Comparative Assessment of Civil Infrastructure Network Performance under Probabilistic and Scenario Earthquakes

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Abstract: The intensity of the seismic demand in a vulnerability assessment of an engineered system can be described in terms of either its annual probability of being exceeded or a scenario earthquake. A probabilistically stated hazard (e.g., one with a return period of 2,475 years) represents an aggregation of numerous earthquakes and may not represent the spatial distribution of seismic intensity from a severe earthquake over a region correctly, making its application to performance evaluation of a large-scale distributed civil infrastructure system questionable. A scenario earthquake models the spatial intensity correctly, but conveys no quantitative measure of the seismic risk. This paper examines the use of probabilistic seismic hazard analysis and corresponding scenario earthquakes as a basis for vulnerability assessment of a networked system. Following an examination of simple spatially distributed series and parallel system models, a vulnerability assessment of an electrical power network in a region of moderate seismicity in the Central United States offers additional insight into the issue.

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Introduction

Seismic fragility and vulnerability assessment are key ingredients of decision making for mitigating earthquake risks to civil infrastructure. In recent years, such assessments have been performed for networked civil infrastructure systems—natural gas, water, electrical power, telecommunications, and transportation—that provide essential services to urban communities. The functionality of a component or facility in a networked infrastructure system or the vulnerability of the system as a whole may be affected by the functionalities of facilities and connecting elements in interfacing systems. As a simple illustration of such interactions, during the electrical power blackout in the Northeast United States in August, 2003, some undamaged electrical power substations were unable to deliver power to their service areas because other substations in the electrical grid on which they depended lost functionality (U.S.–Canada Power Systems Outage Task Force 2004). Such failures are referred to as *cascading failures* (Rinaldi et al. 2001).

In assessing the seismic vulnerability of civil infrastructure, the earthquake hazard generally is specified using one of two basic approaches: a probabilistic seismic hazard (McGuire 1995) or a scenario earthquake. In a probabilistic seismic hazard analysis (PSHA), the seismic hazard at any location is described by a complimentary cumulative distribution function (CDF) defining the probability of exceeding specific earthquake intensities. The probabilistic seismic hazard reflects the aggregated effect of the range of possible earthquakes in proximity to a site, weighted by the probability of occurrence of each earthquake (McGuire 1995). Probabilistic seismic hazard maps (otherwise known as uniform hazard maps) that display contours of seismic intensities corresponding to peak ground acceleration (PGA) or peak ground velocity or spectral parameters at specific return periods are published by the U.S. Geological Survey (USGS 2002b). The seismic intensities from these uniform hazard maps are used in building design (FEMA 2004; ASCE 2005). A PSHA is particularly suited to designing individual facilities since the intensities can be represented at a probabilistically stipulated level of the seismic hazard in codes and other regulatory documents (e.g., 2% probability of being exceeded in 50 years). However, the spatial distribution of seismic intensity (SI) from any large earthquake cannot be reflected correctly in the probabilistic seismic hazard map because the mapped contours represent the aggregated effects of numerous earthquakes. This fact does not pose a problem when only one facility is analyzed or designed since a risk assessment of that one facility does not require information on the spatial distribution of SIs. However, when the damage or risk to a spatially distributed networked infrastructure system must be assessed, information regarding the spatial distribution of SIs is essential (Eguchi 1991; Chang and Shinozuka 2000). This spatial distribution of SIs is difficult to assess on the basis of a PSHA because information on the spatial distribution of ground motion intensity due to one (severe) earthquake is lost in the process of aggregation on which the uniform hazard contours are based.

A scenario earthquake (SE)-based hazard analysis depicts the spatial variation in intensity of a specific large earthquake (usu-

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ally stipulated in terms of magnitude and epicenter) with respect to a facility or group of facilities. A SE-based hazard can be a valuable risk communication tool, especially in explaining seismic risk to civil infrastructure systems to decision makers who are not familiar with the mathematical concepts that underlie a PSHA but understand the concept of an earthquake magnitude from the popular media. Furthermore, McGuire (2001) observed that the SE-based analysis is useful for high seismic regions (e.g., California or Japan) since "*a deterministic scenario for this event will allow details to be examined such as ground motion effects caused by rupture propagation*." McGuire also noted that "*in moderate and low seismic regions, extreme deterministic scenarios will have probabilities of occurrence that are too low to be useful for most decision purposes*."

Using a SE-based analysis, Shinozuka et al. (1992) and Hwang et al. (1998) analyzed the performance of a municipal water delivery system in Memphis, Tenn., under a $M_w=6.5$ earthquake centered at Marked Tree, Alaska, which has an epicentral distance of approximately 60 km from the center of the city. Piers et al. (1996) and Ang et al. (1996) evaluated the seismic performance and serviceability of the electrical power system in the San Francisco Bay area following the 1989 Loma Prieta earthquake. Later, Shinozuka et al. (1998) evaluated the serviceability of the electrical power system managed by Memphis Light, Gas and Water Division under a SE centered at Marked Tree, Alaska, with $M_w=7.5$ and electrical power availability in the Los Angeles area following the 1994 Northridge earthquake (Shinozuka et al. 1999). Recently, Adachi and Ellingwood (2008) and Adachi (2007) analyzed the performance of the water distribution system in Shelby County, Tenn., under an $M_w=7.7$ earthquake centered at 35.3N and 90.3W (which has an approximate epicentral distance of 33 km to the city of Memphis). These most recent studies are distinguished from earlier studies by their consideration of the dependence of the performance of the water distribution system on electrical power availability.

In a SE-based hazard analysis, one specific earthquake is selected from an examination of the seismicity surrounding the site or from a disaggregation analysis of potential earthquakes. The deaggregation charts provided by the USGS can be used for selecting this SE (USGS 2002a). Since decision making regarding public or private investment in hazard mitigation usually focuses on low-probability/high-consequence events, the earthquake contributing most to the seismic hazard at a stipulated low-probability level (e.g., 2% in 50 years for the *maximum considered earthquake*) often will be selected. Occasionally, an earthquake is simply selected from recordings of severe ground motion (e.g., El Centro, 1940; San Fernando, 1971; Northridge, 1994). Although the SE-based approach is very useful for investigating the damage to an infrastructure system when a specific earthquake occurs, it conveys no quantitative information on the probability of occurrence of the scenario event. Thus, its conditional nature limits its usefulness in probabilistic risk analysis and derivative decision making (e.g., annualizing expected losses; insurance rate setting and portfolio loss underwriting).

In this paper, the applicability and limitations of both PSH-based and SE-based analyses in the assessment of seismic risk to distributed (networked) infrastructure systems are examined. We first consider simple systems in which performance can be characterized by either series or parallel system representations (system logic); this analysis is intended to reveal the effect of such representations on estimated system risk. Following these simple applications, the seismic risk to the electrical power system in Shelby County, Tenn., which includes the Memphis metropolitan area, is analyzed by both approaches to illustrate their applicability in evaluating an actual infrastructure system.

