4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1578

SEISMIC RISK ANALYSIS OF INTERDEPENDENT LIFELINE SYSTEMS

Kalliopi KAKDERI [1], Maria ALEXOUDI[2] and Kyriazis PITILAKIS[3]

ABSTRACT

Lifeline systems' co and post seismic performance and functionality are controlled by the vulnerability and intraconnectedness of their elements, while various components have a different response for a given level of earthquake intensity. Furthermore, interconnectedness with other external systems may have an equally important role in the global seismic performance. Herein, the main objective is the estimation of the expected seismic performance of infrastructure elements through a probabilistic approach taking into account their interactions with other lifeline systems. A method is proposed based on the use of adequate interdependency indices between lifeline systems. They are evaluated using an "input-output model", which comprises a linear, deterministic, equilibrium approach and an adequate framework describing the degree of interconnectedness. The notion of propagated inoperability and systemic vulnerability or "vulnerability of interdependent elements" is introduced. Fragility curves of the interdependent components are estimated based on vulnerability functions of independent elements and the propagated inoperability matrix. The applicability of the proposed methodology is illustrated using an explanatory example.

Keywords: seismic risk, lifeline interactions, interdependency indices, Input-Output model, vulnerability analysis.

INTRODUCTION

Risk assessment of lifeline systems is a very complex and challenging issue. Each system's co and post seismic performance and functionality are determined by the seismic hazard, vulnerability and intraconnectedness of its elements, and interconnectedness with other lifeline systems. Incorporating infrastructure dependences can lead to a more rigorous assessment of lifeline seismic vulnerability, system reliability and risk mitigation actions.

However, little research has been made so far; interactions between different critical infrastructures which may seriously affect the seismic risk management (response, recovery and mitigation) are only beginning to emerge in lifeline engineering. Several researchers have proposed different types of interdependency simulation models (Wong and Isenberg 1995, Kameda 2000, Giannini and Vanzi 2000, Rinaldi et al. 2001, Peerenboom 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 & McNeil 2004, Santos and Haimes 2004). Only few methodologies have incorporated interdependencies in the seismic risk analysis of lifelines (Hoshiya and Ohno, 1985, Nojima and Kameda, 1991, Scawthorn, 1992, Eidinger, 1993, Shinozuka et al., 1993, Shinozuka and Tanaka, 1996, Menoni, 2001, Dueñas-Osorio 2006).

[1] Civil Engineer, MSc, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece. Email : kakderi@civil.auth.gr
[2] Civil Engineer, MSc, PhD, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece. Email: alexoudi@civil.auth.gr
[3] Professor, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece Email: kpitilak@civil.auth.gr

There is a need for comprehensive simulation frameworks that allow the coupling of multiple interdependent infrastructures in order to improve the seismic risk management.

Seismic risk (S.R.) of interdependent lifeline systems is given as following:

$$\{S.R.interdependent\}=\{S.R.independent\}*\{Interaction\ function\} \quad (1)$$

The risk of failure or deviation from normal operating conditions in one infrastructure (or part of it) can affect the risk in another infrastructure if the two are interdependent. In case of an earthquake event, malfunction of a system's components can result in cascading effects within the same system and other connected systems. The nature of the identified interactions as well as the degree of interconnectedness (type and degree of coupling) is the determinant of the interdependent systems' seismic behavior. To define interaction function different approaches can be used: economic, fuzzy logic, decision making approaches or composite approaches. The economic approach is selected herein as being more suitable in practice. Adequate interdependency indices can be estimated to measure the degree of connection between different lifelines and resulted perturbations to one system from induced malfunctions to the other. The concept of systemic vulnerability or "vulnerability of interdependent elements" is introduced through the definition of a propagated inoperability matrix and a methodology is proposed for the vulnerability assessment of interdependent systems using "interdependent" fragility curves. The latter are derived based on the use of independent components' fragility curves and adequate inoperability matrices. The importance of each lifeline component is assigned through adequate weight coefficients. The proposed methodology is illustrated in figure 1.

