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# Seismic Fragility Assessment of Non-fixed Hospital Equipment

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**Abstract:** Hospitals should be able to resume operations after a large seismic event in order to address possible health issues after the event. Unfortunately full operational capacity may not be possible if the structural integrity of the hospital is compromised or non-structural elements including hospital equipment are damaged due to seismic ground motion. The dysfunction of damaged hospital equipment may impede medical operations for post-seismic activities. In light of this, the authors assessed the overturning and sliding responses of different hospital equipment. Hospital equipment were classified into three types based on wheel states: un-wheeled, locked wheeled, and unlocked wheeled. Nine strong-motion earthquakes from the PEER Ground Motion Database were used as input ground motion. Four limit states were considered: for sliding (in displacement), LS1 = 10 cm; LS2 = 25 cm and LS3 = 40 cm and for overturning or toppling. These data were used to construct individual sliding and overturning fragility curves for each equipment. Simulation for collision, sliding and rocking of the equipment within the patient, ward and operating rooms were also conducted using the Surigao 2017 time vs. acceleration earthquake data. The results show the equipment with the least b/h ratios has a high probability to overturn except the wheeled equipment that have very low friction. Unlocked wheeled equipment is a hazard due to an increased probability of collision with other equipment.

**Key Words:** hospitals; seismic event, hospital equipment; fragility curve

## 1. INTRODUCTION

Every year numerous earthquakes occur in the Philippines. A few of the most devastating earthquakes in the past 30 years include Luzon earthquake 1990 with a magnitude of 7.7, Bohol earthquake 2013 with a magnitude of 7.2, and Surigao Earthquake 2017 with a magnitude of 6.7. The ground motion exhibited by an earthquake can damage structural and non-structural elements of buildings. In hospitals, these damages can greatly affect and threaten its operations when needed most. In order to address this problem, risk assessments can be conducted on the various components of hospitals. The construction of seismic fragility curves is one of the methods that can be used to predict a sample's fragility under a seismic intensity measure. The main objective of this study is to test and study the performance of non-fixed equipment in hospitals through a seismic fragility analysis. Another objective is the risk assessment of selected rooms in the hospital. The first assumptions of this research are that each block representing a particular hospital equipment has its center of mass in the centroid. The second assumption is the equipment experiences damage when its response exceeds a set limit state. The third assumption is that the rooms that are tested are on the ground floor. The fourth assumption is that the static friction and kinetic friction for unlocked wheeled equipment, $\mu_k = \mu_s = 0.002$, for locked wheeled equipment, $\mu_k = \mu_s = 0.6$ and for unwheeled equipment, $\mu_k = \mu_s = 0.8$.

Baker (2014) formulated a study testing the incremental dynamic analysis and the multiple stripes analysis by fragility function fitting. Baker concluded that the multiple stripes analysis is more efficient as compared to the incremental dynamic analysis because it is more efficient to target a specific intensity measure rather than looking at the high or low IM level that is associated with the structural collapse. Zolfaghari and Jahanbakhsh (2012) has done a study wherein simulation of a hospital surgery room was done using a shaking table. It examined the equipment inside the surgery room for sliding, overturning, and impact when exposed to a seismic motion. Afterwards fragility curves were made by fitting a log-normal distribution to the variability of the responses of each equipment and PGA value.

## 2. METHODOLOGY

### *2.1 Materials*

Only a computer was needed for this study as the data gathering and processing were done through software. The software used were the following: Working Model 2D, Microsoft Excel, SeismoSignal and Adobe Photoshop CS6.

### 2.2 *Setup for Simulation*

Using the program Working Model 2D, a virtual shake table was made in order to assess the behavior of the equipment under seismic excitations. The acceleration time history of the earthquake was sent to the virtual actuator using the data table control.

Two setups were made: one for the fragility assessment, and the other one for the case study. For determining the fragility curves of hospital equipment, the virtual shake table was set up with the following conditions:

1. If the block slides at a displacement greater than the specified limit state, stop simulation.
2. If the scaled PGA exceeds the set maximum PGA, stop simulation.
3. For assessing the sliding behavior of the block, prohibit the rocking behavior in order to prevent fluctuations in displacement.

For the case study, the dimensions of the shake table were based on the dimensions of the room layout. The equipment were placed on their respective positions based on the room setup.

### 2.3 *Fragility Assessment of Hospital Equipment*

Using a virtual shaking table of which the dimensions were based on the room, 8 hospital equipment were exposed to 9 earthquake seismograms whose PGA were scaled from 0.1g-2g. These hospital equipment include the hospital bed, anesthesia machine, intravenous (IV) pole, operating table, trolley cart, bedside cabinet, wardrobe, and storage cabinet. The earthquake data was gathered from the PEER Ground Motion Database and in a raw format. In order to process the data, the program SeismoSignal was used. Four limit states were considered: for sliding (in displacement), LS1 = 10 cm; LS2 = 25 cm and LS3 = 40 cm and for overturning or toppling. The fragility assessments will be divided into two cases: Case 1 (C1, L-H side with L<W) and Case 2 (C2, W-H side). The simulation was stopped once the limit states were exceeded or the current PGA exceeded 2g.