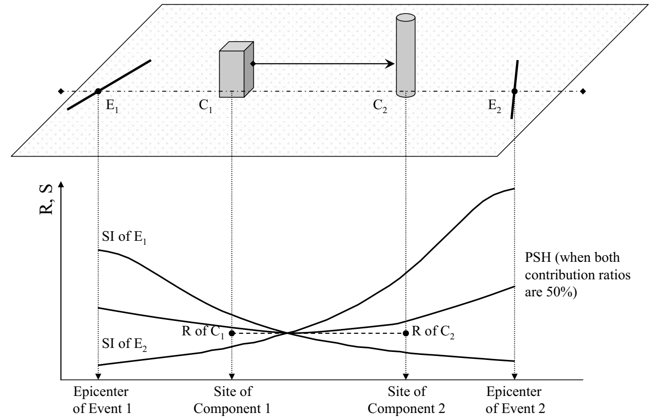

Fig. 1. Networked system with two seismic zones

Comparison of PSHA and SE Applied to a Simple System

Since the probabilistic seismic hazard at a site represents a weighted average of individual earthquakes, the spatial distribution of SIs over a region due to each earthquake is not reflected in the uniform hazard contours. Thus, when the PSH-based approach is used to analyze the functionality of a facility in a networked system, aspects of system functionality that depend on the spatial distribution of SI are not modeled correctly. Fig. 1 illustrates this point. The upper half of Fig. 1 shows a simple networked system with two facilities (C_1 and C_2) located between two seismic sources (E_1 and E_2). It is assumed that C_2 requires a commodity (e.g., electrical power and water) *from* C_1 to maintain its function. The lower half of Fig. 1 shows the earthquake resistances of the two facilities (R of C_1 and R of C_2), which are assumed deterministic, and the attenuation of SIs with increasing distance generated by the two seismic sources (SI of E_1 and SI of E_2), which is also assumed deterministic. The functionality of each facility is described by a Bernoulli random variable: 0% (nonfunction) or 100% (complete function).

Suppose, for simplicity, that the SI represented by curve "PSH" is computed under the assumption that the two seismic zones cause earthquakes with equal frequency. The average functionality of the two facilities (C_1, C_2) in the networked system, when evaluated on the basis of the PSH-based approach, is 0% since resistances of both facilities fall below the PSH curve. However, when the functionalities of the two facilities are evaluated for each earthquake separately, the average functionality is 25%, computed as follows (see direction arrow in Fig. 1). The earthquake occurring at E_1 causes loss of function of C_1, which, in turn, causes loss of function of C_2 due to cascading failure (implying 0% average functionality since both facilities lose the functions). However, an earthquake at E_2 causes loss of function of C_2 but does not cause loss of function of C_1 (implying 50% average functionality since one of the two facilities maintains its function). Thus, the average functionality (or "functionality ratio") is 25%. Fig. 1 shows clearly that a PSH-based analysis cannot capture the spatial distribution of seismic damage to infrastructure accurately because no single earthquake can generate a spatial distribution of SIs that has the two peaks at Epicenters 1

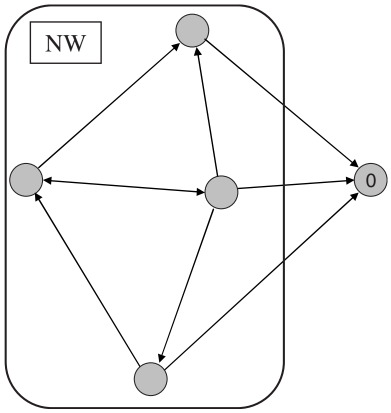

Fig. 2. Model of a networked system

and 2. In the following section, some of the basic issues involved in the analysis of seismic demand on distributed civil infrastructure systems are examined using several simple infrastructure system models, as background to the subsequent analysis of the electrical power transmission system in Shelby County, Tenn.

Functionality Logic of Facilities in a Networked System

Modeling Cascading Failures and Survivor Functions

A general model of a networked infrastructure system involves facilities and connecting elements. Fig. 2 shows a simple example of a networked system. The circles represent facilities and the arrows represent connecting elements and the directions in which the commodity (e.g., electrical power, water, or natural gas) flows. In Fig. 2, the function of Facility 0 is affected by the functionalities of the other facilities in the network (cascading failures). Modeling cascading failures by a reliability block diagram (e.g., Rausand and Hoyland, 2004), the function of the facility can be described as a series system. The survivor function, which represents the functionality ratio of the target facility, is expressed by the following equation, assuming that the failures of the facilities are statistically independent events (this assumption is reasonable when the facilities are separated at some distance geographically):

$$Rs_0(x_0,x_{\mathrm{NW}}) = P[S_0 \cap S_{\mathrm{NW}}] = [1 - Pf_0(x_0)] \cdot [1 - Pf_{\mathrm{NW}}(\boldsymbol{x}_{\mathrm{NW}})] \tag{1}$$

where function Rs_0 represents the functionality ratio of the target facility 0, $Rs_0=0$ and $Rs_0=1$ implying, respectively, that Target Facility 0 is either nonfunctioning or functioning; and S_0 and S_{NW} represent, respectively, the events that Target Facility 0 and the remaining networked system, not including the target facility, are functional. Probabilities Pf_0 and Pf_{NW} represent the probabilities of failure of Facility 0 and the remainder of the networked system excluding Facility 0; x_0 is the SI at the site of Facility 0 and $\boldsymbol{x}_{\mathrm{NW}}$ is the vector of representative SIs for components in the remainder of the networked system excluding Facility 0. These SIs differ for different components in the network, especially for components that are distant from one another.

The relation between the survivor function and component fragilities is illustrated in Fig. 3, in which the $Pf_{\mathrm{NW}}-x$ surface represents a system fragility curve involving all facilities of the networked system except Facility 0, the Pf_0-x surface represents the fragility curve of Facility 0, and the $Pf_{\mathrm{NW}}-Pf_0-Rs_0$ space illustrates the relationship among them [Eq. (1)]. Fig. 3 illustrates the dependence of the functionality ratio of Target Facility 0 on the two component fragilities (Facility 0 and the remaining network system in Fig. 2) and corresponding SIs. Note that the system structure and fragility curves are both required to evaluate the functionality ratios of the facilities targeted since the system fragility $[Pf_{\mathrm{NW}}(\boldsymbol{x}_{\mathrm{NW}})]$ is dependent on the structure of the system, even though the facility fragilities $[Pf_0(x_0)]$ are independent of the structure of the network.

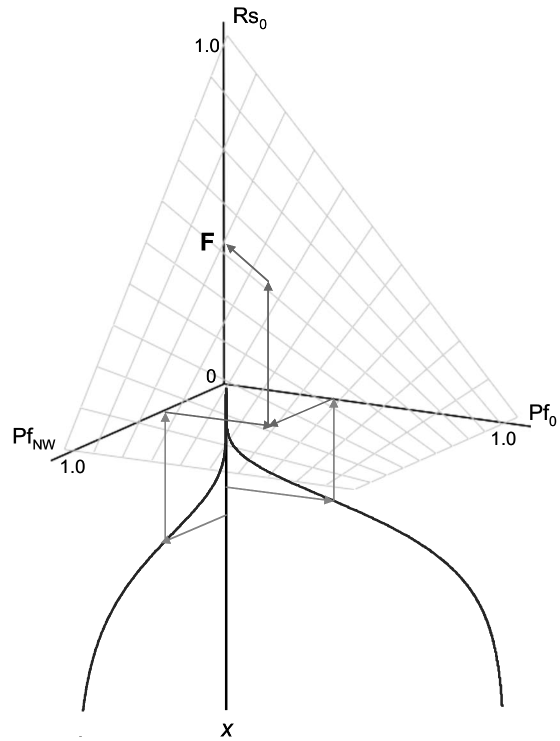

Fig. 3. Evaluation of facility functionality ratio

Models of Simple Networked Systems

In order to assess the effect of the structure of the networked system, systems which have purely series (Fig. 4) and purely parallel structures (Fig. 5) are modeled and the functionality of a particular facility in each network is evaluated. In Figs. 4 and 5,

