m, with a total length of 30 km is considered herein. Each one of them is characterized by its RR/km and the population mean for the entire network (μ_r) is computed. The mean μ_r, normally distributed for central limit theorem, is then compared with appropriate values of the thresholds of μ_r (t_1 and t_2) separating the (non)-functionality states. In practice, the probability of complete functionality is the probability of $\mu_r<t_1$, the one of partial non-functionality the probability of $t_1<\mu_r<t_2$, and the one of complete non-functionality the probability of $\mu_r>t_2$. The thresholds are chosen according to the age and the connectivity degree of the system, the physical and the actual non-functionality of the network are estimated. The uncertainty is modeled using a 3-d Dirichlet distribution. For this application, a new and moderately connected network is considered. The uncertainty on thresholds t_1 and t_2 is modeled through uniform distribution, that is $t_1 \sim$ Unif (0.28, 0.33) and $t_2 \sim$ Unif (0.50, 0.55). By applying the method above, the means of the Dirichlet distribution of the Physical Non-Functionality (PNF) for the Pipeline Network are set, while Λ is subjectively set to 10 (quite low confidence).

Note that for the case of pipelines the seismic intensity to be considered is Peak Ground Velocity (PGV) which presents a better correlation with damages. Also, only ground shaking and not ground failure is examined. For simplicity, we assume uniform stiff soil conditions in the area and hence, PGV may be assessed starting from PGA using simplified empirical relationships (Seed and Idriss 1982). Each sampled PGA_i is translated in terms of PGV_i through an empirical linear relationship. The constant of proportionality is chosen for stiff soils, and it is sampled from a uniform distribution between 90 and 190 cm/sec (due to the variability on source magnitude M_w from 6.5 to 8.5 and source-site distance from 0 to 100 km) to simulate the uncertainties. Also, for reasons of simplicity, PGA values (and thus PGV) are treated as completely spatially uncorrelated. In real applications however, some level of correlation should be taken into consideration, as well as the dependence of the spatial variability of PGV on the specific site effects, which in turn, will be also influenced by the seismic magnitude, source and azimuth effects. However, the correlation given by spatial proximity cannot affect the results since we do not assume any specific spatial configuration for the sub-system.

4. RESULTS

The Physical Non-Functionality (PNF) and the Actual Non-Functionality (ANF) of the three sub-systems, Electric Substation (ETMS), Pumping Station (PST) and Pipeline Network (PN) are presented in Figure 3 for Case 1 (PN independent), Case 2 (PN dependent on PST) and Case 3 (PN dependent on both PST and ETMS). The results of all the elements are given at all PGA levels (0-1.0 g). For Case 1 and for the Pipeline Network the Physical and Actual Non-Functionality are plotted in respect to PGV values, to facilitate the critical consideration of the results also in respect to available fragility relations and real earthquake damage records. By comparing out the Physical Non-Functionality (PNF, dots) and the Actual Non-Functionality (ANF, continuous lines) curves the effect of interaction on each component of the system becomes evident. If, for one component, the PNF and ANF are not significantly different, the component is substantially independent from the other ones, since its functionality depends essentially only on its physical state. On the contrary, great differences in PNF and ANF indicate strong levels of interdependency.

The model seems to capture well the anticipated behavior of the system for all three cases. In case of the independent Pipeline Network (Case 1) the probability of Physical Non-Functionality for both the Electric Substation

(ETMS) and the Pumping Station (PST) seems to increase with PGA, but the probability of Actual Non-Functionality to the supply of water (final system service) is zero since the two systems are not connected with the Pipeline Network considered as the final supply point to the end users. The same is true for the ETMS in Case 2. Another observation is that both the Pumping Station (PST) in Case 2 and the Electric Substation (ETMS) in Case 3 are completely independent from the other elements, i.e., their PNF and ANF are equal.

The effect of interaction is obvious in the alteration of the Actual Non-Functionality of the dependent sub-systems in Cases 2 and 3. The complete non- functionality state seems to be more affected compared to partial non-functionality. The effect of the interaction between the Pumping Station (PST) and the Pipeline Network (PN) is more predominant compared to the interaction with the Electric Substation (ETMS) and always in respect to the level of final supply of water. This could be attributed to the quite “soft” connection assumed between the ETMS and PST with the “probability of transition” equal to 0.3.

