Quantifying Hospital Resilience to Earthquakes Based on System Dynamics Modeling

Zaishang Li, S.M.ASCE[1]; Nan Li, M.ASCE[2]; Gian Paolo Cimellaro, A.M.ASCE[3]; and Dongping Fang[4]

[1]Ph.D. Student, Dept. of Construction Management, Tsinghua Univ., Beijing 100084, China. E-mail: lizs15@mails.tsinghua.edu.cn
[2]Associate Professor, Dept. of Construction Management, Tsinghua Univ., Beijing 100084, China. E-mail: nanli@tsinghua.edu.cn
[3]Associate Professor, Dept. of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin 10129, Italy. E-mail: gianpaolo.cimellaro@polito.it
[4]Professor, Dept. of Construction Management, Tsinghua Univ., Beijing 100084, China. E-mail: fangdp@tsinghua.edu.cn

ABSTRACT

Hospitals play a crucial role in the mitigation and recovery of earthquake-hit regions, which are expected to be resilient enough so as to provide medical care that is badly needed in the aftermath of earthquakes. Nevertheless, there lack appropriate quantitative assessment approaches of hospital earthquake resilience, which makes it challenging for devising and benchmarking resilience enhancement measures. In this paper, a quantitative assessment approach of hospital resilience to earthquakes considering the physical damage and the recovery of hospital functionality is proposed. A system dynamics (SD) model is developed to simulate the hospital functionality hence enabling quantification of hospital resilience to earthquakes. The efficacy of the proposed approach is validated in a case study. The proposed approach can provide a tool for hospitals to quantitatively assess their resilience to earthquakes so as to propose targeted resilience enhancement measures for future earthquakes.

INTRODUCTION

Earthquakes are one of the most destructive disasters in the world, which usually cause not only severe economic losses but also a mass of injuries and fatalities. Hospitals play a crucial role in the mitigation and recovery of earthquake-hit regions, providing continued access to care (Cimellaro et al. 2018). Meanwhile, hospitals are themselves likely subjects to disaster impacts. Damage of hospital buildings and medical equipment and loss of supplies and staff will undoubtedly result in a loss of hospital functionality, which exacerbates the disaster effects. The disaster resilience of hospitals, which is focused on "a system's overall ability to prepare and plan for, absorb and recover from catastrophic events, and sustain required operations under both expected and unexpected conditions", has attracted increasing attention (Cimellaro et al. 2018). The Sendai Framework for Disaster Risk Reduction 2015 - 2030 highlighted that the enhancement of hospital resilience to disasters was one important part of the "Priorities for action" (UNISDR 2015). In order to improve the disaster resilience of hospitals, quantifying the resilience level is of fundamental importance, as it can benchmark the effectiveness of resilience improvement measures. However, prior quantitative assessment approaches of hospital disaster resilience have been more concerned about organizational aspects, using "waiting time" as a primary indicator of hospital functionality, and have a large extent ignored the physical damage and the recovery of hospital functionality.

In this paper, a new quantitative assessment approach of hospital resilience to earthquakes is proposed by introducing a definition of hospital functionality during earthquakes and an SD model which depicts the hospital operation and calculates hospital functionality, considering both the physical damage and the recovery process of hospitals. The proposed approach can serve as a tool to understand the dynamics of hospital functionality and quantify hospital resilience to earthquakes, the results of which can assist hospitals to propose targeted resilience enhancement measures to cope with future earthquakes.

RELATED WORK

Current assessment approaches of hospital disaster resilience can be divided into qualitative assessment approaches and quantitative assessment approaches. In studies on qualitative assessment approaches, hospital resilience is evaluated based on a series of indicators. WHO (2015) released the Hospital Safety Index Guide for Evaluators (Second Edition) in 2015, which provided a comprehensive checklist of indices for hospital safety and resilience assessment. Similarly, Zhong et al. (2015) established a framework of hospital disaster resilience and proposed a set of indicators for resilience assessment. However, many of the indicators are usually described qualitatively, which sometimes makes them challenging to evaluate. Meanwhile, it is difficult to conduct parametric analysis in different scenarios using qualitative assessment approaches, which is crucial to the proposition and evaluation of possible resilience enhancement measures. Quantitative resilience assessment approaches can overcome the limitations. The resilience of a system (R) can be calculated by integrating the system functionality ($Q(t)$) from the occurrence of the event (t_0) over a control time (t_{LC}), as shown in Eq. (1) (Cimellaro et al. 2016).

