# The effects of the vertical distribution of medical services on hospital post-earthquake function

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## Abstract

Resilient hospitals are important in the emergency response and community recovery following a major earthquake. Hospitals are complex systems involving many services to support the delivery of medical processes. The operability of different services after an earthquake will determine the hospital's ability to carry out various functions. The damage and operation of various hospital services can depend on supporting infrastructures' spatial location, horizontally and vertically within a building. The purpose of this paper is to explore the effect of the vertical distribution of medical services on hospital functionality. This study adopts fault tree analysis (FTA) to relate the damage and function of different essential medical services after earthquakes. The FTA is coupled with a linear structural model to predict the earthquake demand and service functionality at different floor levels of a 7-storey concrete moment frame hospital. A total of 72 vertical distribution patterns of health care services are generated following the architectural design and then simulated under three earthquake intensities. The failure probabilities of hospital function decrease from 0.16 and 0.91 to 0.11 and 0.81 under two of the three earthquake events. The effect of layouts on reducing the failure probability of a hospital is more prominent in a strong earthquake. Placing the ICU and LAB on lower floors or IMG, OPT and WARD on higher floors would enhance the hospital's reliability. The results demonstrate that the intentional layouts of medical services during the architectural design phase can impact the reliability of hospitals. Considering optimal layout plans in future designs is important to mitigate hospital function loss.

**Keywords:** hospital; resilience; fault tree; reliability

## 1 Introduction

Hospitals are essential during the post-earthquake response phase for providing medical services for the injured. However, earthquakes often cause service disruption in hospitals. A functional hospital relies on available space, supplies and staff (Barbisch & Koenig, 2006). Available space refers to a functional physical environment, and this extends to all necessary structural elements, non-structural components (i.e., partition walls, suspended ceilings, etc.), and supporting infrastructures (i.e., power and water) being available to support function. Available staff includes medical professionals and support staff. Available supplies comprised of availability of supporting auxiliary stock and equipment, such as blood bags, medical gas, medical records, laundry, etc. The unavailability of any of these elements would affect a hospital's ability to deliver medical services efficiently.

The layout of a hospital, which is the spatial distribution of various departments within the building, affects the operational efficiency of the hospital. This is confirmed by in-depth studies under routine circumstances (Benitez et al., 2019; Helber et al., 2016; Li et al., 2020). However, hospital layout is particularly important in post-earthquake scenarios as different locations in a building may sustain different levels of damage, and the location of different departments within the building would affect available space and supplies, which affects hospital functionality. Leveraging the FEMA-P58 framework (Federal Emergency Management Agency (FEMA), 2018) and a structural model of the hospital, the damage states of different structural and non-structural components can be probabilistically determined based on the engineering demand at the location of the component. By establishing the relationships between damaged components to hospital function, we can predict the performance of the hospital.

The most widely used tool for relating building damage to hospital functionality after earthquakes is fault tree analysis. Jacques et al. (2014) examined the effectiveness of fault trees to model the functionality of hospitals affected by the 2010 Canterbury earthquakes in Christchurch, New Zealand. Yu et al. (2019) combined the fragility functions of components with a fault tree to derive the probability of hospitals at various functional states. This study showed that even when building layouts meet architectural code requirements, layouts can have a significant impact on the post-earthquake functionality of hospitals.

# 2 Method

This study first establishes a virtual hospital and identifies the essential medical services after an earthquake. Then, a shear-type MDOF model is developed to represent hospital. The seismic response of each floor under different earthquake intensities is calculated using this shear building model based on a response spectrum analysis. Finally, the predicted Engineering Demand Parameters (EDP) such as peak floor acceleration (PFA), Inter-storey Drift Ratio (IDR), and Peak Floor Velocity (PFV) are used to look up fragility functions to produce damage state probabilities. These probabilities are used as inputs for a further fault tree analysis (FTA) to determine the likelihood of essential medical services being operational. This produces a quantitative measure of the reliability of hospital function.

## *2.1 Hospital services and layout planning*

The primary function of hospitals after the earthquake is to provide urgent medical services for injuries. Yi et al. (2010) investigated the injuries caused by past earthquakes and classified them into seven types:

- Minor injuries that do not need surgery.
- Fractures requiring examination to determine surgery or discharge.
- Head injuries and burns necessitating immediate treatment.
- Neurological/psychiatric, respiratory, gastrointestinal and other symptoms.
- Cardiovascular conditions.
- Obstetrics/gynaecology may require further examination and surgery.
- Patients who need emergency operations.