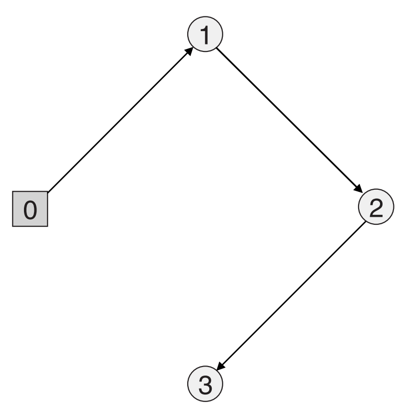

Fig. 4. Networked system with purely series structure

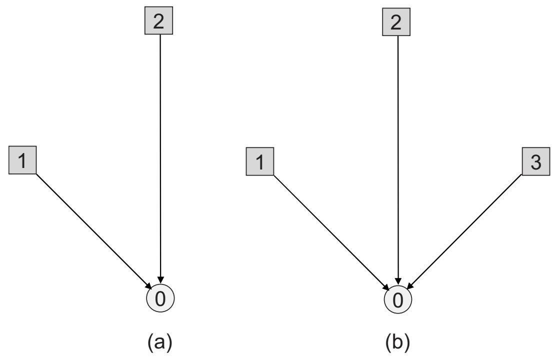

Fig. 5. Models of networked systems with purely parallel structure

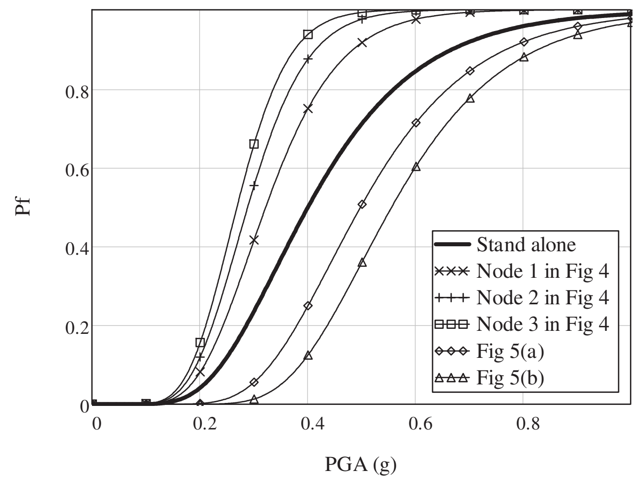

Fig. 6. System fragility curves (all components subjected to same PGA and failure events are statistically independent)

the networked systems contain facilities that are interconnected by distribution elements. The facility identified by a square represents a supply facility which generates the commodity distributed in the networked system (for example, such as electrical power or water). The facility identified by a circle is the demand facility which is the relay point that conveys the commodity from the supply facility to other demand facilities and customers (for example, a substation in a power transmission system or a pumping station in a water distribution system). Cascading failures of demand facilities occur when they cannot receive the commodity from any supply facility either directly or indirectly as a result of damage to upstream components.

Fig. 4 illustrates a simple series network system, in which the functionalities of three facilities, 1 to 3, are to be analyzed. Facility 3 is strongly dependent on the series structure since its functionality is determined by not only the fragility of Facility 3 but also the fragilities of Facilities 0 to 2. Conversely, Facility 1 is only weakly dependent on the series structure since its functionality is determined only by the fragilities of Facilities 0 and 1. The survivor functions for Facilities 1 to 3, when the facility failures are statistically independent, are

$$Rs_{S,1}(\boldsymbol{x}) = P[S_0 \cap S_1] = [1 - Pf_0(x_0)] \cdot [1 - Pf_1(x_1)] \tag{2}$$

$$\begin{aligned} Rs_{S,2}(\boldsymbol{x}) &= P[S_0 \cap S_1 \cap S_2] \\ &= [1 - Pf_0(x_0)] \cdot [1 - Pf_1(x_1)] \cdot [1 - Pf_2(x_2)] \end{aligned} \tag{3}$$

$$\begin{aligned} Rs_{S,3}(\boldsymbol{x}) = P[S_0 \cap S_1 \cap S_2 \cap S_3] &= [1 - Pf_0(x_0)] \cdot [1 - Pf_1(x_1)] \\ &\cdot [1 - Pf_2(x_2)] \cdot [1 - Pf_3(x_3)] \end{aligned} \tag{4}$$

Fig. 5 illustrates two parallel network systems, in which the functionality ratios of Facility 0 in networked Systems (a) and (b) are to be evaluated. Facility 0 in System (b) sustains the strongest effect of the parallel structure since its functionality ratio depends on the fragilities of three facilities, 1 to 3. However, Facility 0 in System (a) is most weakly dependent on the parallel system structure since its functionality ratio is determined by the fragilities of only Facilities 1 and 2. Assuming that the facility failures are statistically independent events, the survivor functions of Facility 0 in Systems (a) and (b) are

$$Rs_{P,(a)}(\boldsymbol{x}) = P[S_1 \cup S_2] = 1 - Pf_1(x_1) \cdot Pf_2(x_2) \tag{5}$$

$$Rs_{P,(b)}(\boldsymbol{x}) = P[S_1 \cup S_2 \cup S_3] = 1 - Pf_1(x_1) \cdot Pf_2(x_2) \cdot Pf_3(x_3) \tag{6}$$

The fragility of each facility in these simple network models is described by the lognormal CDF

$$Pf_x(x) = \int_0^x \frac{1}{\sqrt{2\pi}\zeta s} \exp\left[-\frac{1}{2}\left\{\frac{\ln(s) - \lambda}{\zeta}\right\}^2\right] ds \tag{7}$$

where λ=mean of $\ln(X)$, computed by $\ln[\text{median}(X)]$, and ζ=standard deviation of $\ln(X)$. In this illustration, all fragilities are defined by median of 0.4 g and logarithmic standard deviation of 0.4; these values are typical for fragilities of components in utility networks (FEMA 2003). The system fragility curves for one stand-alone facility, three facility nodes in Fig. 4, and two networks in Fig. 5 are shown in Fig. 6, under the assumption that all facilities in the network are subjected to the same SIs. The benefits of redundancy in the systems modeled in Fig. 5 on system fragility are apparent and expected.