$$R = \int_{t_0}^{t_0+t_{LC}} \frac{Q(t)}{t_{LC}} dt \tag{1}$$

When assessing hospital resilience to disasters like earthquakes using the quantitative approach, it is necessary to define hospital functionality first. Previous studies took "waiting time" as an indicator of hospital functionality (Cimellaro et al. 2011). These studies assumed that the hospital was normally operated and the physical damage of the hospital was considered in a highly simplified way (e.g. introducing a "penalty factor" to the waiting time) (Cimellaro et al. 2011). However, the operation of hospitals may change significantly when hospitals are damaged by disasters, which in turn results in the change of waiting time. Moreover, few studies are focused on the recovery of hospital functionality which is an important part of resilience. Therefore, a new definition of hospital functionality during earthquakes as well as a quantitative assessment approach of hospital disaster resilience is needed.

RESEARCH FRAMEWORK

According to Eq. (1), $Q(t)$, namely the hospital functionality during earthquakes, should be defined and calculated first in order to quantify hospital resilience to earthquakes. In this paper, a quantifiable definition of hospital functionality during earthquakes is proposed based on semi-structured interviews conducted in China. Considering the complexity of hospitals and the dynamics of hospital operation, the SD approach is suggested to simulate and calculate the hospital functionality during earthquakes. Then, after calculating $Q(t)$ and setting t_0 and t_{LC}, the hospital resilience to earthquakes can be quantified using Eq. (1).

HOSPITAL FUNCTIONALITY DURING EARTHQUAKES

In order to have an in-depth understanding of hospital functionality, semi-structured interviews were carried out in Mianzhu City in December 2017, which was one of the worst-hit areas in the 2008 Sichuan Earthquake. Seven senior medical staff, who participated in the medical rescue in the earthquake, were interviewed. The medical staff were requested to introduce the scenario of the medical rescue during the earthquake and give opinions on hospital functionality during earthquakes. Qualifications of the interviewees are summarized in Table 1.

Table 1. Qualifications of the medical staff involved in the interviews

Interviewee	*Hospital*	*Current title*	*Length of service*
Doctor 1	A	Associate chief physician	25 years
Doctor 2	A	Associate chief physician	18 years
Doctor 3	B	Associate chief physician	24 years
Doctor 4	C	Attending doctor	23 years
Nurse 1	A	Senior nurse	23 years
Nurse 2	B	Senior nurse	29 years
Nurse 3	D	Senior nurse	44 years

Hospitals are multifunctional. It's meaningful to focus on the basic function under the condition of limited resources. During emergencies, minimizing mortality and morbidity has been seen as a primary objective of hospital services (West 2001). Similarly, according to the interviews, the medical staff also argued that their primary job during the earthquake was just to treat as many patients as possible. Therefore, in this paper, the hospital functionality during earthquakes ($Q(t)$) is defined as the ratio of the number of patients which a hospital is able to treat ($N^a(t)$) to the number of patients which a hospital is required to treat ($N^r(t)$) over a period as shown in Eq. (2):

$$Q(t)=\frac{N^a(t)}{N^r(t)}=\frac{\sum\beta_i N_i^a(t)}{\sum\beta_i N_i^r(t)}=\sum\frac{\beta_i N_i^r(t)}{\sum\beta_i N_i^r(t)}\cdot\frac{\beta_i N_i^a(t)}{\beta_i N_i^r(t)}=\sum\alpha_i(t)\cdot\frac{N_i^a(t)}{N_i^r(t)} \tag{2}$$

where t denotes the time in days, $N_i^a(t)$ denotes the number of patients with disease i which the hospital is able to treat on day t $(N_i^a(t)\leq N_i^r(t))$, $N_i^r(t)$ denotes the number of patients with disease i which the hospital is required to treat on day t, β_i denotes the weight of disease i and $\alpha_i(t)$ can be seen as the adjusted proportion of patients with disease i the hospital is required to treat. $N_i^r(t)$ can be set by the hospital or the local health authorities according to the capability of the hospital and the historical data of patient arrivals during similar disasters. β_i can be set by medical experts according to the urgency of diseases.