Finally, the effect of interaction is obvious in the functionality curves of the final supply point, i.e. the Pipeline Network (PN). Moving from Case 1 to 3 with increasing level of interaction, the functionality curves become more spread (less steep) and move towards greater values of seismic intensity. Even for the case of independent network (Case 1) the probability of both states of non-functionality (partial and complete) seem to be in line with existing fragility functions and experience from past earthquakes. For example given a PGV equal to 80-90 cm/sec, the probability of complete non-functionality is almost 100%, while for PGV values around 60 cm/sec, the partial non- functionality of the network is almost certain. The quite steep shape of the functionality curves of the Pipeline Network (PN) could be attributed to the very stable average RR/km with very small errors. This sudden change in functionality for the PN can be understood when plotting the average RR/km, as a function of both PGA and PGV (Figure 4 for Case 1).

In Figure 5, the results regarding the serviceability of the system are reported. In particular, the probability of serviceability of the system for end-users and emergency operators are reported along with the respective realizations of serviceability. The determinant role of the Pumping Station (PST) is thus identified; a fact of major importance in possible future risk management and mitigation studies.

5. CONCLUSIONS

A generic, modular procedure for the assessment of the serviceability of a system (a single system or a system of systems), if one or more interacting components of the system are damaged by an earthquake is developed. The serviceability (functionality) of each single system, as well as of the entire system of systems, is evaluated, starting from the expected degree of damage (physical damage) of the single components and accounting for their functional interaction. The serviceability is then expressed as the expected (normalized) performance of the system(s) in terms of the service provided to final user(s).

The proposed methodology is quite general and it is developed in a way in order to be applicable to real systems with diverse degrees of complexity and knowledge of system and components details (engineering sound simplifications and assumptions are always necessary). This is established through an illustrative example given for 3 different cases: a single system comprised of the same components (Pipeline Network; Case 1); a simple system (water system) composed by two main interacting components (Pipeline Network and Pumping Station; Case 2) and a system of systems which includes two main water system components (Pipeline Network, Pumping Station) that interact with a main component (Electric Substation) of another lifeline (electric power system). The method presented briefly herein, through the three representative illustrative examples, gives the basis to account for the interdependency among different components of the same system, to assess and merge the different levels of both “physical damage” and “non-functionality” that each component may experience and to circularly apply the procedure from single systems to higher-level system of systems, accounting for the significant uncertainties at each of these steps. The analysis of (aleatory and epistemic) uncertainties plays a central role in the developed methodology, allowing a full treatment of the different sources of uncertainty.

The proposed approach can straightforwardly be applicable to any set of interacting systems, as for example modern urban regions, where the existence of strong dependence between lifeline systems and infrastructures makes the assessment of their functionality a very challenging issue. The quite high level of complexity inherent in such cases can be encountered for, providing not exactly “precise” but, what is most important, “reliable” and “accurate” estimates of the system(s) serviceability after the occurrence of earthquakes with variable levels of seismic intensity. On the other hand, the identification of the more uncertain steps allows concentrating future research efforts on these specific topics.

Incorporating infrastructure dependences in the analysis of post-seismic serviceability of complex systems can lead to a more rigorous assessment of lifeline seismic vulnerability and system reliability. Finally the identification of possible weak points and/or components/ systems with larger influence on the whole performance of the integrated “urban lifeline network”, also allows the definition and implementation of effective risk mitigation actions.