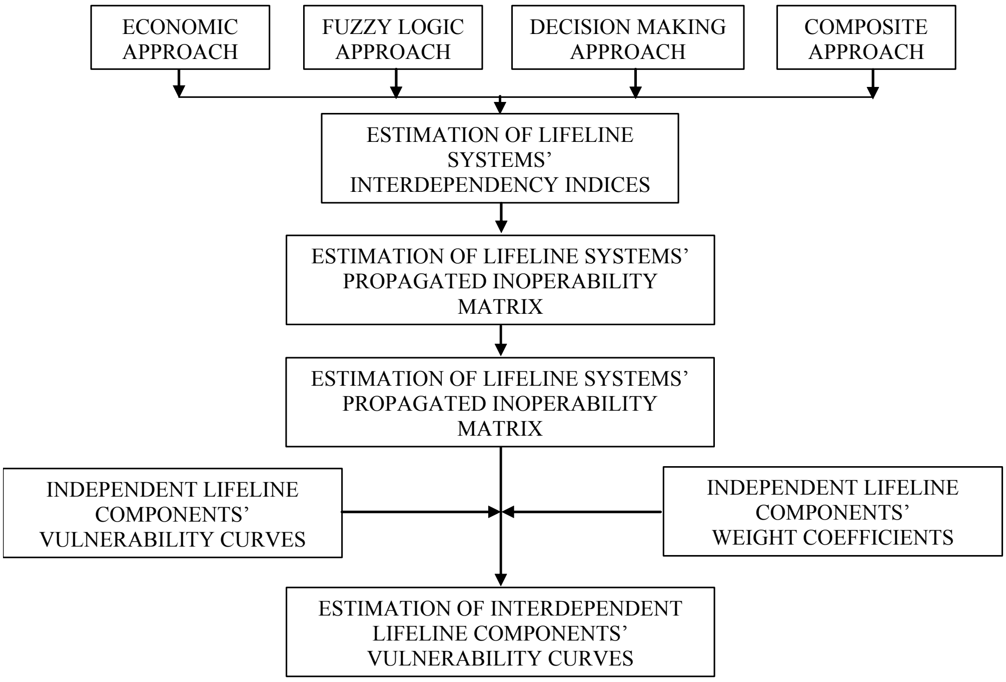

Figure 1. Flowchart of the proposed methodology

INTERACTIONS BETWEEN LIFELINE SYSTEMS

Lifelines are highly intra-dependent and inter-dependent systems, showing a great degree of coupling between sub-components of the same system and with other infrastructures. These dependences among different lifeline systems and also with other essential facilities are very important for the global seismic risk management in a city scale. An efficient seismic vulnerability analysis, rescue policy and an optimum recovery strategy require the evaluation of the interactions between different lifeline systems.

A representative case of interactions among different lifeline systems during the restoration period is reported after the 1995 Kobe earthquake by Hada and Meguro (2000). They outlined the problems in the restoration activities of water and gas network in Kobe area due to traffic congestion, street blockades, damaged buildings and water flowed into gas pipelines; they also analyzed their effects based on real data.

Dependencies between lifelines vary in different periods prior, during and after the occurrence of a seismic event (normal system operations, emergency operations, repair and recovery operations). Different types of interactions between critical infrastructures can be identified and classified for the pre, co-seismic and post seismic period. Table 1 provides an example of interaction features among lifeline systems during the crisis period.

Table 1. Indicative example of interactions between lifeline systems - Crisis period

	EPS	WS	WWS	TS	NG/LF	RW/RL
EPS	equipment operation, centralized control system, cascading failure effects, emergency back-up power	pumps, valves/ equipment operation, centralized control system, fire suppression damage due to water pipe leakage/ break, emergency back-up power	pumps, valves/ equipment operation, centralized control system, damage due to waste-water pipe leakage/ break, emergency back-up power	telecommunication building and equipment, SCADA, centralized control system, central cooling system, emergency back-up power	valves operation, centralized control system, damage due to gas pipe leakage/ break, fire ignition	illumination, centralized control system, rail operation, damage due to (rail)road/ bridge/ roadbed/ pavement failure, emergency back-up power
WS		pumping stations central cooling system, fire suppression damage due to water pipe leakage/ break	fire suppression pollution due to waste-water pipe leakage/ break, damage due to water pipe break, damage due to waste-water leakage/ break	SCADA, cooling system, fire suppression, damage due to water pipe leakage/ break	fire suppression damage due to water pipe leakage/ break, damage due to gas pipe leakage/ break, fire ignition	fire suppression, settlement due to water pipe leakage/ break, damage due to (rail)road/ bridge/ roadbed/ pavement failure
WWS			pollution due to waste-water pipe leakage/ break	SCADA, damage due to waste-water pipe leakage/ break	damage due to waste-water pipe leakage/ break, damage due to gas pipe leakage/ break, fire ignition	settlement due to waste-water pipe leakage/ break, damage due to (rail)road/ bridge/ roadbed/ pavement failure
TS				communication equipment operation, centralized control system	damage due to gas pipe leakage/ break, fire ignition	centralized control system, damage due to (rail)road/ bridge/ roadbed/ pavement failure
NG/ LF		SYMMETRIC TABLE			damage due to gas pipe leakage/ break, fire ignition, cascading effects from failures of liquid fuels/ tanks	damage due to gas/fuel pipe leakage/ break, fire ignition, cascading effects from (rail)road/ bridge/ roadbed/ pavement failures
RW/ RL						cargo/ people transfer, damage due to (rail)road/ bridge/ roadbed/ pavement failure