Moreover, shortage of doctors, loss of medical supplies, and malfunction of operating rooms and other medical equipment almost appeared in all the hospitals in Mianzhu City during the 2008 Sichuan Earthquake according to the interviews, which made it much more challenging to provide effective and timely treatment and resulted in many deaths of patients. Hence, it is assumed that $N_i^a(t)$ mainly relies on the minimum level of three types of necessary medical resources: medical staff (e.g. doctors, nurses…), medical supplies (e.g. drugs, bandages, beds…) and medical equipment (e.g. X-ray, operating rooms…) as shown in Eq. (3):

$$N_i^a(t) = \min[(S^a{}_{i,1}(t),\ldots,S^a{}_{i,p}(t)),(M^a{}_{i,1}(t),\ldots,M^a{}_{i,q}(t)),(E^a{}_{i,1}(t),\ldots,E^a{}_{i,r}(t))]$$
$$p \in (1,n_S); q \in (1,n_M); r \in (1,n_E) \qquad (3)$$

where $S_{i,p}^a(t)$, $M_{i,q}^a(t)$ and $E_{i,r}^a(t)$ denote the service capacity (the maximum number of patients treated with the resources) of each kind of medical staff, medical supplies and medical equipment respectively for disease i on day t; n_s, n_M and n_E denote the number of kinds of each type of medical resources. There are some hypotheses for the proposed equations: (1) once a patient receives treatment, he or she will be cured; (2) the number of patients who can receive treatment only relies on medical staff, medical supplies and medical equipment; (3) medical resources for the treatment of each disease are independent with each other, which means that the resources for disease i cannot be used for other diseases; and (4) utilities such as roads, power and water are considered to affect hospital functionality by affecting medical resources.

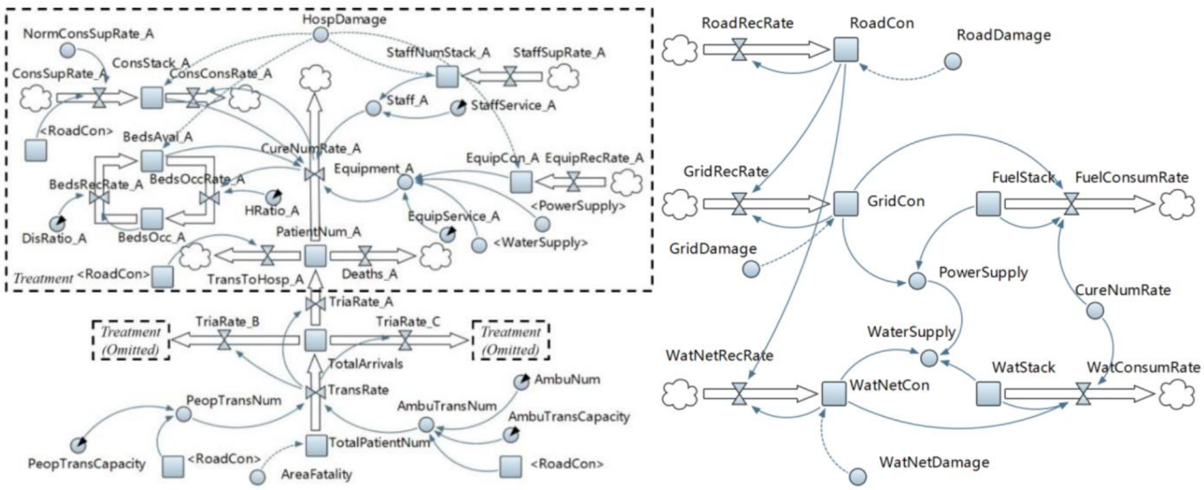

Figure 1. A brief illustration of the proposed SD model

SD MODELING FOR HOSPITAL FUNCTIONALITY

The SD approach has been widely used in healthcare modeling during emergencies (Arboleda et al. 2007). However, these studies usually assumed that the operation of the hospital was not affected during disasters. In this paper, an SD model is developed to calculate the hospital functionality during earthquakes, which is then used to assess the hospital earthquake resilience.

After the earthquake happens, patients are generated and then transferred to the hospital by ambulance or themselves. Patients get treated after being triaged. Those who receive effective treatment may be discharged while the rest will be transferred to other healthcare facilities or morgues (Cimellaro et al. 2017). Based on the above basic process, an SD model to depict hospital operation and calculate hospital functionality during earthquakes was proposed. Different from prior studies which detailed the intermediate process of treatment, it was assumed that whether a patient could be cured only depended on the level of the three types of medical resources (medical staff, medical supplies and medical equipment) considering that the treatment process would change a lot once the hospital was damaged. Three utilities, namely roads, power and water were also taken into account (Arboleda et al. 2007). The road condition would affect the transfer of patients and the supplement rate of medical supplies. The accessibility of power, which relied on the condition of the power grid as well as the fuel storage for generators in the hospital, would affect the availability of medical equipment. Currently, only medical water for equipment was considered necessary for treatment in this study and the water supply depended on the condition of the water network, the water storage and the power supply. Damage and recovery of medical resources and utilities was taken into account. It should be noted that estimation of the damage and fatalities was considered in the SD model but not detailed since it was out of the scope of this paper. However, the variables related to hospital damage and fatalities set in the SD model could serve as "interfaces" to the models of damage and fatality analysis. Factors such as communication, management and so forth were not included since their influence on hospital functionality were challenging to quantify. A brief illustration of the SD model is shown in Figure 1.