PSHA- and SE-Based Approaches

The functionality of a facility in a networked system differs when SI is modeled using PSH-based and SE-based approaches. The comparison in the example that follows utilizes the simple models of networked systems described above and simple models of seismicity. The process is summarized in Fig. 7; accessibility analysis involves determining whether a facility in the networked system can (or cannot) receive the commodity from a supply facility, taking the effect of cascading failure into account. For simplicity, it is assumed that only accessibility *from* supply facilities *to* de-

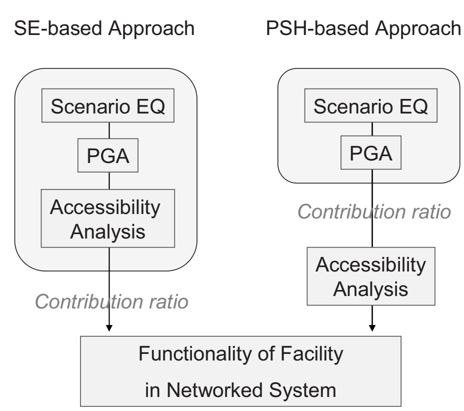

Fig. 7. Comparison of approaches to assess the functionality ratio of a facility in a networked system

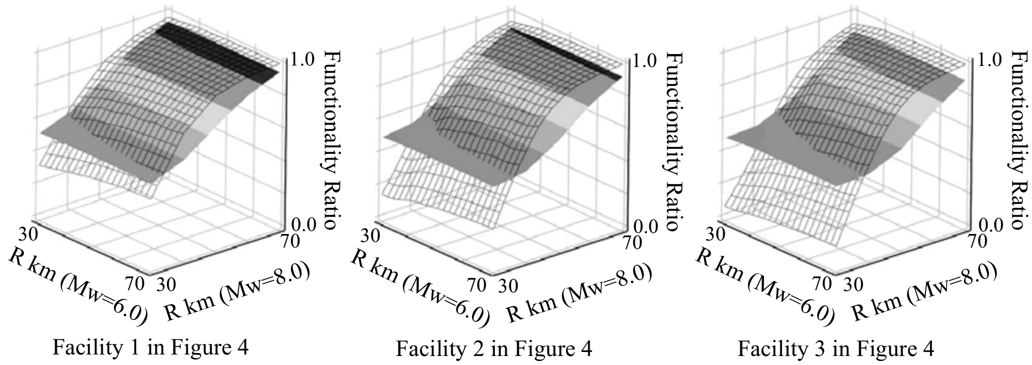

Fig. 8. Functionality of a facility within a series system: M_W (8.0, 6.0) (mesh surface: PSH-based approach; solid surface: SE-based approach)

mand facilities (e.g., as illustrated in Fig. 1) is of interest. The following additional assumptions are made:
1. The network is impacted by two earthquakes;
2. In the first example, the two earthquakes have M_w's equal to 8.0 and 6.0. In the second example, both earthquakes have M_w equal to 8.0. For simplicity, each earthquake is assumed to contribute 50% of the earthquake hazard;
3. Epicentral distances of both earthquakes, measured from the location of the epicenter to the geographic center of the network, are set as 30, 40, 50, 60, and 70 km;
4. The azimuth of each epicenter with respect to the target system is defined by an angle θ, which is a uniformly distributed random number in $[-180°, 180°)$; and
5. Finally, each facility is located 10 km from the geographic center of the network.

In order to determine SIs at each facility, the attenuation equation of Toro (1997) for PGA is used

$$\ln(\text{median PGA}) = 2.20 + 0.81 \cdot (M_w - 6.0) - 1.27 \cdot \ln(\sqrt{R^2 + 9.3^2}) + 0.11 \cdot \max\left[\ln\left(\frac{R}{100}\right), 0.0\right] - 0.0021\sqrt{R^2 + 9.3^2} \tag{8}$$

The variability in SI for a given magnitude, M_w, and epicentral distance, R, is described by the logarithmic standard deviation associated with Eq. (8); its value is 0.6. In this paper, which focuses on civil infrastructure systems rather than buildings, we assume that the SI can be described by the PGA rather than spectral acceleration, which is a common intensity measure used in seismic performance assessment of buildings. The attenuation model has a significant impact on the performance of the simple illustrative system, as will become apparent.

It should be noted that the (epistemic) uncertainty resulting from the choice of a particular attenuation law would have an impact on the functionalities of components and the networked system. However, the estimation error caused by the use of PSHA in evaluating functionality of a networked civil infrastructure system should be treated separately from other sources of uncertainty; it is not attributable to unavoidable uncertainty but rather to the approach taken to model spatially distributed demand. Accordingly, this source of uncertainty was not considered in this study.

The PSH-based approach consists of the following steps:
1. SIs at all facility sites within the network are computed for the two earthquakes defined in the previous section;
2. A weighted average of SIs at each site is computed by weighting the attenuated intensities by the relative frequencies of the contributing earthquakes (contribution ratio); and
3. The functionality ratio of each facility in the networked system is evaluated using these average SIs and a corresponding survivor function, defined, as appropriate, by Eqs. (2)–(6).

In the SE-based approach, the functionalities of the facilities in a networked system are evaluated for each SE, and the resulting system functionalities are weighted by the probability of occurrence of each earthquake to arrive at an overall estimate of the system functionality. If it were possible to take the probability of occurrence of all possible earthquakes into account, then the functionality ratio of a facility evaluated by the SE-based approach would in fact be the "exact" functionality of that facility in the networked infrastructure system. The SE-based approach consists of the following steps:
1. SIs at all facility sites are computed for two earthquakes, as in Step 1 of the PSH-based approach;
2. The functionality of each facility in the networked system is evaluated using these SIs and a corresponding survivor function; and
3. The weighted average functionality of each facility in the networked system is evaluated, taking into account the relative frequency of the corresponding SEs (contribution ratio).

The functionalities of the facilities in the simple networked systems illustrated in Figs. 4 and 5 are calculated from Eqs. (2)–(6) from the PGAs resulting from SEs or from the PGAs that have been weighted by the contribution ratios of the earthquakes comprising the probabilistic seismic hazard. Figs. 8–11 display the average functionality ratios corresponding to the facilities within networked systems characterized by series and parallel structures. Two typical trends are evident in Figs. 8–11.

First, in the cases where M_w (8.0, 6.0) shown in Figs. 8 and 10, the facility functionality ratio is more dependent on the distance of the M_w=8.0 earthquake than on the distance of the smaller M_w=6.0 earthquake. This can be explained by comparing the attenuations of earthquakes with M_w=6.0 and M_w=8.0. The PGA from the attenuation of the M_w=8.0 earthquake changes drastically at shorter epicentral distances, leading to a wider range of functionality ratios for a facility. However, the PGA from the attenuation of the M_w=6.0 earthquake varies less than for the M_w=8.0 earthquake. Thus, the functionality ratio of a facility due to the M_w=6.0 earthquake has a narrower range.