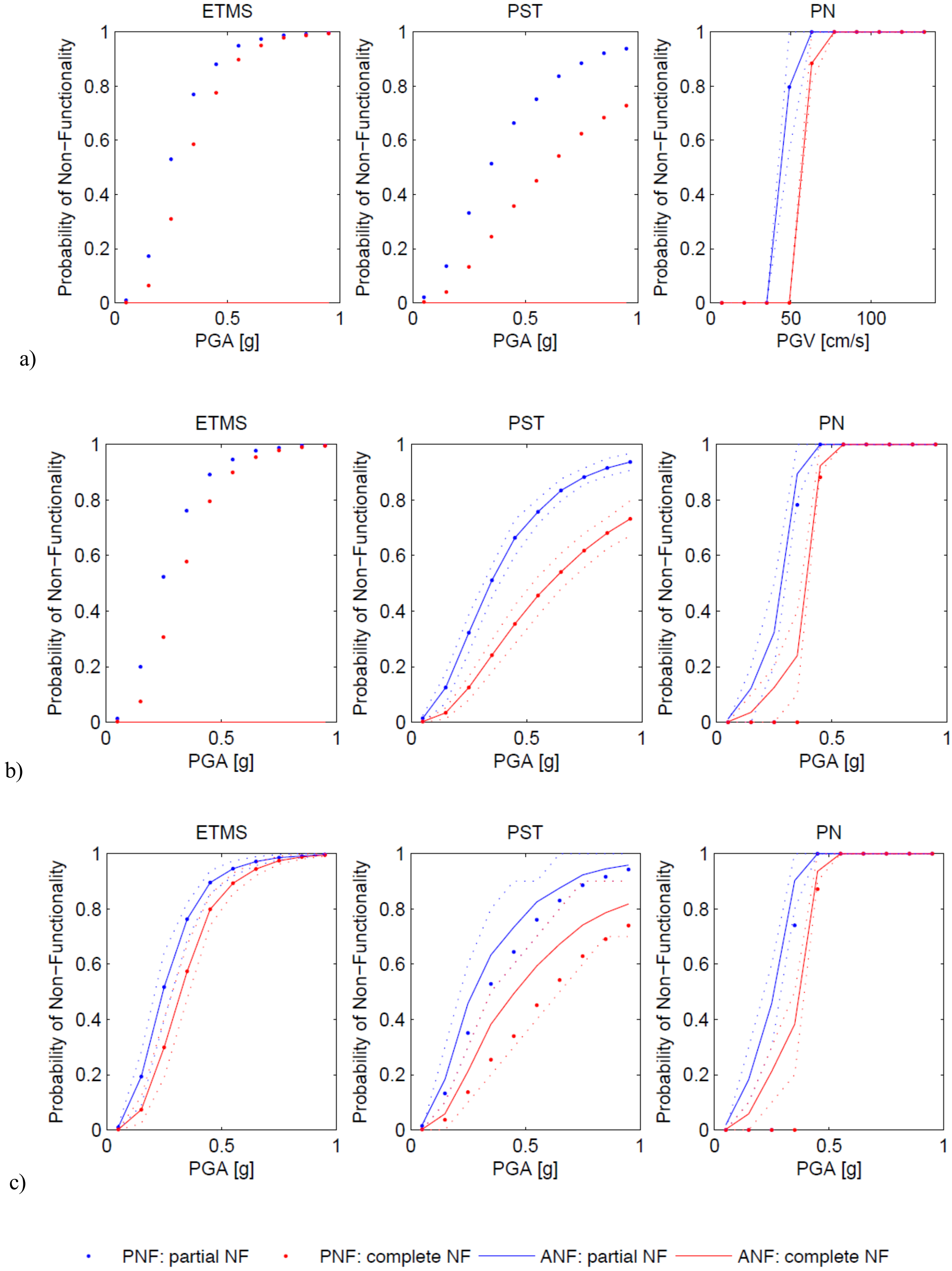


Figure 3. Physical Non-Functionality (PNF), illustrated with dots, and Actual Non-Functionality (ANF), illustrated with lines, for the Electric Substation (ETMS), Pumping Station (PST) and Pipeline Network (PN) and for the three Cases; a) Case 1/ PN independent, b) Case 2/ PN dependent on PST and c) Case 3/ PN dependent on both PST and ETMS. In blue is reported the partial functionality degree (f = 1)) and in red the complete non-functionality degree (f = 2).