The departments that hospitals need to keep running to treat these seven types of casualties are emergency rooms, laboratory, operating rooms, Intensive care unit (ICU) and wards. Horspool (2022) emphasised the importance of delivering a higher level of medical care and employing advanced medical technologies, such as X-rays or surgical interventions, for individuals with moderate to severe injuries. Lu-Ping et al. (2012) explored the pattern of injuries caused by the Wenchuan earthquake in 2008. The study revealed that diagnostic tools during the medical process were lab tests, Computer Tomography (CT), x-ray, colour ultrasound, and physical examination. All the medical services mentioned above will affect the hospital's ability to provide urgent care after earthquakes.

Guided by these findings, the virtual hospital in this study allows for eight medical units; the emergency department, laboratory, CT, X-ray, colour ultrasound, operating rooms, ICU and wards.

An important factor for hospital layout planning is the degree of connection between the different medical services. Proximity values are adopted to reflect these connections and quantify the services' vertical distribution within a building. Proximity, as shown in Table 1 below, refers to the specified closeness between pairs of medical services, represented as a value ranging from zero to ten (Kvillum & Vigerust, 2018). Higher values indicate a stronger need for proximity. These values are established through an analysis of the relationship between services, considering the significance and magnitude of patient, medical staff, material, and information flows among these services.

*Table 1. Proximity values between medical services*

| Medical services | ED | IMG | LAB | OP | ICU | WARD |
|---|---|---|---|---|---|---|
| Emergency department (ED) | 10 | 8 | 0 | 5 | 5 | 0 |
| Imaging department (IMG) | | 10 | 0 | 8 | 8 | 0 |
| Laboratory (LAB) | | | 10 | 0 | 0 | 0 |
| Operating theatre (OP) | | | | 10 | 8 | 0 |
| Intensive care unit (ICU) | | | | | 10 | 0 |
| Ward (WARD) | | | | | | 10 |

Considering all distribution combinations will lead to a large number of layout patterns. To restrict the number of distributions to practical and feasible options, several assumptions have been proposed:

- The hospital has seven floors above ground.
- The emergency department is located on the ground floor for ambulance access.
- Medical services related to examination (laboratories, x-ray, colour ultrasound and CT) are only permitted on the first to third floors for the convenience of patients.
- Surgical operating rooms should not be located on the ground floor to avoid pollution and interference (MHURD, 2014).
- The CT, X-ray, and colour ultrasound facilities are combined as an imaging service to reflect common real-world hospital arrangements.
- While hospitals typically have various departments, this study focuses on essential services and assigns only one service to each floor.
- The hospital includes two levels of wards to represent the capacity of a seven-level hospital.

Based on the constraints above, a total of 72 different configurations of medical service distribution were generated. One potential medical services distribution is shown in Figure 1a) for illustration.

## 2.2 Structural model and analysis results

The structural model for the virtual hospital is based on a regular concrete frame building. It is a simple lumped mass MDOF model with constant inter-storey stiffness, equal mass (except for the roof, which has half the mass) lumped at each floor level, and a constant 3 m inter-storey height. The hospital building is assumed to be situated in Wellington, New Zealand, and founded at a site with class C subsoil conditions based on NZS 1170.5 (Standards New Zealand, 2004). This study considers three seismic intensity levels prescribed under three return periods: 100 years, 250 years, and 500 years. The hospital building under these three intensities is assumed to maintain service limit states (Standards New Zealand, 2009). The seismic input is derived by scaling the NZS 1170.5 elastic response spectrum, and they are as presented in Figure 2a).

A damping ratio of 5 % is assumed for the building. For the ground floor, the peak floor acceleration is assumed to be zero period acceleration in the respective elastic design spectrum. The peak ground velocity is computed using the Equation (1) as proposed by Bommer & Alarcon (2006).

$$PGV = SA_{5\%}(T = 0.5)/20 \quad (1)$$

For the upper levels, the structure's mode shapes and natural periods were first calculated. Then, the spectral accelerations for each mode were derived from the response spectrum according to their periods. The pseudo spectral velocity and spectra displacement for each mode are subsequently computed using Equation (2).