- EPS: Electric Power System, WS: Water System, WWS: Waste Water System, TS: Telecommunication System, NG/LF: Natural Gas & Liquid Fuels, RW/RL: Roadway/ Railway

LIFELINE INTERDEPENDENCY INDICES BASED ON AN "INPUT-OUTPUT MODEL"

Modelling of interconnectedness can be achieved by modelling the way that "inoperability" propagates throughout the critical infrastructure systems. For this purpose, the inoperability Input-Output Model (IIM) is introduced based on the input-output (I-O) model for economics, for which Wassily Leontief won a Nobel prize in economics in 1973. In the case of lifelines initially the model is developed in the form of a physical-based model (Haimes and Jiang 2001, Jiang 2003, Jiang and Haimes 2004) and later as a demand reduction model (Santos and Haimes 2004, Haimes et al., 2005 a and b). The above models are mostly developed to assess the impacts of wilful attacks (e.g., terrorism) on interdependent sectors. Their application can be extended to other natural hazards, like earthquakes.

Input-Output model comprises a linear, deterministic, equilibrium approach and a framework capable to describe the degree of interconnectedness. It is generally constructed from observed economic data for a specific geographic region. Basic input data refer to the flows of products between economic sectors. These inter-sector flows are measured for a particular time period and in monetary terms. The model's basic parameters are:

- The input of sector i to the production of sector j (intermediate consumption) denoted by x_{ij}.
- The proportion of sector i's input to j, with respect to total production requirements of sector j. It is referred to as the Leontief technical coefficient and is denoted by α_{ij}.
- The final demand (or final consumption) for the i^{th} sector – the portion of sector i's total output for final consumption by end-users, denoted by ci.
- The total output of sector i, denoted by X_i.
- The amount of the i^{th} sector (resource) input in the production of the j^{th} commodity (goods) denoted by r_{ij}. Total inputs are referred to as value-added.
- The total supply of the i^{th} sector input r_i.

These parameters are recorded in tables (Input-Output tables) which are the core of the I-O analysis. Table 2 illustrates the form of an Input-Output table.

Table 2. Form of Input-Output table

		SECTORS				FINAL DEMAND	TOTAL OUTPUT
		1	2	…	n		
SECTORS	1	x_{11}	x_{12}	…	x_{1n}	c_1	X_1
	2	x_{21}	x_{22}	…	x_{2n}	c_2	X_2
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	n	x_{n1}	x_{n2}	…	x_{nn}	c_n	X_n
VALUE ADDED		z_1	z_2	…	z_n		
TOTAL SUPPLY		r_1	r_2	…	r_n		

A group of n interacting sectors is assumed, where each "sector" produces one commodity. Coefficients are considered to be constant for a fixed unit of time (static, equilibrium-competitive system). In its most basic form, the I-O model consists of a system of linear equations, each one of which describes the distribution of a sector's production throughout the economy. The following balance equation is introduced:

$$X = Ax + c \Leftrightarrow \left\{ X_i = \sum_j a_{ij} x_j + c_i \right\} \forall i \qquad (2)$$

where i,j = 1,2,………,n are the system's interacting sectors, X is the total output matrix, c is the final demand matrix and A is the technical coefficient matrix.

The proportionality assumption also applies to the resources:

$$r_{ij} = b_{ij} x_j \qquad (3)$$

$$\sum r_{ij} = \sum b_{ij} x_j \qquad (4)$$

where r_{ij} is the amount of the i^{th} sector (resource) input in the production of the j^{th} commodity (goods).

Finally, since the demand for the i^{th} resource cannot exceed its supply (r_i), the following condition must stand:

$$\sum b_{ij} x_j \le r_i, \; r_i \ge 0, \; i=1, 2, \ldots, n \qquad (5)$$

The technical coefficient matrix A can be derived from intermediate sectors' consumptions x_{ij} and is the key to account for inter-sectoral linkages.

Making the basic assumption that the level of economic dependency is the same as the level of physical dependency, the original Leontief model can be used to specify systems' interactions and quantify the degree of coupling. A different interpretation of the model parameters adequate for lifeline systems is incorporated as follows:

- The interacting sectors i=1, 2, …., n are different lifeline systems.
- The c and X matrices represent lifeline commodities measured in monetary terms. In detail:
- x_{ij} is the input commodity (in monetary terms) of lifeline system i to the production of the commodity of lifeline system j (intermediate consumption).
- X_i is the total output commodity (in monetary terms) of lifeline system i.
- ci is the final demand (or final consumption) for the i^{th} lifeline system – the portion of the total commodity output (in monetary terms) of lifeline system i for final consumption by end-users.
- r_{ij} is the amount of the i^{th} lifeline system (resource) input commodity in the production of the j^{th} commodity. Total inputs are referred to as value-added.
- r_i is the total supply of the i^{th} lifeline system input commodity.
- The A matrix describes the degree of dependence between infrastructures and it is determined on the basis of the physical connections that exist among infrastructures. α_{ij} is the proportion of the commodity input of lifeline system i to j, with respect to total production requirements of lifeline system j. It is referred to as the Leontief technical coefficient.

