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Using discrete event simulation to evaluate the post-earthquake surge capacity in hospital emergency departments

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ABSTRACT

Damage to structural and nonstructural components of hospital buildings can limit emergency department functionality after a large seismic event. Integrating post-earthquake functionality assessments into emergency department simulations is therefore critical to understanding a hospital's surge capacity. This paper presents a methodology to estimate the ratio of patient demand from casualties within a hospital catchment area to expected post-earthquake emergency department capacity, considering damage-induced loss of function. Discrete Event Simulation (DES) was used to simulate patient flow through a damaged emergency department and to quantify hospital performance by estimating patient wait time and length of stay. A case study hospital, constructed in the 1970s in Vancouver, Canada, was subjected to 30 M_w9.0 Cascadia Subduction Zone earthquake simulations. DES results show the patient wait time limit of 2 hours was exceeded in 7 of the 30 scenarios. The mean patient length of stay for all 30 scenarios nearly doubled from 6.5 hours to 12.5 hours. The methodology developed supports planning efforts by enabling the simulation of emergency department operability in hospitals after an earthquake with explicit consideration of the impact of building damage on functionality. The results can be used as a decision support tool to improve healthcare disaster planning.

Introduction

The performance of existing hospital buildings in past earthquakes demonstrates the need to integrate expected structural and nonstructural component damage into emergency planning protocols. Loss of function in hospitals and other healthcare infrastructure has been observed in recent earthquake events. Following the 2011 Christchurch earthquake (New Zealand), healthcare facilities experienced weeks to months of downtime despite little structural damage [1]. Significant losses in beds and services (i.e., radiology, laboratory, sterilization) were also observed in the 2010 Maule earthquake (Chile); structural damage, however, was only observed in one hospital [2]. The impedance of nonstructural component damage on the ability of healthcare professionals to provide care highlights the need to link nonstructural damage to loss of function in hospitals.

A supply-demand methodology was developed by Ceferino et al. [3] to assess a network of hospitals in Lima, Peru and the surrounding areas to account for the likely disparity between the reduced capacity of hospitals and the surge of patients from the surrounding area. In this study, this concept was applied to a single emergency department in a hospital in Vancouver, Canada, to determine the deficit in care due to the loss of function in the hospital and the surge in patients from the hospital catchment area, following a novel methodology developed by Palomino Romani et al. [4]. A multi-severity casualty estimation was performed

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to determine the number and acuity of patients arriving to the emergency department under a range of earthquake scenarios. A simplified nonlinear dynamic analysis of the hospital structure was then performed, under the same earthquake scenarios, to determine engineering demand parameters, which were used to explicitly calculate the anticipated loss of function based on expected damage.

Discrete Event Simulation (DES) has been used in previous studies [5–7] to model patient flow through an emergency department to estimate patient wait times and lengths of stay. However, few studies have incorporated the loss of hospital capacity into their assessments. Notably, Cimellaro, Malavisi and Mahin [7] used DES to estimate wait times, incorporating expected loss of hospital capacity for various earthquake intensity levels using penalty factors. In this work, we used DES to model an emergency department response and build on previous studies by explicitly calculating patient arrivals using multi-severity casualty estimation and loss of function using decision trees developed by Yavari et al. [8]. This methodology enables the simulation of post-earthquake emergency department operability in existing hospitals with explicit consideration of the impact of structural and nonstructural damage on functionality.

Methodology

The steps of the proposed methodology are summarized in Figure 1. The methodology consists of four phases: (1) seismic hazard, (2) hospital demand, (3) hospital functionality loss, and (4) post-earthquake surge capacity. Details of the methodology can be found in [4].