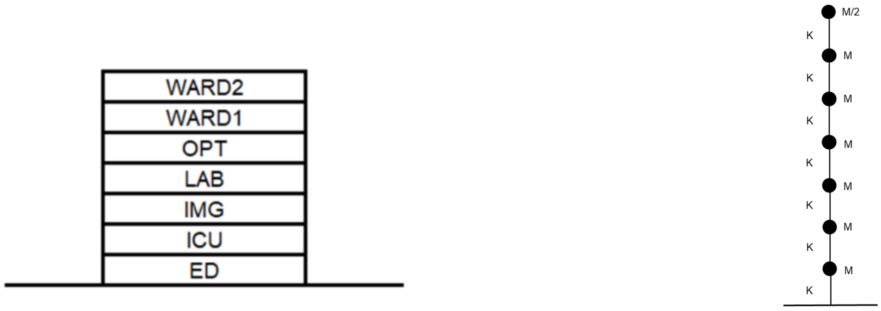
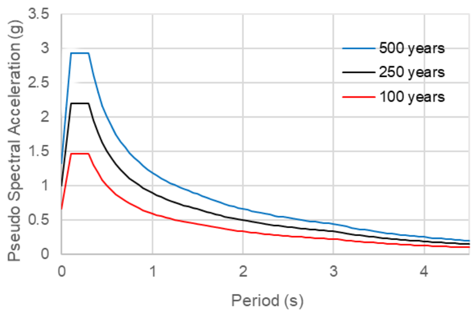


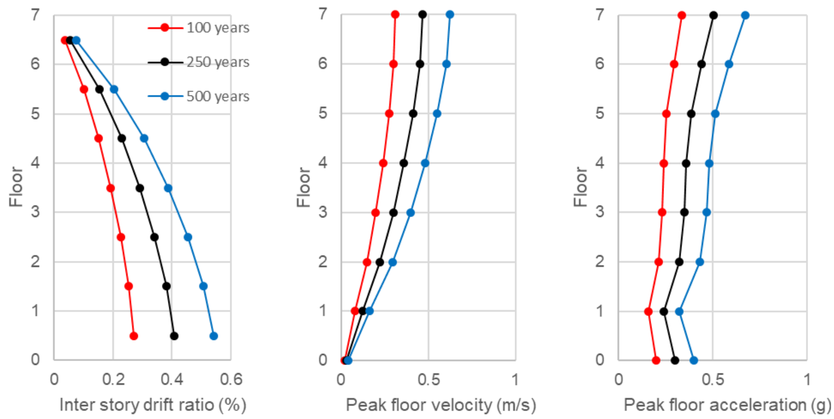

*Figure 1 a) A potential medical distribution pattern* *b) Stiffness and mass distribution of the model*

The participation factors for each mode were then determined to convert the maximum response from modal coordinates to structural response in natural coordinates for each floor due to each respective mode. Finally, the design structural response was obtained by combining the contribution from each mode using the SRSS method. The results are shown in Figure 2.

$$\omega^2 SD = \omega PSV = SA \quad (2)$$




*a) Input ground motion intensity*




*b) IDR* *c) PFV* *d) PFA*

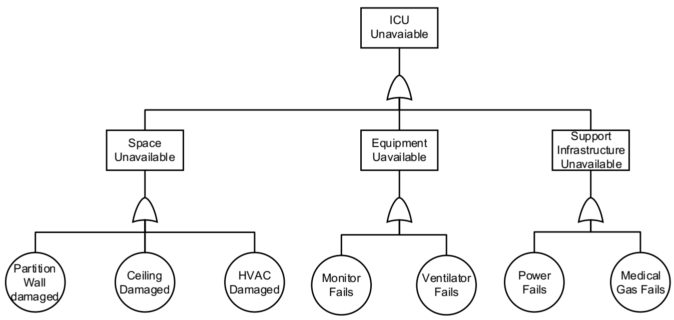
*Figure 2 Response spectra and EDP of the hospital under different intensity earthquakes*

## 2.3 Reliability analysis using fault tree analysis

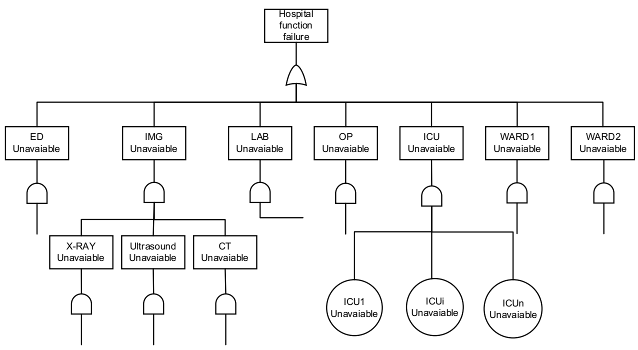
In this study, hospital functionality is evaluated using Fault Tree Analysis (FTA). FTA systematically analyses the failure of a system by decomposing a system failure event into smaller causes (NRC, 1981). FTA describes the pathway and probability of failure through a series of logic gates between interacting events and causes. The system's failure is treated as the “Top event”, while the lowest cause in each branch of the fault tree that cannot be broken down further is known as a “Basic event”.