Finally, the interdependency matrix A* is introduced, that indicates the degree of coupling between the different infrastructures. It is given from the following equation:

$$A^* = \left[diag(X)\right]^{-1} \cdot \left[A\right] \cdot \left[diag(X)\right],\ a^*_{ij} = a_{ij}\left(\frac{X_j}{X_i}\right) \tag{6}$$

Estimated interdependency indices vary between 0 and 1, with higher values referring to higher degree of interconnectedness.

DEFINITION OF LIFELINE PROPAGATED INOPERABILITY MATRIX

In general, inoperability is defined as the inability of the system to perform its intended natural or engineered functions. It is often expressed as a percentage of the system's "as-planned" level of operation. Alternatively, inoperability can be interpreted as a degradation of a system's capacity to deliver its intended output (or supply) due to internal failures or external perturbations.

In the framework of lifeline dependencies simulation, the inoperability transferred from one system in another due to the existence of multiple unilateral and/or bilateral connections is considered. It is assumed to be a constant variable evaluated between 0 and 1. Independent systems' seismic performance is contingent on the system's specific characteristics and the level of induced seismic input motion; thus the propagated inoperability among infrastructures is zero. In case of interacting systems, the propagated inoperability is assumed to be proportional to the degree of their interconnectedness. In other words, infrastructure interdependencies are projected into propagated inoperability matrices $I=[i_{ij}]$, where the coefficient i_{ij} depicts the probability of inoperability that failure in the i^{th} infrastructure component triggers in the j^{th} infrastructure component.

The propagated inoperability matrix I is assumed to be given form the following equation:

$$I = \lfloor i_{ij} \rfloor, \quad i_{ij} = \begin{cases} a^*_{ij}, i \neq j \\ 1, i = j \end{cases} \tag{7}$$

where,

$i_{ij}, i \neq j$ is the propagated inoperability coefficient due to the interdependency between the ith and jth infrastructure systems. It is assumed to be equal to the interdependency coefficient a_{ij}^{*}.

$i_{ij}, i = j$, is the propagated inoperability coefficient due to the intradependency between the ith infrastructure system. It is assumed to be to be equal to 1.

The performance and functionality of a network is conditioned on the state of additional interacting networks. Using adequate I matrices, the seismic risk assessment of interdependent critical infrastructures can be performed. It should be noted though that only first order interdependencies (direct dependent effects) are simulated.

ESTIMATION OF COMPOSITE – "INTERDEPENDENT" FRAGILITY CURVES

The vulnerability of a system of interacting lifeline elements depends on the vulnerability of the individual components, the way in which the components are connected and the degree of their interdependency. The fragility of the system can differ significantly from the fragilities of its components. The concept of systemic vulnerability or "vulnerability of interdependent elements" is introduced to evaluate the system fragility in addition to the individual component fragilities. It refers to how prone a system is to be damaged or to fail not only as a consequence of some kind of physical rupture occurring to one of its components, but additionally as the indirect effect of some physical, organizational or functional failure suffered by other lifeline systems.

Fragility curves are a measure of performance in probabilistic terms (Shinozuka et al., 2000). They are described in terms of the probability of exceeding, in an independent lifeline component, a specific limit state as a function of ground motion intensity. In the traditional fragility curve approach, each system's element is examined as an individual component with no interaction between sub-components of the same system or/and other external infrastructures. The anticipated seismic performance is assigned in a probabilistic manner based on statistical, analytical or composite functions. Intra-dependency of a system can be assigned through network analysis. Herein, the main objective is the estimation of the expected seismic performance of infrastructure elements taking into account their interactions with other lifeline systems. Thus, fragility curves of the interdependent components are estimated based on vulnerability functions of independent elements and the propagated inoperability matrix I.

In the current literature fragility curves can be described by (cumulative) lognormal distribution functions defined by a median value and a standard deviation β. Assuming a lognormal distribution [common assumption in fragility studies, including HAZUS (NIBS, 2004)], the conditional probability of being or exceeding, a particular damage state ds_i, given the peak ground acceleration (PGA) is defined by the relationship:

$$P[ds \geq ds_i / PGA] = \Phi\left[\frac{1}{\beta_{ds_i}} \ln\left(\frac{PGA}{\overline{PGA}, ds_i}\right)\right] \quad (8)$$

where,
$\overline{PGA}, ds_i$ is the median value of peak ground acceleration at which the component reaches the threshold of damage state ds_i,
β_{ds_i} is the standard deviation of the natural logarithm of peak ground acceleration for damage state, ds_i,
and Φ is the standard normal cumulative distribution function.

