Assessing Seismic Failure Probability of Hospital Emergency Power Supply Systems and Software Development

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ABSTRACT: First-aid hospitals are facilities that play a critical role in receiving the injured and performing emergency operations during severe earthquake events. Hospitals must not only maintain the safety of their building structures but also ensure the functionality of their nonstructural components and systems, including emergency power supply systems (EPSSs), water supply systems, communication systems, and a range of medical equipment and systems. Since EPSSs provide electric power for other equipment and systems, it is reasonably considered the most important. Therefore, in this study, we focused on the failure probability analysis of EPSSs and took one hospital in the Great Taipei metropolitan area as our research target. Fragility data of its EPSS components were firstly analyzed by using the fragility function proposed in a previous study. Then, a system logic tree observing the relationship among components would be plotted, enabling failure probability estimation of the whole system in response to varying peak ground acceleration (PGA) values at the site. In order to efficiently identify the seismic risk for medical facilities, this study applied the assessment model and further developed a seismic risk assessment system of first-aid hospitals, or T-Hospital. In T-Hospital, the Rapid Earthquake Information Release System is integrated for real-time earthquake event information, and all first-aid hospitals are classified to three levels: low, moderate, and high. At present, the seismic risk of EPSSs in hospitals could be shown on T-Hospital immediately after an earthquake event.

1 INTRODUCTION

Past earthquake records have documented serious destruction of local hospitals and consequent paralysis of medical services, as what had happened in 1971 San Fernando earthquake, 1994 Northridge earthquake, and 1995 Hanshin earthquake. Since Taiwan is located in Circum-Pacific earthquake zone, over the past few years this situation happened several times when earthquakes with an intensity over 6 hit the island, e.g., 1999 Chi-Chi earthquake, 2006 Taitung earthquake, Hengchun earthquake, and 2010 Jiaxian earthquake in Kaohsiung. It is learned from past events that one of the critical factors determining victims' life safety lies in how to transport patients crowding into nearby hospitals to other medical institutions that still afford certain extent of emergency care within the golden 24 hours.

After the 921 Chi-Chi earthquake, seismic performance of non-structures has drawn researchers' attention. In a survey of four hospitals in Nantou, Chuang and Yao (2001) pointed out that falling objects (e.g. brick walls, ceilings, and dry-hanging stone slabs), floods, a failure of emergency power supplies, and medical equipment malfunction have a significant impact on the functionality of hospitals after a disaster. Chuang and Yao (2001) focused their study on the functionality of hospitals based on the component seismic scoring system proposed by MCEER. It is suggested that to plot a logic tree for systems like air conditioning systems, emergent power, water, as well as heat supply systems, and communication systems, the first step researchers should take is to figure out the relationship among each component in the system. Then, with fragility data of each component plotted in the logic tree, seismic performance scores of the comprehensive system can be calculated.

As studies on the seismic performance of hospitals after the 921 Chi-Chi earthquake were successively completed, to continue researchers' previous efforts and solve the problem of delayed patient transport to appropriate hospitals when disastrous earthquakes attack, the current study is a follow-up research to the previous study on the fragility of emergency power supply components by Lin's et al. (2016; 2017a; 2017b). This study aims at exploring the overall EPSS of our cooperative hospital in Taipei, including evaluating seismic performance of the system, assigning fragility parameters of components, and plotting a system logic tree. Four major types of emergency power supply components (EPSC) were identified, namely generators (G), batteries (B), diesel tanks (DT), and cooling towers (CT). The seismic fragility analysis of these components was based on the component seismic scoring system developed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). On the other hand, a system logic tree would be constructed after interview surveys to depict the relationship of the four components in the system. With that logic tree, seismic fragility of the entire EPSS could be obtained by mathematical calculations.