Second, the functionality ratios of each facility evaluated by the PSH-based and SE-based approaches are quite different. For example, Figs. 8, 9, and 11 show that when the distances of the

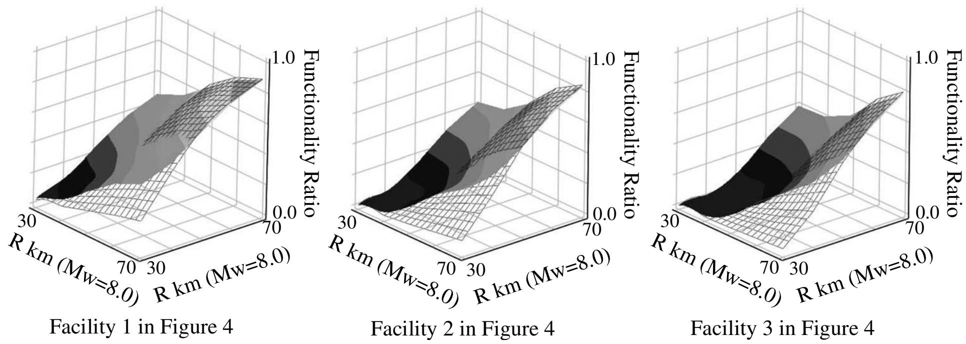

Fig. 9. Functionality of a facility within a series system: M_W (8.0, 8.0) (mesh surface: PSH-based approach; solid surface: SE-based approach)

M_w=8.0 earthquake(s) are larger, the functionality of the three facilities evaluated by the SE-based approach are lower than those by the PSH-based approach. Conversely, for smaller epicentral distances of the M_w=8.0 earthquake(s), the functionality ratios of the three facilities evaluated by the SE-based approach are higher than those by the PSH-based approach. In Fig. 10 the functionality ratios of facilities evaluated by the SE-based approach are always less than those from the PSH-based approach. The second trend can be explained by the relation between the fragility curves and the survivor function shown in Fig. 3. For simplicity, the three-dimensional model in Fig. 3 is idealized by the two-dimensional models in Figs. 12(a and b), where the left half surface (SI-failure probability surface) shows a system fragility curve, and the right half surface (failure probability-functionality ratio surface) shows a survivor function.

Fig. 12(a) illustrates the case when two PGAs generated from two seismic zones are relatively small but are different in value, such as SIs $E_1(M_W=6.0, R=70\text{ km})$ and $E_2(M_W=8.0, R=70\text{ km})$ in Figs. 8 and 10. Following the SE-based approach illustrated in Fig. 7, failure probabilities Pf_{E_1} and Pf_{E_2} are computed from SIs E_1 and E_2, respectively, leading to functionalities Rs_{E_1} and Rs_{E_2}. By weighting the functionalities Rs_{E_1} and Rs_{E_2} by the contribution ratios (50% for each scenario event), the expected functionality $Rs_{E_{2,1\text{-}2}}$ is evaluated. In contrast, following the PSH-based approach illustrated in Fig. 7, seismic intensity $\text{PSHA}_{1\text{-}2}$ is used to evaluate failure probability $Pf_{\text{PSHA},1\text{-}2}$ leading to functionality $Ps_{\text{PSHA},1\text{-}2}$. A comparison of $Rs_{\text{SE},1\text{-}2}$ and $Rs_{\text{PSHA},1\text{-}2}$ reveals that the PSH-based approach results in a larger functionality than the SE-based approach when two PGAs are relatively small but are different in value.

Fig. 12(b) illustrates the case when the PGAs generated from two seismic zones are relatively large and different in value, such as SIs $E_1(M_W=8.0, R=40\text{ km})$, $E_2(M_W=8.0, R=40\text{ km})$ in Figs. 9 and 11. In this case, the functionality ratio, $Rs_{\text{PSHA},1\text{-}2}$, based on the PSH-based approach is smaller than the expected functionality ratio based on the SE-based approach, $Rs_{\text{SE},1\text{-}2}$. Such differences are common to both series and parallel systems in Figs. 8–11. In a series system, the facility whose functionality ratio is more highly affected by cascading failure is more sensitive to the analysis methods than the other facilities since the difference of functionality ratios estimated by the two methods is amplified in proportion to the number of facilities between the demand facility and the target supply facility, as in Eqs. (2)–(4). Conversely, in a parallel system, this trend is less apparent because the parallel system negates the cascading effect by providing alternate routes to connect a supply facility with a target demand facility.

Although this simple example contains some idealizations (e.g., the two SEs contribute equally), it shows that the function of a facility within a networked system can be affected significantly by the functionality of other facilities. The functionality of each facility is affected by not only its fragility but also the fragility of the entire system of which it is a part. A PSH-based approach generally leads to a facility functionality that is different from what would be evaluated by the SE-based approach. These differences are explored in more detail in the example for Shelby County, Tenn., that follows.

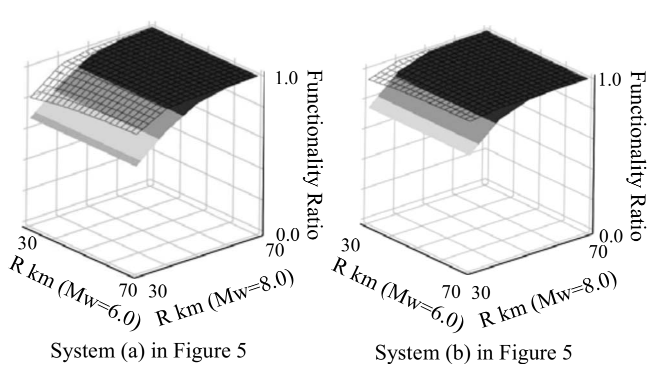

Fig. 10. Functionality of a facility within a parallel system: M_W (8.0, 6.0) (mesh surface: PSH-based approach; solid surface: SE-based approach)

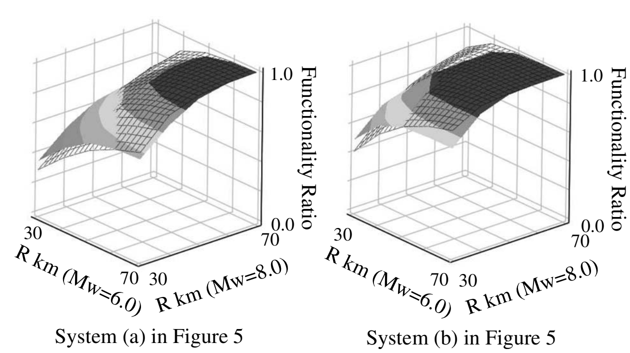

Fig. 11. Functionality of a facility within a parallel system: M_W (8.0, 8.0) (mesh surface: PSH-based approach; solid surface: SE-based approach)

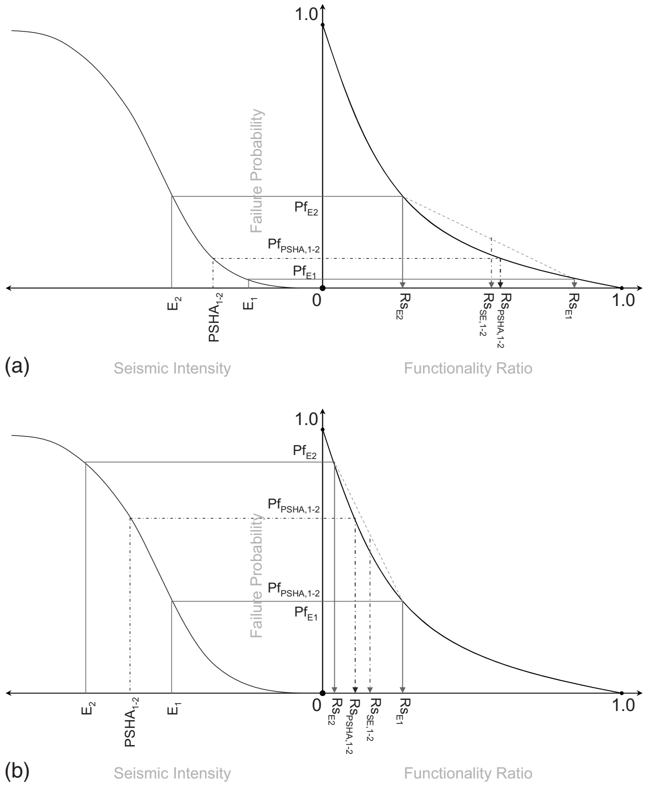

Fig. 12. (a) Simplified model from Fig. 3—small SIs; (b) simplified model of Fig. 3—large SIs