The discrete probabilities of being in each damage state are calculated at each PGA level a as follows:

$$dpa_i = \begin{cases} cp_i & \text{, i=complete damages} \\ cp_{i-1} & \text{, i=extensive, moderate, minor damages} \\ 1 - cp_{i-1} & \text{, i=no damages} \end{cases} \quad (9)$$

where dp_a is the discrete probability at PGA level a, i = is the respective damage state and j = the examined infrastructure's component.

A network of m interacting infrastructure components is assumed, each one of them being a part of different interacting lifeline systems. The discrete probability matrix accounting for the interdependency between individual infrastructure components at each damage state and for the assumed PGA level a, is given as:

$$DP_{ai}^* = diag(DP_{ai}) \cdot I^* \quad (10)$$

where I^* is the propagated inoperability matrix of the m infrastructure components defined as:

$$I^* = [i_{ij}^*], \quad i_{ij}^* = \begin{cases} w_i \cdot a_{ij}^*, i \neq j \\ 1, i = j \end{cases} \quad (11)$$

and

$$diag(DP_{ai}) = \begin{bmatrix} dpa_{i,1} & 0 & . & 0 \\ 0 & dpa_{i,2} & . & 0 \\ . & . & . & . \\ 0 & 0 & . & dpa_{i,m} \end{bmatrix} \text{ for j=1, …., m} \quad (12)$$

A set of weight coefficients w_i can be estimated for the sub-components constituting a lifeline system based on their importance for the system's functionality. The following relationship must stand for each infrastructure:

$$\sum_i w_i = 1 \quad (13)$$

For each PGA level a, and for each damage state, the final discrete probability of each infrastructure element j is estimated from the following function:

$$dpa_j^* = \sum dPa_{1j} \cdot a_{1j} + dPa_{2j} \cdot a_{2j} + ... + dPa_{mj} \cdot a_{mj} = \sum_i dpa_{ij}^* \leq 1 \text{, for i=1, …., m} \quad (14)$$

Then the cumulative probabilities of exceedance for each damage state and each PGA level are estimated from equation 9. An illustrative example of the proposed methodology is provided in the following section.

ILLUSTRATIVE EXAMPLE

A system of four interacting lifeline components is assumed as illustrated in figure 2. Multiple connection links exist between these elements, which can be captured in the total amount of the i^{th} lifeline system's product (commodity) consumed by the j^{th} lifeline system. These figures are recorded in an Input-Output table, as given in table 3 (relative values refer to lifeline systems which the examined components are part of). Naturally, intermediate consumption between independent systems (e.g. components with no linkage between them as is the case of the telecommunication centre and the well in this example) is zero. Final demand and value added are assumed to have non-zero values. The total output for each component (for example the electric power substation) is calculated by the summation of intermediate consumptions and final demand.

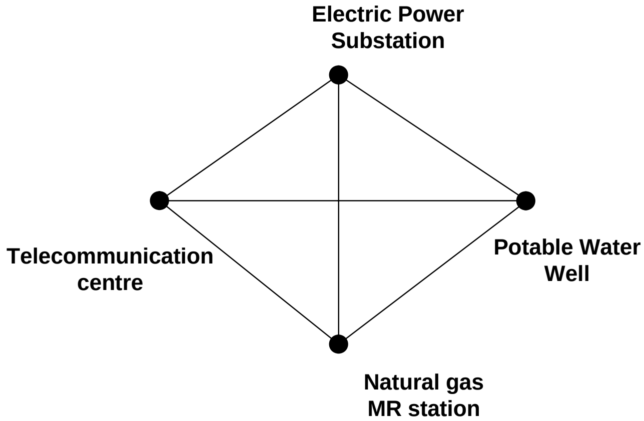

Figure 2. Indicative system of interacting lifeline components

Table 3. Indicative Input-Output table (intermediate and total consumptions in euros)

	EPS	PWW	NGMR	TC	FINAL DEMAND	TOTAL OUTPUT
EPS	0	0	250	150	16000	16400
PWW	100	0	280	230	5390	6000
NGMR	150	0	0	280	9750	10180
TC	270	0	230	0	2500	3000
VALUE ADDED	15880	6000	9420	2340		
TOTAL SUPPLY	16400	6000	10180	3000		

* EPS: Electric Power System, PWW: Potable Water Well, NGMR: Natural Gas MR Station and TC: Telecommunication Centre

Intermediate consumptions x_{ij} in monetary terms are: $x = \begin{bmatrix} 0 & 0 & 250 & 150 \\ 100 & 0 & 280 & 230 \\ 150 & 0 & 0 & 280 \\ 270 & 0 & 230 & 0 \end{bmatrix}$, while the total output matrix is equal to $X = \begin{bmatrix} 16400 \\ 6000 \\ 10180 \\ 3000 \end{bmatrix}$.