The ultimate goal of this study is to develop seismic scenario-based simulation techniques with automatic failure probability assessment, and taking advantage of the techniques, we further build a seismic risk assessment software, named T-Hospital. At the current stage, T-Hospital is constructed for failure probability assessment of EPSSs, but it will not be restricted to this single function. In the future, we intend to extend its assessment function to equipment as well as supply systems of all kinds. In addition to failure probability assessment, what is more important should be the estimation of recovery cost and time if the failure unfortunately happens so that patient accommodation and transport can be more effectively and efficiently administered. Moreover, hospital operators' concerns in the long run are also considered. Estimation of financial losses as a result of repairs and declined medical capacity will also be integrated into the system. Briefly speaking, T-Hospital is designed as a comprehensive system that thoroughly provides estimation of every aspect of hospitals under the condition of earthquakes.

2 FRAGILITY ANALYSIS OF THE EMERGENCY POWER SUPPLY SYSTEM IN THE HOSPITAL

2.1 Main equipment

The hospital cooperating with us in this study is in the Great Taipei metropolitan area and has an independent three-floor building serving for electrical mechanical center. After interviews with the management technician, four important equipment items in the EPSS were identified: generators (G), batteries (B), diesel tanks (DT), and cooling towers (CT), as shown in Figure 1.

Generator: 7 generators in total, 4 in Group A (1A-4A) and 3 in Group B (1B-3B).

Battery: one set for each generator, i.e., 7 sets in total.

Diesel Tank: one diesel tank for each generator, with a total of 7 tanks.

Cooling Tower: one cooling tower for each generator, i.e., 7 cooling towers in total.

Figure 1. Main components in the emergency power supply system.

2.2 Seismic fragility of equipment

In earthquake engineering, seismic fragility is commonly used to quantify the failure probabilities of both structures and non-structures. Current study takes Peak Ground Acceleration (PGA) as the parameter of ground shaking. We assume that fragility has a logarithmic normal distribution with two parameters, χ_m (median) and β (standard deviation). The equation is described as follows:

$$P(\alpha) = \Phi\left[\frac{ln(\alpha/x_m)}{\beta}\right] \quad (1)$$

where P is the failure probability, Φ[·] is the standardized normal distribution, and α is the parameter of ground shaking (i.e. PGA here).

Based on the previous study on the fragility of emergency power supply components by Lin et al. (2016; 2017a; 2017b) and results of site surveys, seismic fragility reports of the four components containing information about their deficiencies regarding seismic performance and the floor where items are placed were completed. The reports of our cooperative hospital are presented below from Table 1 to Table 4.

Table 1. Reports of seismic fragility for generators

Item	Item ID	Seismic performance	Floor	χ_m	β
Generator	G_1A	Poor anchorage	3	0.91	0.5
	G_2A	Poor anchorage	3	0.91	0.5
	G_3A	Poor anchorage	3	0.91	0.5
	G_4A	Poor anchorage	3	0.91	0.5
	G_1B	High-standard installation	3	2	0.4
	G_2B	Vibration isolator concerns	3	0.91	0.5
	G_3B	Vibration isolator concerns	3	0.91	0.5

Table 2. Reports of seismic fragility for batteries

Item	Item ID	Seismic performance	Floor	χ_m	β
Battery	B_1A	No anchorage	3	0.67	0.5
	B_2A	No anchorage	3	0.67	0.5
	B_3A	No anchorage	3	0.67	0.5
	B_4A	No anchorage	3	0.67	0.5
	B_1B	No battery restraints	3	0.58	0.5
	B_2B	No anchorage	3	0.67	0.5
	B_3B	No anchorage	3	0.67	0.5

Table 3. Reports of seismic fragility for cooling towers

Item	Item ID	Seismic performance	Floor	χ_m	β
Cooling tower	CT_1A	Unanchored skid	RF	0.91	0.5
	CT_2A	Unanchored skid	RF	0.91	0.5
	CT_3A	Unanchored skid	RF	0.91	0.5
	CT_4A	Unanchored skid	RF	0.91	0.5
	CT_1B	Unanchored skid	RF	0.91	0.5
	CT_2B	Unanchored skid	RF	0.91	0.5
	CT_3B	Unanchored skid	RF	0.91	0.5

*RF stands for roof floor.