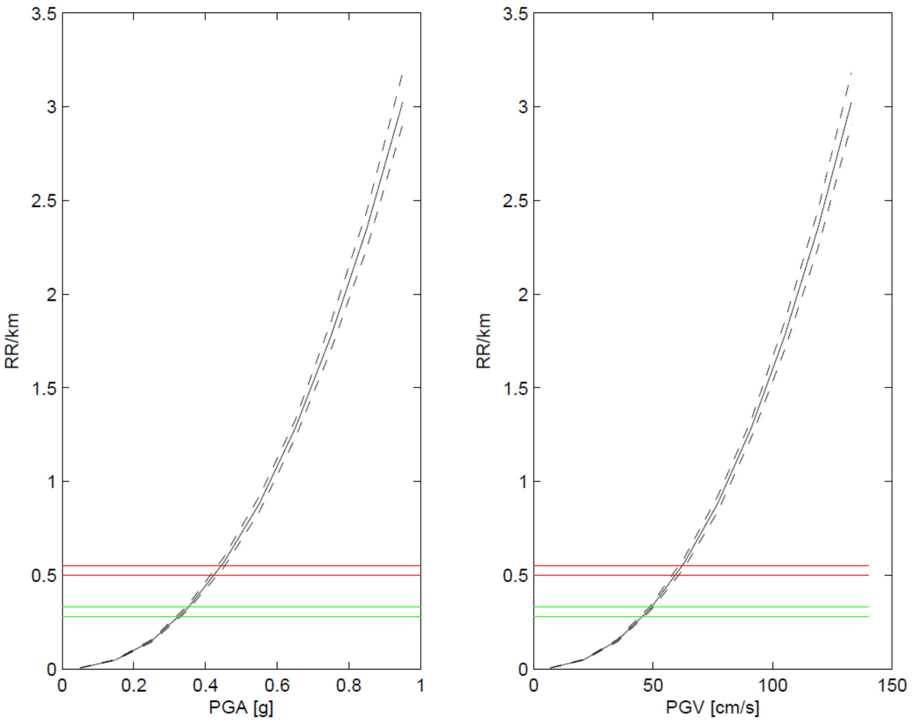
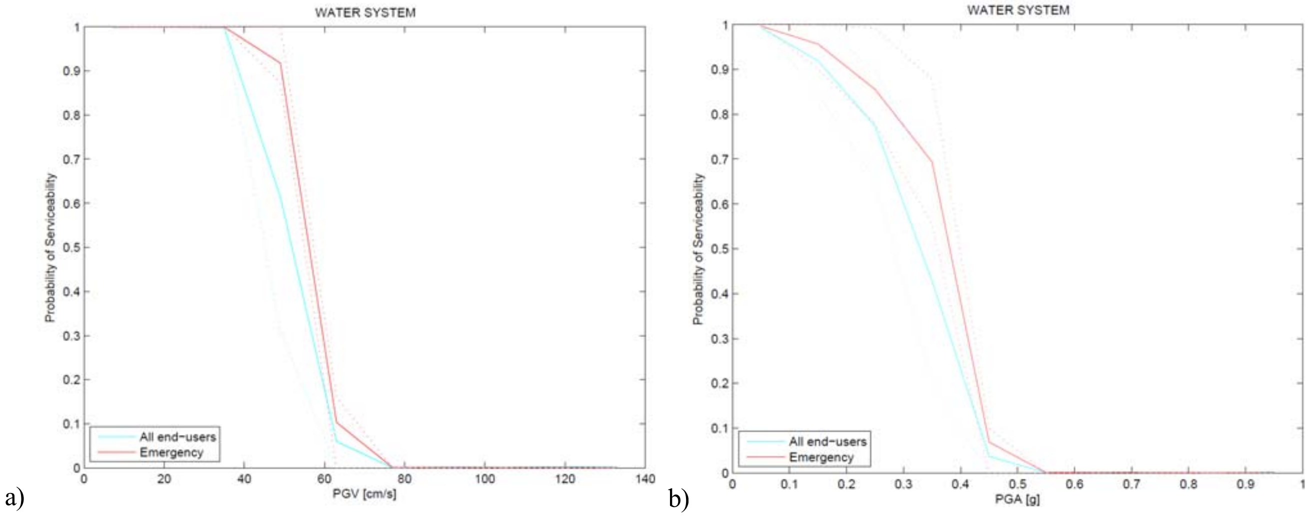
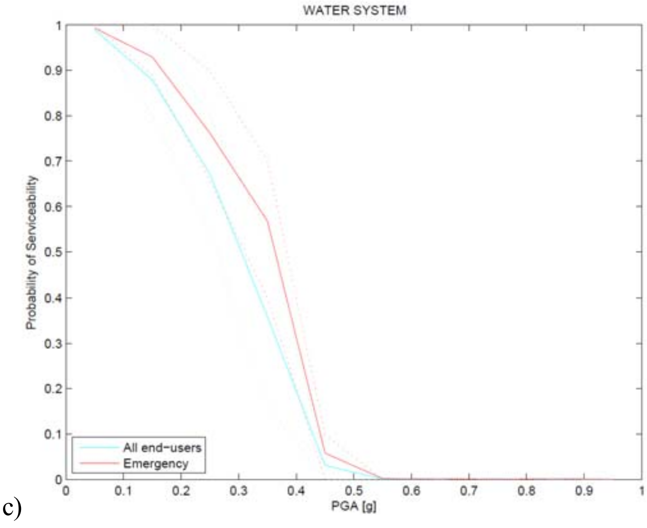


Figure 4. Average Repair Rate/km (RR/km) as a function of both PGA and PGV for Case 1(Pipeline Network independent).



a)

b)



c)

Figure 5. System Serviceability S_s for all end-users (blue) and emergency uses (red) for the three Cases; a) Case 1/ PN independent, b) Case 2/ PN dependent on PST and c) Case 3/ PN dependent on both PST and ETMS.

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