The Leontief technical coefficient matrix A is (equation 2): $A = \begin{bmatrix} 0 & 0 & 0.025 & 0.050 \\ 0.006 & 0 & 0.028 & 0.077 \\ 0.009 & 0 & 0 & 0.093 \\ 0.016 & 0 & 0.023 & 0 \end{bmatrix}$

Finally, applying equation (6), the interdependency matrix A* is calculated as follows:

$$A^* = \begin{bmatrix} 6.10E-05 & 0 & 0 & 0 \\ 0 & 1.67E-04 & 0 & 0 \\ 0 & 0 & 9.82E-05 & 0 \\ 0 & 0 & 0 & 3.33E-04 \end{bmatrix} \cdot \begin{bmatrix} 0 & 0 & 0.025 & 0.050 \\ 0.006 & 0 & 0.028 & 0.077 \\ 0.009 & 0 & 0 & 0.093 \\ 0.016 & 0 & 0.023 & 0 \end{bmatrix} \cdot \begin{bmatrix} 16400 & 0 & 0 & 0 \\ 0 & 6000 & 0 & 0 \\ 0 & 0 & 10180 & 0 \\ 0 & 0 & 0 & 3000 \end{bmatrix} =$$

$$= \begin{bmatrix} 0 & 0 & 0.015 & 0.009 \\ 0.017 & 0 & 0.047 & 0.038 \\ 0.015 & 0 & 0 & 0.028 \\ 0.090 & 0 & 0.077 & 0 \end{bmatrix}$$

The strongest interconnectedness exists between the electric power and telecommunication system ($a^*_{TC,EPS} = 0.9$). Following eq. 7 the propagated inoperability matrix I is: $I = \begin{bmatrix} 1 & 0 & 0.015 & 0.009 \\ 0.017 & 1 & 0.047 & 0.038 \\ 0.015 & 0 & 1 & 0.028 \\ 0.090 & 0 & 0.077 & 1 \end{bmatrix}$

An electric power system is constituted of various elements: power – generating facilities, electric substations, transmission and distribution lines. An electric substation is a facility that serves as a source of energy supply for the local distribution area; thus its importance for the system's functionality is quite high. A weight coefficient of 0.50 is assigned to the electric power substation for this example. The weight coefficients assigned to all four infrastructure elements are: $[w_i]^T = [w_{EPS} \;\; w_{PWW} \;\; w_{NGMR} \;\; w_{TC}] = [0.50 \;\; 0.10 \;\; 0.30 \;\; 0.42]$.

$$I^* = [i^*_{ij}], \quad i^*_{ij} = \begin{cases} w_i \cdot a^*_{ij}, i \neq j \\ 1, i = j \end{cases} , \quad I^* = \begin{bmatrix} 1 & 0 & 0.008 & 0.005 \\ 0.002 & 1 & 0.005 & 0.004 \\ 0.004 & 0 & 1 & 0.008 \\ 0.038 & 0 & 0.032 & 1 \end{bmatrix}$$

Fragility curves for the aforementioned individual components (without taking into account the interdependency between them) are illustrated in figures 3-6, while the corresponding parameters (mean values and standard deviations of lognormal distribution functions) are given in table 4.

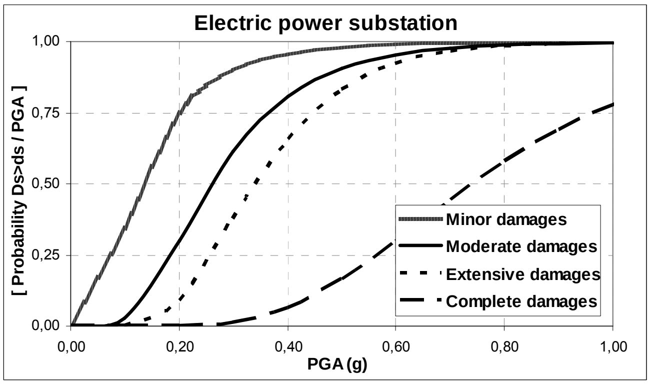

Figure 3. Fragility curves of electric power substation (EPS) – independent element