Table 4. Reports of seismic fragility for diesel tanks

Item	Item ID	Seismic performance	Floor	χ_m	β
Diesel tank	DT_1A	Unanchored or poor anchorage	3	0.56	0.5
	DT_2A	Unanchored or poor anchorage	3	0.56	0.5
	DT_3A	Unanchored or poor anchorage	3	0.56	0.5
	DT_4A	Unanchored or poor anchorage	3	0.56	0.5

DT_1B	Unanchored or poor anchorage	3	0.56	0.5
DT_2B	Unanchored or poor anchorage	3	0.56	0.5
DT_3B	Unanchored or poor anchorage	3	0.56	0.5

2.3 Logic tree of the emergency power supply system

According to the data provided by the management technician in charge of the EPSS, a logic three was plotted, as presented in Figure 2 below. The seven generators are grouped to Group A and Group B, with 4 generators in Group A and 3 in Group B. Generators within each group are connected in parallel, and so are the two generator groups. Every generator is equipped with one diesel tank, batteries, and one cooling tower.

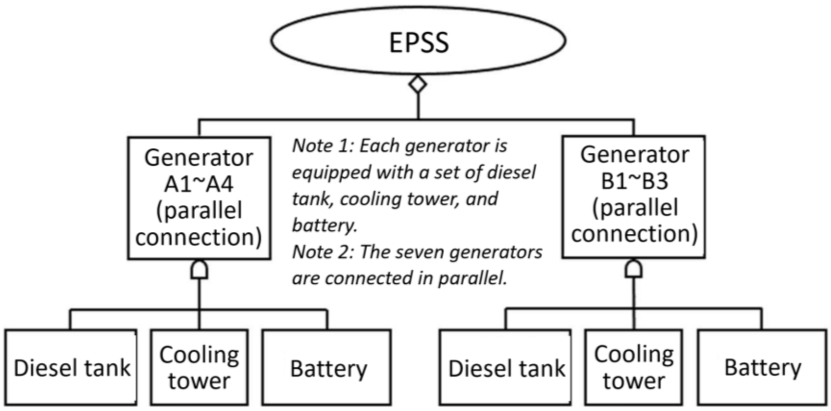

Figure 2. Logic tree of the emergency power supply system.

As shown in Figure 2, the logical relationship among components can be directly perceived by graphically connecting and arranging components in a logic tree. The upmost oval block in the tree names the overall system. Each component in the system is represented by a square and is hierarchically arranged. Two types of symbols are used to represent relationship of the two immediate layers. The symbol ⌂ is "and gate" and the other symbol ◊ is "or gate". Connection of layers by "and gate" implies that the components or systems at the upper level can function properly only if all the components at the next level are available. As for the connection by "or gate", it means that the proper function of at least one subordinate component is enough to keep the function of the superordinate components or systems intact.

Failure probability of the whole system can be calculated by using the mathematic equations of logic trees. The equations for "and gate" and "or gate" are respectively provided below:

$$P[u] = 1 - \prod_{i=1}^{n}(1 - P[l_i]) \quad (and\ gate\ ⌂) \tag{2}$$

$$P[u] = \prod_{i=1}^{n} P[l_i] \quad (or\ gate\ ◊) \tag{3}$$

where $P[li]$ is the failure probabilities of the component li, $P[u]$ refers to the failure probabilities of the upper event, Π is the product, and n refers to the number of lower events.

With the seismic fragility analysis of main equipment and the mathematic equations of logic trees, fragility of a comprehensive emergency power supply system can be obtained. Take the hospital discussed in this paper as an example. Figure 3 exhibits the fragility of its EPSS with a median of 0.34g and a standard deviation of 0.20g.