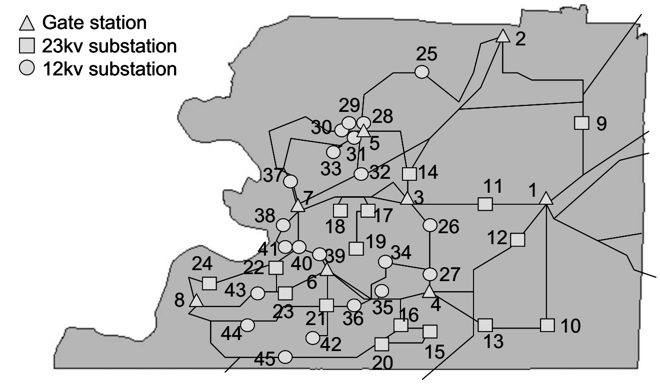

Fig. 13. Electrical power transmission system in Shelby County, Tenn.

Comparison of PSHA and SE Applied to Electrical Power

Transmission System in Shelby County, Tenn.

In the previous section, the functionalities of facilities evaluated by the PSH-based and the SE-based approaches were compared using simple networked systems impacted by two earthquakes, and it was shown that applying a PSH-based demand on a networked system may lead to erroneous estimates of facility functionality ratios within that system. In this section, the two approaches are applied to assess facility functionalities within the electrical power transmission system in Shelby County, Tenn.

Description of Power Transmission System in Shelby County, Tenn.

The electrical power transmission system for Shelby County, illustrated in Fig. 13, includes eight gate stations, fifteen 23-kV substations, twenty-one 12-kV substations, and transmission lines. Since there are no electrical power-generating stations in Shelby County, the gate stations are assumed to be the supply facilities in the network analysis, and the other substations are the demand facilities. Thus, when a substation cannot receive electrical power from any gate station, the substation loses its function due to cascading failure. Since the conducting elements of the transmission system are highly compliant (Jin et al. 2002), it is assumed that the earthquake impacts only the gate stations and the substations.

Determination of SEs

The SEs and corresponding spatially distributed PGAs are determined from the disaggregation analysis provided by the USGS (2002a) for a seismic hazard at a 2% probability of being exceeded in 50 years (2%/50 years). This disaggregation analysis revealed that a relatively small number of earthquakes contribute most of the seismic hazard at this probability level. For the purposes herein, the 10 most likely earthquakes, which contribute about 70% of the total hazard, are selected, as summarized in Table 1. In order to compute a PGA that is comparable to the PGA obtained directly from the PSHA and to have a consistent basis for making comparisons between the PSH- and SE-based approaches, the original contribution ratios are normalized in the last column of Table 1 to sum to 100%. The distances R shown in Table 1 are the approximate distances between each epicenter and the City of Memphis. The attenuation equation proposed by Toro et al. (1997) with a logarithmic standard deviation of 0.6 [Eq. (8)] is used to evaluate the PGA at the facility sites within the network. The maximum and minimum PGAs at all facility sites due to each SE and the weighted PGA from the (modified) PSHA are shown in Table 2.

Damage Assessment of a Facility within the Networked System

The examination of simple networked systems revealed that both the fragilities of individual facilities and the structure of the system network affect the functionalities of the facilities in the infrastructure network. Accordingly, two fragility curves corresponding to "complete" and "extensive" damage states, as defined

Table 1. Scenario Earthquakes

Longitude (W)	Latitude (N)	Epicentral distance to Memphis (km)	M_w	Contribution ratio (%)	Modified contribution ratio (%)
90.3	35.3	33	8.0	9.78	13.07
			7.7	24.78	33.10
			7.5	7.85	10.49
			7.3	4.70	6.28
90.5	35.5	61	8.0	6.44	8.61
			7.7	12.26	16.38
			7.5	3.18	4.24
			7.3	1.52	2.03
90.7	35.6	83	8.0	1.64	2.19
			7.7	2.70	3.61
Total				74.86	100.00

Table 2. Maximum and Minimum PGAs

Event	1	2	3	4	5	6	7	8	9	10	Weighted PGA
maxPGA (g)	0.62	0.55	0.50	0.73	0.30	0.33	0.35	0.40	0.27	0.31	0.45
minPGA (g)	0.28	0.25	0.23	0.32	0.15	0.17	0.20	0.23	0.16	0.19	0.27

in HAZUS (FEMA 2003), are used to model the performance of each facility in this section. The HAZUS technical manual (FEMA 2003) defines extensive damage as "the failure of 70% of disconnect switches, 70% of circuit breakers or 70% of transformers, or by the building being in extensive damage state." Complete damage is defined as "the failure of all disconnect switches, all circuit breakers or all current transformers, or by the building being in complete damage state." [The "minor" and "moderate" damage states defined in HAZUS (FEMA 2003) are not included in this study because the functionalities of all facilities are almost 1 (Adachi 2007) and there is little distinction between the PSH-based approach and the SE-based approach in that case.] The fragilities are modeled by lognormal distributions [Eq. (7)], with parameters listed in Table 3.

The failure of a facility due to cascading failures of other interconnected facilities is evaluated using the Floyd-Warshall algorithm (Floyd 1962; Warshall 1962), a method which is widely used in the operations research field to find the shortest path connecting two arbitrary points in a networked system. Using this algorithm, the failure of a facility due to the loss of connection as a result of cascading failures of the supply facilities can be evaluated.

Since it is difficult to create and display the reliability block diagrams and the system fragility curves of facilities in a complex networked system such as that in Fig. 13, the functionality ratio of each substation within the electrical power transmission network is evaluated by Monte Carlo simulation. The uncertainties in PGA at each site are modeled by lognormal distributions, with medians determined from the attenuation described by Eq. (8) and logarithmic standard deviations set equal to 0.6. The following steps are followed:

1. Assume that the facilities in the electrical power transmission network are initially in their undamaged states;
2. Determine the PGAs at each site, identify the failed facilities, and remove them from the network, yielding a damaged network;
3. Identify inaccessible demand facilities by applying the Floyd-Warshall algorithm to the damaged network;
4. Assign measures 0 to the inaccessible demand facilities and 1 to the accessible demand facilities in a damaged networked system. (In this study, an individual facility is assumed to be either fully functional or nonfunctional, as noted previously.); and
5. Repeat Steps 1–4 a sufficient number of times to permit the functionality ratio of each facility to be estimated by taking a numerical average.

Table 3. Parameters of Fragility Curves (FEMA 2003)

Damage state	Gate station Median (g)	Gate station Beta	23-kV substation Median (g)	23-kV substation Beta	12-kV substation Median (g)	12-kV substation Beta
Complete	0.47	0.40	0.70	0.40	0.90	0.45
Extensive	0.20	0.35	0.35	0.40	0.45	0.45

The number of networks analyzed by Monte Carlo simulation for purposes of estimating functionality and serviceability is 10^4 in this study to achieve an acceptable sampling error. The pseudorandom numbers are generated by the Mersenne twister algorithm (Matsumoto and Nishimura 1998).