AND logic gate and OR logic gate define the relationships which leads the progression of failure from basic events towards the top-level failure. The AND gate prescribes the upward progression of an event when all input events are “True”. While the OR gate permits upward progression when at least one of the input events is “True”. Other more complex logic gate such as Exclusive OR, voting gate and Priority AND gate also exist but are not used in this project.

Each of the basic events in the FTA can be assigned a failure probability, which enables the system failure probability to be determined quantitatively. Higher failure probabilities imply lower reliability, and vice versa. Past research has provided examples of using FTA to assess the functionality of hospitals following earthquakes (Jacques et al., 2014; Terzic et al., 2021; Zhai et al., 2021). This paper draws upon these studies and develops fault trees for each medical department. Each medical service has its own fault tree. Under the same earthquake intensity, the failure probabilities of one service on different floors will change. Notably, this study only focuses on the failure of non-structural components. The structural response is assumed to remain linear, so no significant structural damage is considered to impede hospital operations. Each fault tree for the medical services room consists of three components: space, medical equipment within the room, and support infrastructure (Zhai et al., 2021). Space considers the impact of partition walls, ceilings, and HVAC systems. Equipment includes the medical equipment required for each medical service. Support infrastructure includes essential resources such as water and electricity for medical services. Each type of medical service is composed of several rooms that possess identical functionalities; they are linked to the failure of this service through an AND gate. The overall failure of hospital functionality is connected to these individual services through an OR gate. Figure 3 presents the fault tree for the ICU room and the whole hospital.




*a) Fault tree for ICU room unavailable*




*b) Fault tree for Hospital function failure*

*Figure 3 Example fault tree for one medical service and the whole hospital*

Each basic event in the fault tree corresponds to a specific failure state of different components. The probability of this undesired state is obtained by utilising the engineering demand parameters (EDP) obtained from structural analysis and the fragility functions of the components. Given a series of basic events (1, 2, ..., i), the occurrence probability of each event in the fault tree can be calculated using the equations (3) and (4) for the “AND” gate and “OR” gate, respectively.

$$P_{AND} = \prod_{k=1}^{i} P_k \quad (3)$$

$$P_{OR} = 1 - \prod_{k=1}^{i} (1 - P_k) \quad (4)$$

In order to reflect the real scale of medical service in a hospital, the number of different medical service rooms is assumed in Table 2. In this study, for simplicity, it is assumed that under a specific Engineering Demand Parameter (EDP), all components of the same type are in the same failure state, and they are mutually independent. When incorporating the individual room of certain medical services into the overall hospital failure probability, the failure probabilities of these rooms are also assumed to be independent. This assumption leads to a higher failure probability of the system since all components are assumed in the damage states that impair the functionality continuity.

*Table 2 Quantity of each medical service*

| Services | ED | ICU | X-RAY | Ultrasound | CT | OPT | LAB | Ward1 | Ward2 |
|---|---|---|---|---|---|---|---|---|---|
| Quantity | 2 | 5 | 1 | 4 | 1 | 4 | 2 | 25 | 25 |

# 3 Results and Discussion

Figure 4 shows the failure probability of hospital function with different medical service distribution patterns under the three ground motion intensities. For earthquakes with a return period of 100 years, the failure probability of the hospital is nearly 0, suggesting a high likelihood of uninterrupted operation.

The difference between medical distribution patterns under the 100-year return period earthquake is negligible, so the following discussion focuses on the analysis of the other two intensities. As shown in Figure 4, during earthquake events with return periods of 250 and 500 years, the probability of hospital disruption is approximately 0.15 and 0.9, respectively. Among the 72 different hospital layout configurations examined, several distributions have been identified to minimise hospital functionality loss. The arrangements of medical services for the optimal and worst configurations are schematically shown in Figure 5, and they remain consistent across the two seismic scenarios.