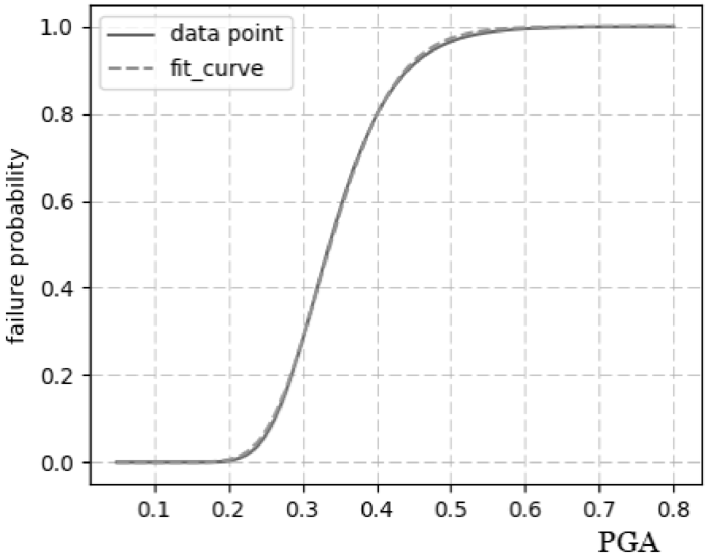

Figure 3. Fragility curve of the emergency power supply system.

3 SEISMIC RISK ASSESSMENT SOFTWARE (T-HOSPITAL)

3.1 Earthquake events

This study applied the Python module *urllib2* to fetch Internet resources, primarily from the Rapid Earthquake Information Release System (RTD) of Central Weather Bureau, P-alert, and seismic stations from National Center of Research on Earthquake Engineering (NCREE). The collected data were compiled for future use.

Central Weather Bureau Seismic Stations: RTD data are from two sources: (1) data sent by Central Weather Bureau after the occurrence of earthquakes and will be received in 3 to 5 minutes in average, and (2) data released on the website of Central Weather Bureau.

P-alert + NCREE: P-alert seismic stations are developed by Professor Wu in National Taiwan University and integrated into the NCREE seismic systems. When an earthquake occurs, the raw data collected from P-alert and each NCREE seismic stations, including the time, the station ID, and PGA, will be pushed to the intranet website of NCREE in about 3 to 5 minutes.

TELES earthquake event database: Seismic risk assessment system of first-aid hospitals (T-Hospital) is developed with a goal to estimate losses in simulated seismic events. In this regard, more than twenty thousand simulated events with hazard data generated by TELES are imported into this system.

3.2 Current T-Hospital interface supporting EPSS assessment

The current version of T-Hospital interface has three panes, respectively for specifying earthquake events, computing hospital assessment, and map demonstration (as shown in Figure 4). Users can directly specify one earthquake event and select a hospital for computation with all its information shown on the interface (including address, hospital level, number of beds, and failure probabilities). The estimated failure probabilities are ranked to three levels marked by different colors (see Table 5). A map that visualizes PGA and location of hospitals is also provided. The visualized exhibition helps users perceive seismic risk of hospitals in a quick and instinctive manner. Figure 4 uses Shanchiao fault movement as an example to demonstrate how it work for the target hospital in this paper. Messages and implications of the results shown on the interface will be further elaborated in the next section.

Table 5. Ranking of EPSS failure probabilities

Level	Color marking	
Slight damage: 0% ~ 40%	Green	Slight damage may be caused but EPSS functionality keeps intact.
Moderate damage: 40% ~ 70%	Yellow	More than 50% EPSS functionality is maintained.
Severe damage: 70% ~ 100%	Red	EPSS may lose more than 50% functionality or even break down completely.