Results and Discussion

The functionality ratios of each substation and the average functionality ratio of all substations are shown in Figs. 14 and 15 for the complete and extensive damage states identified above. The numbers on the horizontal axis correspond to the substation numbers in Fig. 13. Fig. 14 shows that the functionality ratios of most substations evaluated by the PSH-based approach are almost same as those evaluated by the SE-based approach when the complete damage state fragilities are used. However, the functionality ratios of facilities evaluated by the PSH-based approach are smaller than those evaluated by the SE-based approach when the extensive damage state fragilities are used (Fig. 15). In the latter situation, then, using the PSH-based approach will lead to a pessimistic appraisal (on the order of 5 to 10%) of the readiness of the network following the earthquake.

The trends shown in Figs. 14 and 15 can be explained by the relation between the system fragility curve and the survivor functions in Figs. 16(a and b), similar to those presented in Figs. 12(a and b) in the case study of the simple networked systems in Figs. 8–11. In Figs. 16(a and b), E_a and E_b represent SIs due to SEs identified in Table 1, such as E_a=min $(E_1,E_2,\ldots,E_{10})$ and E_b=max$(E_1,E_2,\ldots,E_{10})$. (The eight remaining intensities are not shown for simplicity.) In contrast, the SI from the PSHA represents the weighted average of the 10 SIs $(E_1,E_2,\ldots,E_{10})$. That SI is within the domain $[E_a,E_b]$. When the fragility curves for the complete damage state are used, Fig. 16(a) shows that the functionality obtained from the SE-based approach $Rs_{\mathrm{SE,complete}}$ is smaller than the functionality obtained from the PSH-based approach $Rs_{\mathrm{PSHA,complete}}$. However, when the fragility curves of extensive damage state are used, Fig. 16(b) shows that the failure probabilities are higher, even though the 10 SIs $(E_1,E_2,\ldots,E_{10})$ and PSHA are the same as those in Fig. 16(a). The functionality from the SE-based approach is larger than the functionality from the PSH-based approach. As in the example with the simple networked systems, the functionalities within the Shelby County electrical distribution system evaluated by the PHS-based approach are different from the functionalities evaluated by the SE-based approach, in some cases significantly.

One can conclude from this study that the use of SI contours from a PSHA yields a conservative estimate of facility function if the network as a whole is exposed to high SIs [e.g., $\mathrm{PSHA}_{1\text{-}2}$ in Fig. 12(b)] or if a less severe damage state is of interest in vulnerability assessment [e.g., DS=extensive in Fig. 16(b)]. Conversely, if the network as a whole is exposed to low SIs [e.g., $\mathrm{PSHA}_{1\text{-}2}$ in Fig. 12(a)] or if a more severe damage state is of interest in vulnerability assessment [e.g., DS=complete in Fig. 16(a)], the PSH-based approach yields an unconservative appraisal of facility and network functionality. Since it is difficult to anticipate what conditions may result in conservative estimates of

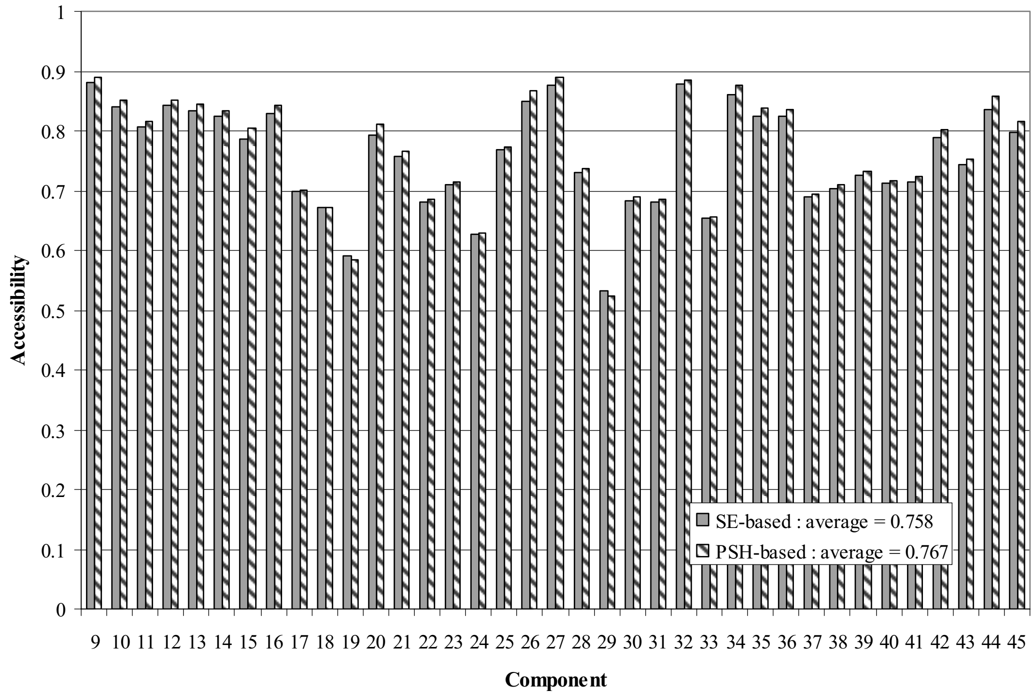

Fig. 14. Functionality ratios of facilities: complete damage state

facility functions, the SE-based approach should be used to provide an accurate assessment of damage to a distributed infrastructure system. Similar trends were obtained for different return periods, which resulted in different weights of seismic events (Adachi 2007).

Conclusions

The functionalities of facilities within a distributed civil infrastructure network were evaluated in this paper for PSH-based and SE-based approaches to specifying seismic hazard. Obstacles to using the PSH-based contours of SI to assess performance of distributed networks were assessed first for simple networks. Further insights then were obtained by an assessment of the electrical power network in Shelby County, Tenn. A comparison of the functionalities obtained revealed that there are inconsistencies in the estimated system functionalities when the PSH-based approach is applied to this particular utility system. The fact that the functionalities within a network are dependent on the system topology, local seismicity, and fragilities of individual facilities