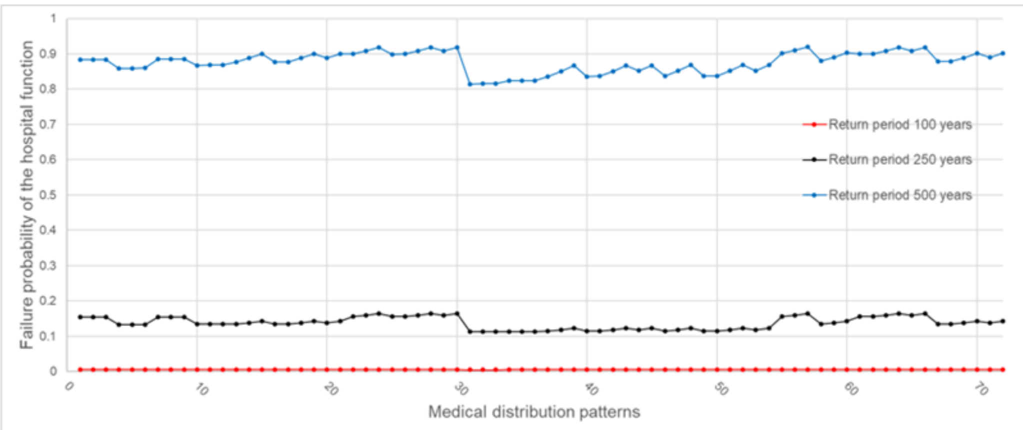
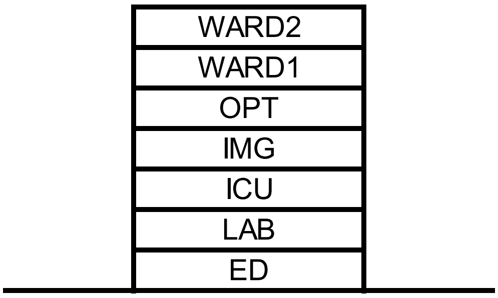
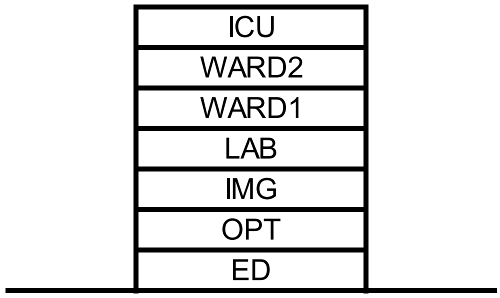



*Figure 4 Failure probability under different layout patterns and earthquake intensities*

Figure 4 illustrates that the failure probability of hospital function is relatively low in specific distribution patterns, particularly in patterns 31 to 54. They are the ones with laboratories located on the first floor. It shows that placing the laboratories on the first floor reduces failure probability from 0.91 to 0.81 and 0.16 to 0.11 under a return period of 500 years and 250 years earthquake events, respectively. The distribution layouts have varying degrees of impact on reducing the failure probability of the hospital under different earthquake intensities. The most significant reduction in failure probability occurs under earthquake events with a return period of 500 years.