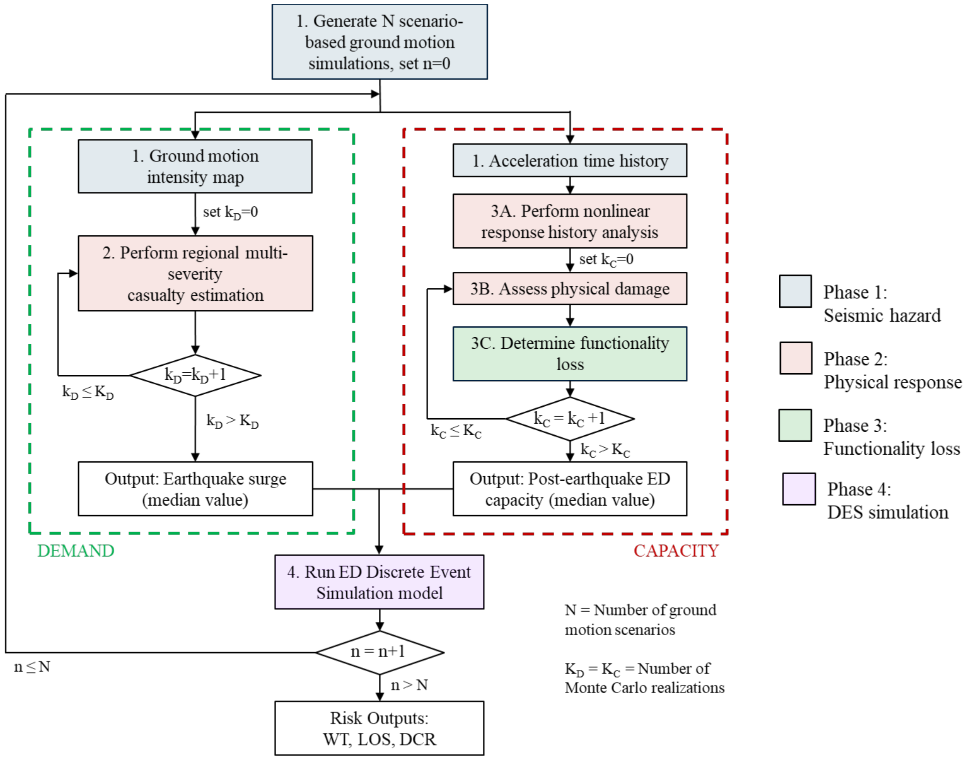

Figure 1. Methodology to quantify post-earthquake surge capacity (after Palomino Romani et al. [4]).

Phase 1: Seismic Hazard

A deterministic scenario-based assessment was used to characterize the seismic hazard, namely, 30 physics-based ground motion simulations of a M_W9.0 Cascadia Subduction Zone earthquake scenario developed by Frankel et al. [9]. Incorporation of physics-based simulations of these 30 scenarios allowed for the generation of (1) a grid of spectral accelerations over the catchment area of the hospital considered, and (2) acceleration-time histories at the site of the hospital emergency department building, for each scenario considered.

Phase 2: Post-Earthquake Demand Estimation

A multi-severity casualty estimation was performed for the hospital catchment area using HAZUS [10], implemented via OpenQuake [11]. The exposure model of the catchment area was provided by Natural Resources Canada (personal communication, 2019). HAZUS casualty estimates were mapped to corresponding ED codes: Severity 1 and 2 were assigned a green code, Severity 3 was assigned a yellow code, and Severity 4 was assigned a red code. Patient arrival rates were calibrated to baseline data provided by hospital staff. One thousand simulations were performed for each ground motion scenario to develop a distribution of patient codes.

Phase 3: Hospital Functionality Loss Assessment

The hospital building studied is a four-story reinforced concrete structure, constructed in 1978, with typical plan dimensions of 85.1 m by 76.0 m. The building houses all the emergency response functions, including emergency rooms, operating rooms, laboratories, and all other support services for the emergency department. A simplified nonlinear multi-degree of freedom flexural-shear structural analysis model (NMFS) was constructed [12]. The suite of 30 M_w9.0 acceleration time histories at the site of the hospital was then applied to determine engineering demand parameters. These demand parameters were used as inputs to a performance model for the building, created using NHERI-SimCenter's Pelicun [13], a python package that implements the FEMA P-58 [14] methodology. One thousand Monte Carlo simulations were performed to create a distribution of damage for each of the structural and nonstructural components considered. For each Monte Carlo simulation, the most likely damage state for each component was mapped to a Performance Level and subsequently to a loss of function of each service area in the emergency department (i.e., emergency rooms, operating rooms, laboratories, etc.) using decision trees developed by Yavari et al. [8]. The loss of function was divided into four categories: Not Functional, Affected Functionality, Functional, and Fully Functional. These categories correspond to a loss of functionality of 100%, 50%, 25%, and 0% respectively. This process was repeated for all 30 ground motion scenarios (30,000 functionality loss assessments in total).

Phase 4: Emergency Department Capacity Estimation

Surge capacity is defined herein as the patient arrival rate at which patient wait times begin to result in negative health outcomes. DES was used to model patient flow through the emergency department in JaamSim [15]. Patient flow was modeled after Yi et al. [16] and was modified based on personal communication with staff of the case study hospital. The DES model was then calibrated under normal operating conditions. To simulate the earthquake surge, patient arrival rates for each color code were added to steady-state patient arrivals. The reduction in functionality of each service area was applied within the DES model. For this study, the emergency department was considered to be independent of other hospital and lifeline functions.