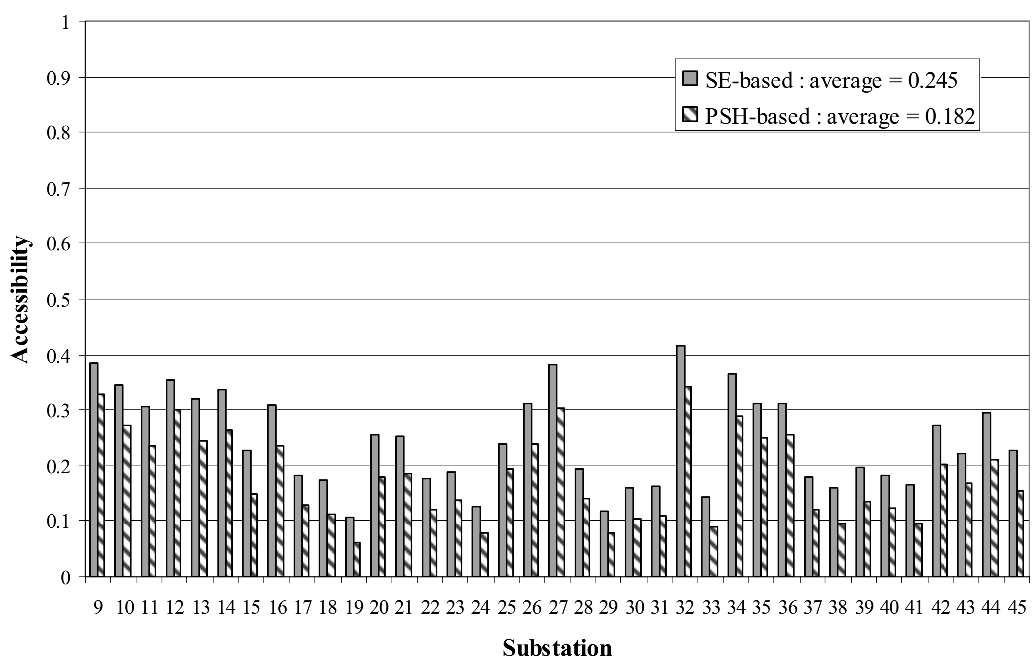

Fig. 15. Functionality ratios of facilities: extensive damage state

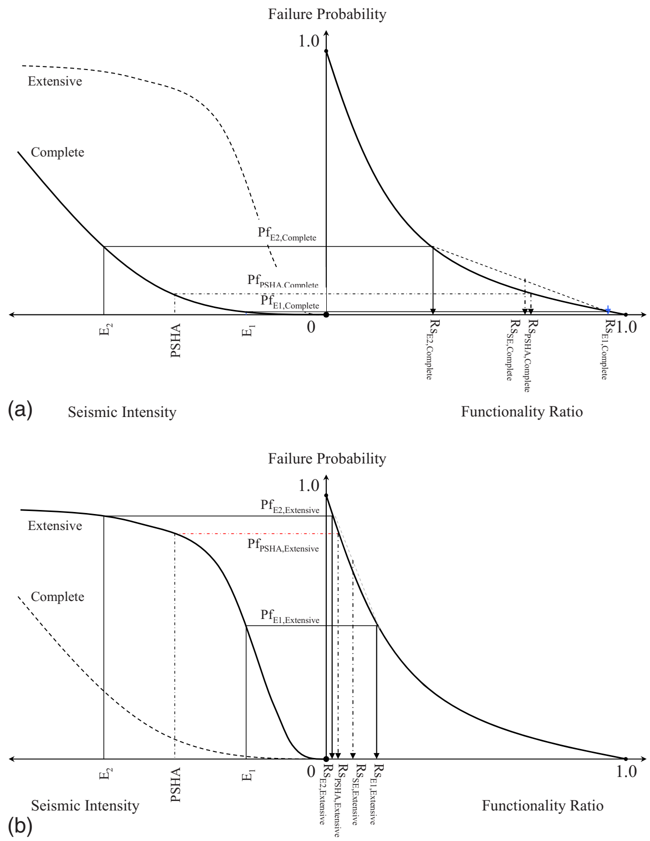

Fig. 16. (a) Functionality ratio evaluated under different system fragility curves: fragility curve of complete damage state; (b) functionality ratio evaluated under different system fragility curves: fragility curve of extensive damage state

makes such conclusions difficult to generalize. Nevertheless, the results of this study suggest that, if at all possible, the SE-based approach should be used to estimate the functionality of facilities in a networked system.

References

Adachi, T. (2007). "Impact of cascading failures on performance assessment of civil infrastructure systems." Ph.D thesis, Georgia Institute of Technology, Atlanta.

Adachi, T., and Ellingwood, B. R. (2008). "Serviceability of earthquake damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability." *Reliab. Eng. Syst. Saf.*, 93(1), 78–88.

Ang, A. H.-S., et al. (1996). "A model for the seismic reliability assessment of electric power transmission systems." *Reliab. Eng. Syst. Saf.*, 51, 7–22.

ASCE. (2005). "Minimum design loads for buildings and other structures." *ASCE 7-05*, New York.

Chang, S. E., and Shinozuka, M. (2000). "Probabilistic earthquake scenarios: Extending risk analysis methodologies to spatially distributed systems." *Earthquake Spectra*, 16(3), 557–572.

Eguchi, R. T. (1991). "Seismic hazard input for lifeline systems." *Struct. Safety*, 10, 193–198.

FEMA. (2003). *HAZUS MH MR1 technical manual*, Washington, D.C.

FEMA. (2004). *FEMA 450: The 2003 NEHRP recommended provisions for new buildings and other structures*, Washington, D.C.

Floyd, R. W. (1962). "Algorithm 97: Shortest path." *Commun. ACM*, 5(6), 345.

Hwang, H., et al. (1998). "Seismic performance assessment of water delivery systems." *J. Infrastruct. Syst.*, 4(3), 118–125.

Jin, X., et al. (2002). "Seismic performance analysis for LADWP power system." *Proc., Power Systems and Communications Infrastructure for the Future*, Beijing.

Matsumoto, M., and Nishimura, T. (1998). "Mersenne twister: 623-dimensionally equidistributed uniform pseudorandom number generator." *ACM Trans. Model. Gener. Methods Appl. Monte Carlo Meth.*, 8(1), 3–30.

McGuire, R. K. (1995). "Probabilistic seismic hazard analysis and design earthquakes: Closing the loop." *Bull. Seismol. Soc. Am.*, 85(5), 1275–1284.

McGuire, R. K. (2001). "Deterministic vs. probabilistic earthquake hazards and risks." *Soil Dyn. Earthquake Eng.*, 21, 377–384.

Piers, J. A., et al. (1996). "Seismic reliability of electrical power transmission systems." *Nucl. Eng. Des.*, 160, 427–439.

Rausand, M., and Hoyland, A. (2004). *System reliability theory*, Wiley-Interscience, New York.

Rinaldi, S. M., et al. (2001). "Critical infrastructure interdependencies." *IEEE Control Syst. Mag.*, December, 11–25.

Shinozuka, M., et al. (1992). "Impact on water supply of a seismically damaged water delivery system." *TCREE Monogr.*, 5, 43–57.

Shinozuka, M., et al. (1998). "Engineering and socioeconomic impact of earthquake—An analysis of electricity lifeline disruptions in the New Madrid area." *MCEER Monogr.*, 2, 33–44.

Shinozuka, M., et al. (1999). "Seismic performance analysis of electric power systems." *Proc., Research Progress and Accomplishments 1997–1999, MCEER*, State Univ. of New York, Buffalo, N.Y., 61–69.

Toro, G. R., et al. (1997). "Model of strong ground motions form earthquakes in Central and Eastern North America: Best estimate and uncertainties." *Seismol. Res. Lett.*, 68(1), 41–57.

U.S.–Canada Power Systems Outage Task Force. (2004). *Final report on the 2003 blackout in the United States and Canada*, U.S. Department of Energy, Washington, D.C.

USGS. (2002a). "Interactive deaggregation." ⟨http://eqint.cr.usgs.gov/eq-men/html/deaggint2002-06.html⟩ (Feb. 26, 2007).

USGS. (2002b). "USGS national seismic hazard maps." ⟨http://earthquake.usgs.gov/research/hazmaps/products_data/2002/us2002.php⟩ (Feb. 26, 2007).

Warshall, S. (1962). "A theorem on Boolean matrices." *J. ACM*, 9(1), 11–12.