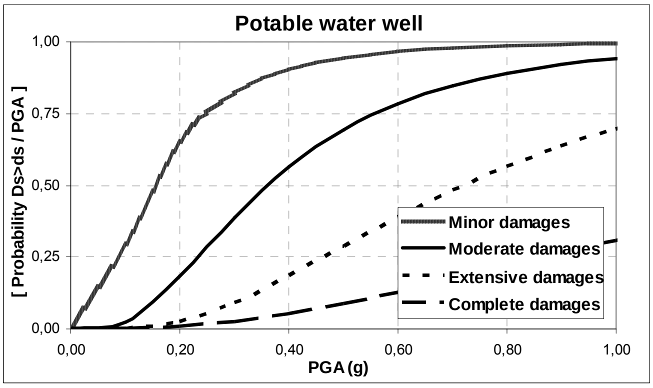

Figure 4. Fragility curves of potable water well (PWW) – independent element

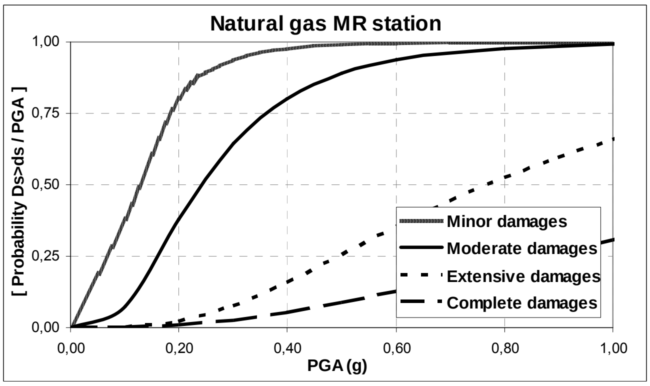

Figure 5. Fragility curves of natural gas MR station (NGMR) – independent element

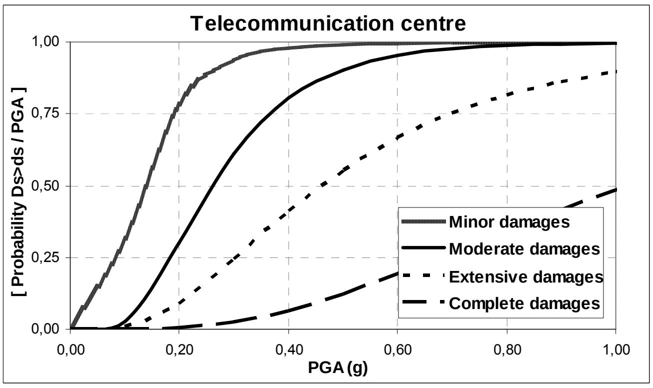

Figure 6. Fragility curves of telecommunication centre (TC) – independent element

Table 4. Fragility curve parameters of independent lifeline elements

Damage State	EPS		PWW		NGMR		TC	
	Median PGA (g)	Standard deviation β	Median PGA (g)	Standard deviation β	Median PGA (g)	Standard deviation β	Median PGA (g)	Standard deviation β
Minor	0.13	0.65	0.15	0.75	0.12	0.60	0.13	0.55
Moderate	0.26	0.50	0.36	0.65	0.24	0.60	0.26	0.50
Extensive	0.34	0.40	0.72	0.65	0.77	0.65	0.46	0.62
Complete	0.74	0.40	1.50	0.80	1.50	0.80	1.03	0.62

Applying eq. 9-14, the cumulative probabilities of exceedance for each damage state and each PGA level are estimated. Plotting these values for each element j, the following fragility curves are derived (fig. 7-10). Lognormal functions are also fitted to the above interdependent vulnerability curves. The respective parameters in terms of mean PGA values and standard deviation β are given in table 5.

Table 5. Fragility curve parameters of interdependent elements

Damage State	EPS		PWW		NGMR		TC	
	Median PGA (g)	Standard deviation β	Median PGA (g)	Standard deviation β	Median PGA (g)	Standard deviation β	Median PGA (g)	Standard deviation β
Minor	0.125	0.55	0.15	0.75	0.115	0.55	0.125	0.55
Moderate	0.255	0.44	0.36	0.65	0.235	0.40	0.255	0.45
Extensive	0.34	0.20	0.72	0.65	0.34	0.10	0.38	0.25
Complete	0.445	0.05	1.50	0.80	0.34	0.05	0.43	0.05

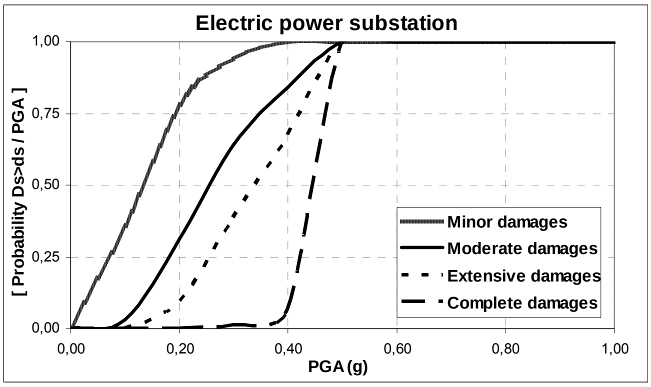

Figure 7. Fragility curves of electric power substation (EPS) – interdependent element