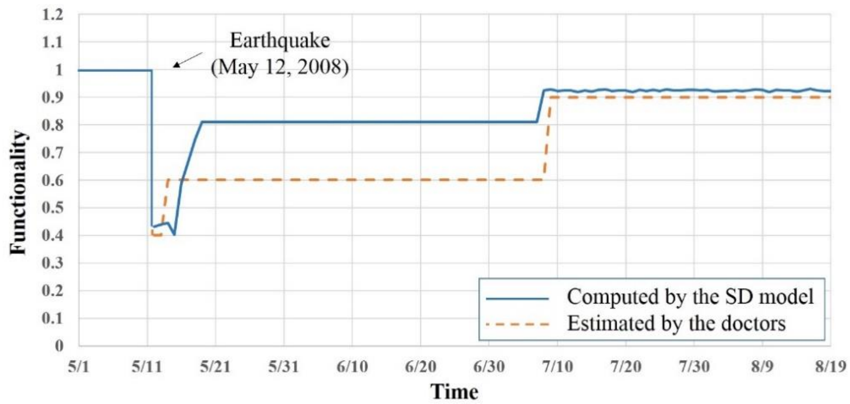

Figure 2. Hospital functionality during the earthquake

Another round of semi-structured interviews was conducted in August 2018 to ensure the model's appropriateness in depicting the structure of the real system. Six senior doctors were interviewed one by one, including the four doctors who had participated in the aforementioned interviews in 2017 and another two senior doctors (one associate chief physician with a 32-year length of service from hospital E and one physician with 27-year length of service from hospital C, both of whom had participated in the medical rescue in the 2008 Sichuan Earthquake). The equations to define hospital functionality and the SD model were introduced comprehensively and the interviewees were asked a series of preset questions to give opinions. The interviewees generally agreed to the equations and the basic structure of the SD model. One doctor advised the authors to add a variable of "knowledge of disaster medicine" to adjust the performance of the medical staff and a variable of "information" to reflect the effectiveness of communication during the supplement of medical supplies. The authors strongly agreed with the doctor but these modifications were not made since the two variables were not easy to quantify, which would be considered in future work.

CASE STUDY

A case study was carried out to apply the proposed approach to quantify the resilience of a tertiary hospital in Mianzhu City to the 2008 Sichuan Earthquake. The hospital, which has 293 doctors and 500 licensed beds currently, was damaged structurally during the earthquake and then reconstructed. Data for the SD simulation were extracted from the local disaster relief records or gathered by interviewing the staff in the case hospital, such as the recovery rate of utilities, the loss of medical resources and service capacities of medical resources. Some necessary data which could not be obtained were reasonably assumed. For example, the data from another hospital of similar level located in another city (Liu et al. 2008), which was also one of the worst-hit areas in the earthquake, were used to estimate the patient arrivals by diseases after being scaled by the total casualties and injuries in the two cities. There were four typical kinds of diseases considered in the case study: trauma A (e.g. abrasion), trauma B (e.g. fractures, head injuries etc.), upper respiratory infection (URI) and enteritis and others. The weights (β) of these four kinds of diseases were set equal (0.25). Operating rooms were the only kind of medical equipment considered and it was assumed that operations were only necessary for trauma B. Delay was considered in the supplement of medical supplies. Gaussian noise was introduced to reflect the fluctuations of the service capacity of the medical resources. After setting all the parameters, the SD model was run to quantify the resilience of the case hospital based on Eq. (2) and (3). The software used in this paper was Anylogic 8.3.1 PLE.

RESULTS AND DISCUSSIONS

The solid curve in Figure 2 illustrated the results of the resilience assessment of the hospital based on the proposed approach. When the earthquake happened, the level of the hospital functionality decreased abruptly to 0.43 due to the loss of medical supplies. Then as the supplement of medical supplies arrived, the functionality recovered a little but then decreased again due to the surge of patients. On around May 19, when the medical supplies were sufficient for the patients but the operating rooms were still unavailable, the level of functionality was about 0.81. From July 8, 2008, the functionality was around 0.92 when the medical staff worked in the well-equipped portable dwellings where, however, major operations were still unable to be conducted due to the limitations of the operating rooms until the new hospital building was put into use in May 2010. Setting t_0 as May 12, 2008, and assuming t_{LC} as three months (90 days), the resilience level was calculated as 0.83 according to Eq. (1).