Results

Results from the DES of the emergency department for a single earthquake scenario are shown in Fig 2. On Day 2, simulated earthquake damage to the first and third stories of the structure resulted in a 25% drop in functionality of the emergency department. An increase in demand from casualties in the hospital catchment area was also modeled. The arrival rate in the calibrated baseline condition was approximately 11 patients per hour (Fig. 2(a)). The earthquake casualties were added to the steady-state demand, which was assumed to remain constant following the earthquake. Wait times were calculated for each service area in the DES model (i.e., Triage, Emergency Rooms (ERs), Operating Rooms (ORs), Labs, etc.). The threshold wait time limit at each service area, set by the health authority, was two hours. The availability of ERs was the bottleneck in the emergency department, with the mean patient wait time reaching 6.5 hours (Fig. 2 (b)). The mean patient Length of Stay (LOS), was also calculated for each ground motion scenario and for each patient color code (Fig. 2 (c)). The threshold limit for patient length of stay was 10 hours, again set by the health authority. In this scenario, the mean LOS increased from 7.5 hours to above the set limit of 10 hours on Day 5. The demand-to-capacity ratio, or DCR, can be obtained by dividing the patient arrival rate due to the regional surge by the reduced hospital capacity. When DCR reaches 1.0, the emergency department is operating at maximum capacity and any additional patient arrivals will result in wait times in excess of 2 hours. The DCR exceeds 2.0 immediately after the earthquake (Fig. 2 (d)), indicating that the emergency department will be severely overwhelmed by patient arrivals. The DCR decreases to 1.0 approximately two days after the earthquake.

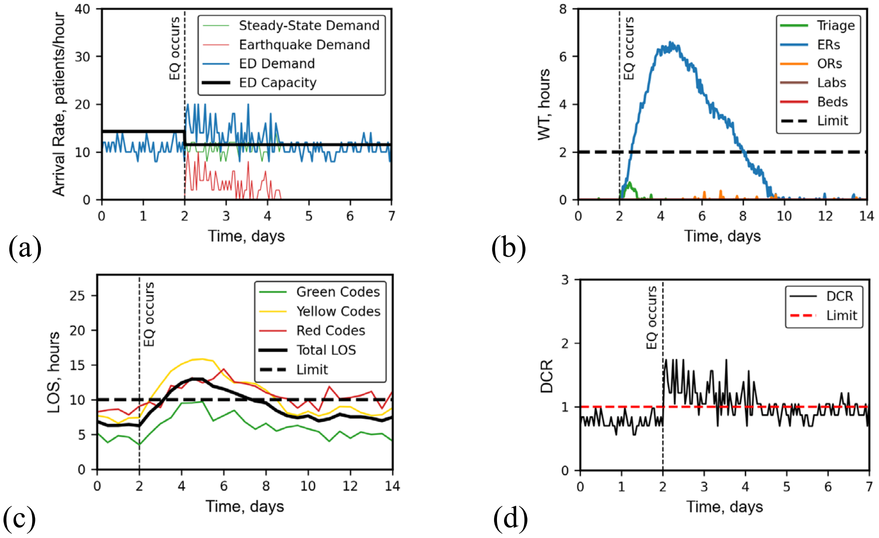

Figure 2. DES results for one earthquake scenario a) Patient arrival rate, b) Patient wait time (WT), c) Patient length of stay (LOS), and d) Demand-to-Capacity Ratio (DCR).

The DES was carried out for all 30 ground motion scenarios. In 7 out of 30 scenarios, the mean ER wait time exceeded the target limit of 2 hours. The mean ER wait time increased to 17 hours in the most unfavorable scenario. The mean patient length of stay averaged for all 30 scenarios increased from 6.5 hours to 12.5 hours, nearly doubling, in the week following the earthquake. The length of stay exceeded the target value of 10 hours in 14 of the 30 scenarios. For the hazard level considered, the expected loss of functionality of the hospital in conjunction with the anticipated surge in healthcare demand results in unacceptable wait times and lengths of stay, suggesting the need to consider mitigation measures, such as the rapid deployment of field hospitals.

Conclusions

A methodology to estimate the surge capacity of a damaged hospital following an earthquake using discrete event simulation (DES) was developed and illustrated for a case study hospital in Vancouver, Canada subjected to a suite of 30 M_w9.0 Cascadia Subduction Zone earthquakes. The patient surge from the hospital catchment area was calculated using multi-severity casualty estimation. The expected loss in functionality for each service area of the hospital was explicitly calculated considering building damage. A DES model was developed to simulate patient flow through the emergency department, integrating both patient surge and service area loss of function. The DES results show the mean patient wait time increased beyond the acceptable limit of 2 hours in 7 of the 30 scenarios and up to 17 hours in the most unfavorable scenario. The mean patient length of stay for all 30 scenarios nearly doubled from 6.5 hours to 12.5 hours. The methodology developed simulates emergency departments after an earthquake with explicit consideration of the impact of structural and nonstructural damage on hospital functionality. The results support the integration of post-earthquake damage predictions into emergency response planning.