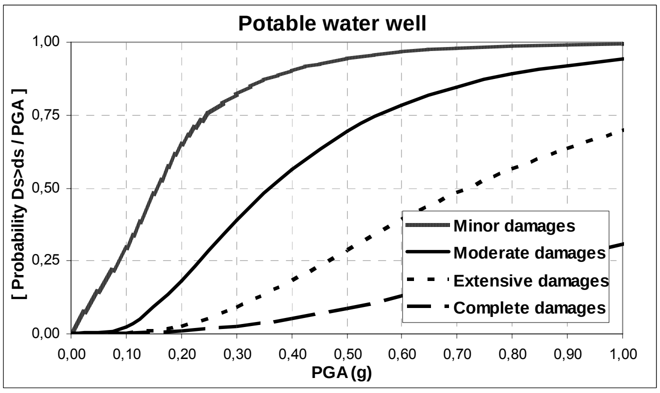

Figure 8. Fragility curves of potable water well (PWW) – interdependent element

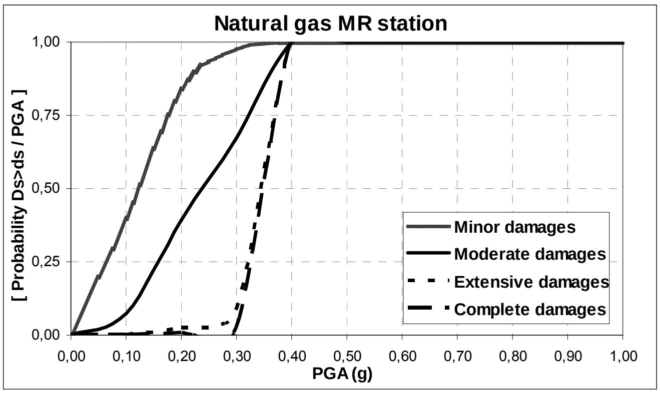

Figure 9. Fragility curves of natural gas MR station (NGMR) – interdependent element

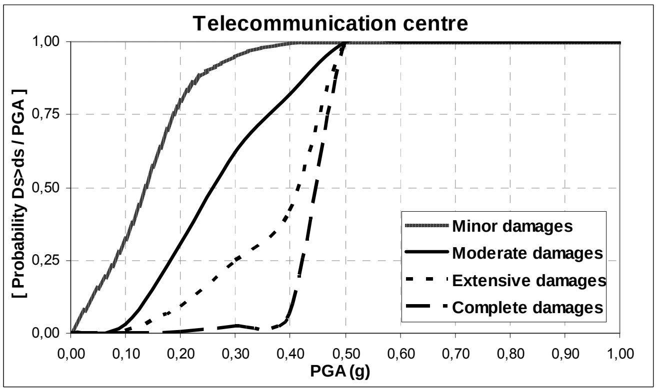

Figure 10. Fragility curves of telecommunication centre (TC) – interdependent element

If infrastructure i depends on infrastructure j, and j has a high risk of failure, then the likelihood of i being disrupted or failing is correspondingly higher than if i were independent of j. In the case of the three interconnected elements (EPS, PWW and TC) the derived fragility curves are quite different from those referring to independent elements. On the other hand, fragility curves of potable water well (PWW) are not altered because they have zero values of interdependency coefficients.

CONCLUSIONS

Infrastructure systems are highly intradependent and interdependent systems. Capturing and quantifying lifeline interactions are very important aspects within an advanced seismic risk management study. Systems' response to external perturbations such as an earthquake event is contingent on their specific features, the level of the induced seismic input motion and also the type and degree of the existing interdependencies. Within this framework, a method is proposed to simulate interdependent lifelines' vulnerability. Interdependency indices are estimated based on an Input-Output economic model. Furthermore, the notion of propagated inoperability and systemic vulnerability or "vulnerability of interdependent elements" is introduced. Fragility curves of the interdependent components are estimated based on vulnerability functions of independent elements and the propagated inoperability matrix I. Using an illustrative example, it is demonstrated the possibility of the proposed methodology to evaluate the expected seismic performance of complex interacting infrastructure components through a probabilistic approach. Incorporation of systems' intradependencies and generalization of the proposed methodology to address the vulnerability assessment of multiple interacting infrastructure systems consisting of a number of different sub-components, are the issues where future research will focus on.

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