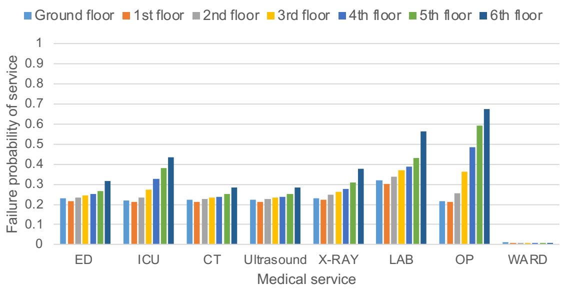



*a) The optimal layouts ( $P_{failure}$=0.81or 0.11)*

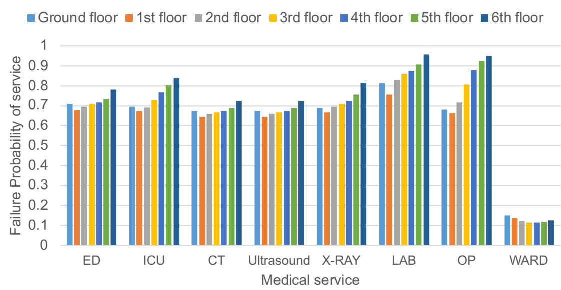



*b) The worst layouts ( $P_{failure}$=0.91or 0.16)*

*Figure 5 Hospital layouts of the optimal and worst configuration*




*a) Return period of 250 years scenario*




*b) Return period of 500 years scenario*

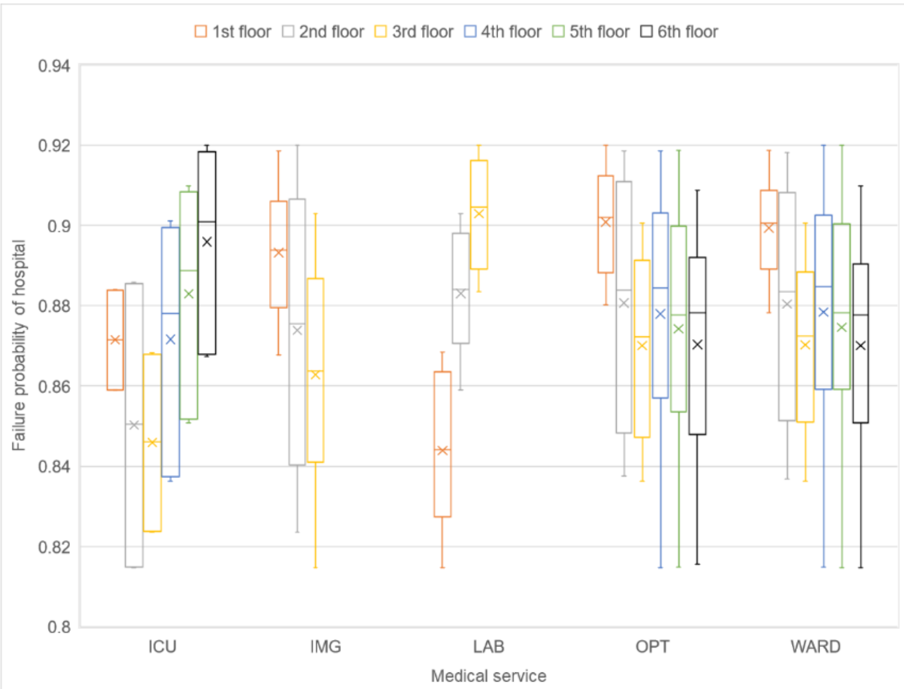
*Figure 6 Failure probability of single medical service under different earthquake intensities*

Figure 6 shows the failure probability of a single medical service room with different locations under the ground motion intensities of a return period of 250 years and 500 years. It can be observed that the failure probability of each medical room generally increases with the rising of its location within the building (except for ward rooms). The operating rooms, laboratories, and ICUs exhibit larger variations in failure probability as they are located on different floors.

Figure 7 shows box plots of hospital function failure probabilities when a specific medical service is fixed at a certain floor under the two seismic scenarios. It can be observed that the dispersion of probabilities is larger under a return period of 500 years events. This implies that when the placement of a particular service is determined, the arrangement of other medical services has a significant impact on the hospital's function reliability under severe earthquake conditions. For instance, if the operating room is fixed on the fifth floor, rearranging the other medical service location can lead to a range of failure probability of 0.82 to 0.91 for a 500-year return period.

The analysis also reveals that the mean failure probabilities of the ICU and LAB rise proportionately with the floor number they are located, whereas the probabilities for IMG, OPT, and WARD exhibit the opposite trend. This phenomenon suggests that, while adhering to architectural design standards, positioning the former two services on lower floors and placing the latter three services on higher floors would be conducive to enhancing the hospital's overall reliability. It is important to note that this study only explored the scenario of a specific hospital configuration, and different structural systems, varying numbers of medical services, and definitions of hospital functionality will all impact the results.


*a) Return period of 250 years scenario*




*b) Return period of 500 years scenario*

*Figure 7 Boxplots for failure probability of hospital function*

# 4 Conclusion

The effect of different medical services distribution vertically in a hospital on post-earthquake functionality is explored in this study. The EDP of the hospital is derived by conducting response spectrum analysis on a simplified MODF shear model with uniform stiffness and mass distribution. A fault tree analysis (FTA) is used to relate the damage of non-structural components to the functionality of a hospital.

In this hospital configuration, placing the medical laboratory on the first floor with the lowest acceleration can reduce the failure probability. The failure probability for every single medical room individually increases with the rising of the floor on which it is located. When a specific medical service is fixed on a particular floor, the impact of the positions of other medical services on the overall probability of functional failure becomes more significant under higher seismic intensities. Strategically arranging the locations of medical services can increase the availability of medical services, thereby increasing the hospital's functional performance after the earthquake and enhancing the emergency management of hospitals.

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