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References

1. Jacques CC, McIntosh J, Giovinazzi S, Kirsch TD, Wilson T, Mitrani-Reiser J. Resilience of the canterbury hospital system to the 2011 Christchurch earthquake. *Earthquake Spectra* 2014; 30(1): 533–554. DOI: 10.1193/032013EQS074M.
2. Mitrani-Reiser J, Mahoney M, Holmes WT, De La Llera JC, Bissell R, Kirsch T. A functional loss assessment of a hospital system in the Bío-Bío province. *Earthquake Spectra* 2012; 28(1): 473-502. DOI: 10.1193/1.4000044.
3. Ceferino L, Mitrani-Reiser J, Kiremidjian A, Deierlein G, Bambarén C. Effective plans for hospital system response to earthquake emergencies. *Nature Communications* 2020; 11(1): 1–12. DOI: 10.1038/s41467-020-18072-w.
4. Palomino Romani G, Blowes K, Molina Hutt C. Evaluating post-earthquake surge capacity and functionality of hospital emergency departments using discrete event simulation. *In review*.
5. Favier P, Poulos A, Vásquez JA, Aguirre P, De La Llera JC. Seismic risk assessment of an emergency department of a Chilean hospital using a patient-oriented performance model. *Earthquake Spectra* 2019; 35(2): 489–512. DOI: 10.1193/103017EQS224M.
6. Gul M, Guneri AF. A discrete event simulation model of an emergency department network for earthquake conditions. *6th International Conference on Modeling, Simulation, and Applied Optimization, ICMSAO 2015 - Dedicated to the Memory of Late Ibrahim El-Sadek* 2015. DOI: 10.1109/ICMSAO.2015.7152244.
7. Cimellaro GP, Malavisi M, Mahin S. Using discrete event simulation models to evaluate resilience of an emergency department. *Journal of Earthquake Engineering* 2017; 21(2): 203–226. DOI: 10.1080/13632469.2016.1172373.
8. Yavari S, Chang SE, Elwood KJ. Modeling post-earthquake functionality of regional health care facilities. *Earthquake Spectra* 2010; 26(3): 869–892. DOI: 10.1193/1.3460359.
9. Frankel A, Wirth E, Marafi N, Vidale J, Stephenson W. Broadband synthetic seismograms for magnitude 9 earthquakes on the cascadia megathrust based on 3D simulations and stochastic synthetics, Part 1: Methodology and overall results. *Bulletin of the Seismological Society of America* 2018; 108(5): 2347–2369. DOI: 10.1785/0120180034.
10. Kircher CA, Whitman R V., Holmes WT. HAZUS earthquake loss estimation methods. *Natural Hazards Review* 2006; **7**(2): 45–59. DOI: 10.1061/(asce)1527-6988(2006)7:2(45).
11. Silva V, Crowley H, Pagani M, Monelli D, Pinho R. Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. *Natural Hazards* 2014; 72(3): 1409–1427. DOI: 10.1007/s11069-013-0618-x.
12. Xiong C, Lu X, Guan H, Xu Z. A nonlinear computational model for regional seismic simulation of tall buildings. *Bulletin of Earthquake Engineering* 2016; 14(4): 1047–1069. DOI: 10.1007/s10518-016-9880-0.
13. Zsarnoczay A, Kourehpaz P. NHERI-SimCenter/pelicun: v2.6 *Zenodo* 2021. Retrieved from https://doi.org/10.5281/zenodo.5167371.
14. FEMA. Seismic Performance Assessment of Buildings, Volume 1 - Methodology, Second Edition. *FEMA P-58-1* 2018; 1(December 2018): 340.
15. King DH, Harrison HS. Open-source simulation software "JaamSim." *Proceedings of the 2013 Winter Simulation Conference: Simulation: Making Decisions in a Complex World*, IEEE Press; 2013. DOI: 10.1109/WSC.2013.6721593.
16. Yi P, George SK, Paul JA, Lin L. Hospital capacity planning for disaster emergency management. *Socio-Economic Planning Sciences* 2010; 44(3): 151–160. DOI: 10.1016/j.seps.2009.11.002.