There was also a dashed curve in Figure 2, which was the estimated functionality level by the doctors from the case hospital during the interviews. In order to facilitate them to understand the question, the functionality was simply described as "the percentage of patients the hospital was able to treat". According to the doctors, there were three obvious stages of hospital functionality: treatment on site, treatment in tents and treatment in portable dwellings. The functionality during the three stages were about 0.4, 0.6 and 0.9 respectively. Setting t_0 as May 12, 2008, and t_{LC} as 90 days, the estimated resilience level was 0.75 based on Eq. (1).

It could be seen from Figure 2 that the two curves varied in similar trends, which demonstrated the efficacy of the proposed approach for assessing the disaster resilience of the hospital. The level of hospital functionality computed by the SD model was higher than that estimated by the doctors most of the time, which might be because of the assumed patient arrivals due to the limitation of data. It should be noted that the objective of this case study was not to accurately quantify the earthquake resilience of the case hospital since there were many assumptions due to data limitations. However, the similar trends of the two curves still showed that the results computed by the SD model could reflect the basic characteristics of the hospital resilience (e.g. the staged variations of functionality). In addition, the proposed approach had the potential to predict the hospital resilience to future earthquakes, which would be helpful for hospitals to propose targeted policies for improving the resilience level.

CONCLUSION

This study proposed a new quantitative assessment approach of hospital earthquake resilience. The hospital functionality was defined, and an SD model was proposed to quantify the hospital functionality during the earthquakes which was for the further resilience assessment. The feasibility and effectiveness of the approach were validated using a case study. However, there are still some limitations in this study. First, some factors such as communication, management and so forth which might also affect the performance of treatment, were not considered in the current stage since they were challenging to quantify. Second, there were many assumptions in the case study as a result of the insufficient data. The results of hospital resilience assessment based on the proposed approach could be more accurate should more data were available.

ACKNOWLEDGMENT

This material is based on work supported by National Natural Science Foundation of China (NSFC) under Grant No. U1709212, Tsinghua University Initiative Scientific Research Program under Grant No. 2015THZ0, Smart City Research Center of Zhejiang Province, Smart City Regional Collaborative Innovation Center of Zhejiang Province and the European Research Council under the Grant Agreement No. 637842 of the project IDEAL RESCUE-Integrated Design and Control of Sustainable Communities during Emergencies. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agencies.

REFERENCES

Arboleda, C. A., Abraham, D. M., Lubitz, R. (2007). "Simulation as a tool to assess the vulnerability of the operation of a health care facility". *Journal of Performance of Constructed Facilities*, 21, 302-312.

Cimellaro, G. P., Malavisi, M., Mahin, S. (2017). "Using Discrete Event Simulation Models to Evaluate Resilience of an Emergency Department". *Journal of Earthquake Engineering*, 21, 203-226.

Cimellaro, G. P., Malavisi, M., Mahin, S. (2018). "Factor Analysis to Evaluate Hospital Resilience". *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems Part a-Civil Engineering*, 4.

Cimellaro, G. P., Reinhorn, A. M., Bruneau, M. (2011). "Performance-based metamodel for healthcare facilities". *Earthquake Engineering & Structural Dynamics*, 40, 1197-1217.

Cimellaro, G. P., Renschler, C., Reinhorn, A. M., Arendt, L. (2016). "PEOPLES: A Framework for Evaluating Resilience". *Journal of Structural Engineering*, 142, 04016063.

Liu, B., Mao, S., Wu, Z., Liu, C., Chen, D., Sun, T., Qiang, C., Yang, C. (2008). "Analysis on the Spectrum of Disease of Outpatients in Wenchuan People's Hospital after Earthquake". *Journal of Preventive Medicine Information*, 24, 860-861.

UNISDR (2015). "Sendai Framework for Disaster Risk Reduction 2015 - 2030".

West, R. (2001). "Objective standards for the emergency services: emergency admission to hospital". *Journal of the Royal Society of Medicine*, 94, 4-8.

WHO (2015). "Hospital safety index: Guide for evaluators". Second edition. Switzerland: World Heath Organization.

Zhong, S., Clark, M., Hou, X., Zang, Y., Fitzgerald, G. (2015). "Development of key indicators of hospital resilience: a modified Delphi study". *Journal of Health Services Research & Policy*, 20, 74-82.