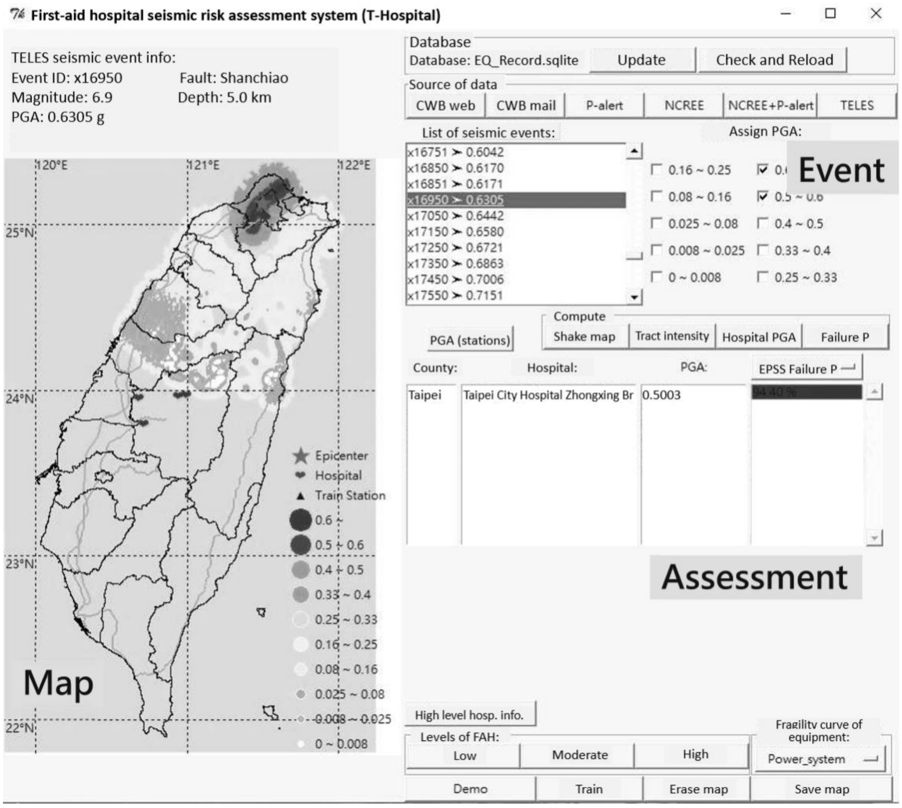

Figure 4. Current T-Hospital interface.

3.3 Earthquake event case elaboration

Figure 4 uses Shanchiao fault movement as a case to demonstrate the seismic risk assessment software. In that scenario, seismic magnitude is 6.9, depth of focus is 5.0 kilometers, and PGA is 0.63g. The EPSS logic tree of the cooperative hospital is already available in the database. Based on the seismic hazards and mathematical calculations, failure probability of its EPSS can be estimated and shown on the screen. The failure probability of the EPSS in the cooperative hospital is 94.40% and, therefore, is marked red.

4 CONCLUSION AND OUTLOOK

Hospitals play a crucial role in providing medical services after a massive earthquake. In order to have the real-time seismic risk assessment data, this study is an initial attempt on the development of the risk assessment model for EPSSs after earthquakes. The assessment model was directly applied to our cooperative hospital in the Great Taipei metropolitan area, and together with the information obtained from site surveys, this model helped estimate the failure probability of its EPSS. The establishment of this assessment model benefits the pioneer design of the risk assessment system, T-Hospital. In the current stage, a preliminary version of T-Hospital that supports failure probability assessment of EPSSs has been produced. In the future, the same approach can be replicated to integrate the assessment of other equipment and supply systems in hospitals into T-Hospital, making its function in failure probability assessment more complete. The function of T-Hospital can also be expanded to the estimation of repair time and repair cost if destruction is already caused in an earthquake event. Finally, this system can even be extended to include a function directed to hospital operators, which provides estimation of possible business losses due to the repairs and a decline in patient accommodation. As long as T-Hospital is fully developed, it should be helpful for the decision makers to plan strategies for emergent medical services and manage medical resources across areas in a more efficient and economical way.

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