The data recorded was used in order to construct the fragility curves. The median $\theta$ and dispersion $\beta$ were calculated using the maximum likelihood estimate. For determining the median and dispersion from a data set gathered using truncated incremental dynamic analysis, Eq.1 was used.

$$\{\widehat{\theta},\widehat{\beta}\} = arg\ max \sum_{j=1}^{m}\{ln\varphi(\frac{ln(IM_i/\theta)}{\beta})\} + (n-m)ln(1-\Phi(\frac{ln(IM_{max}/\theta)}{\beta}))\} \quad \text{(Eq. 1)}$$

where:

| | | |
|---|---|---|
| $IM_i$ | = | intensity measure at which a limit state is exceeded |
| $IM_{max}$ | = | the maximum set intensity measure. |
| $\varphi(x)$ | = | the probability density function |
| $\Phi(x)$ | = | the cumulative distribution function |
| n | = | the number of samples |
| m | = | the number of samples in which the limit state is exceeded |
| $\theta$ | = | the median of the fragility function |
| $\beta$ | = | the dispersion of the fragility function |

If all PGA's recorded did not exceed 2g, then there is no need for truncations and the median and dispersion can simply be calculated using Eq. 2 and 3. Since it is easier to maximize the logarithm of the likelihood, Eq. 2 was implemented in Microsoft Excel to solve for the fragility curve parameters. The fragility curves can then be constructed using Eq. 4.

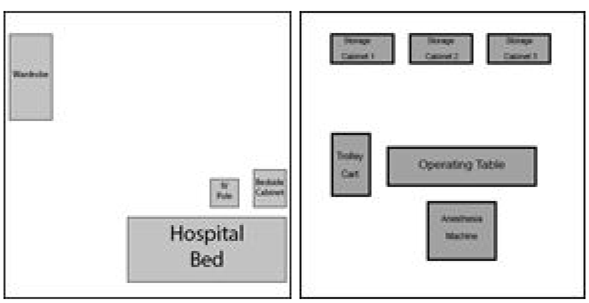
$$\widehat{\theta} = e^{\frac{1}{n}\sum_{i=1}^{n} ln(IM_i)} \quad \text{(Eq. 2)}$$

$$\widehat{\beta} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ln(IM_i/\widehat{\theta}))^2} \quad \text{(Eq. 3)}$$

$$P(C|IM = x) = \Phi(\frac{ln(x/\theta)}{\beta}) \quad \text{(Eq. 4)}$$

### 2.4 *Case Study: Hospital Rooms under the Surigao 2017 Earthquake*

The hospital rooms to be examined are the patient room, ward room, and operating room. Since the program Working Model 2D only accommodates the x-y axis, two simulations per room will be conducted. Case 1 is where the earthquake occurs in the west-east direction while in case 2, the direction is north-south. The behavior of each equipment will be observed, such as collisions, sliding, and rocking. The room setups which were sketched using Adobe Photoshop CS6 are demonstrated below.



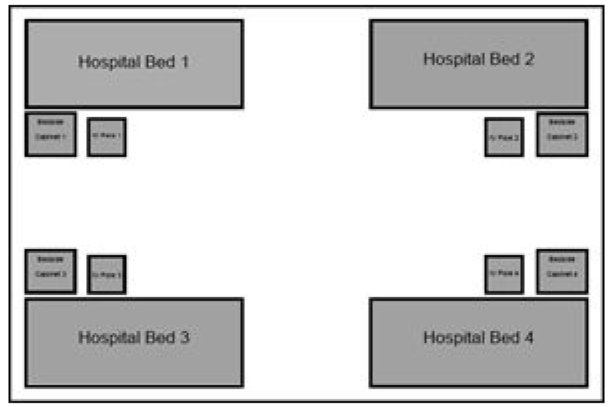




Fig. 2.1. Top view of the patient room (top left), operating room (top right), and ward room (bottom).

## 3. RESULTS AND DISCUSSION

### *3.1 Sliding and Overturning Fragility Curves of Selected Hospital Equipment*

Table 1. Fragility Curve Parameters for All Equipment

| Hospital Equipment | $\theta$, $\beta$ (C1&C2, LS1) | $\theta$, $\beta$ (C1&C2, LS2) | $\theta$, $\beta$ (C1&C2, LS3) | $\theta$, $\beta$ (C1, O) | $\theta$, $\beta$ (C2, O) |
|---|---|---|---|---|---|
| Bedside Cabinet | 0.69, 0.32 | 0.99, 0.32 | 1.32, 0.27 | 1.21, 0.28 | 1.47, 0.29 |
| Storage Cabinet | 0.76, 0.28 | 1.11, 0.25 | 1.41, 0.25 | 0.51, 0.28 | 1.05, 0.31 |
| Wardrobe | 0.86, 0.32 | 1.12, 0.28 | 1.44, 0.27 | 0.73, 0.33 | 1.51, 0.30 |
| Anesthesia Machine | 0.52, 0.21 | 0.91, 0.26 | 1.11, 0.21 | 1.23, 0.29 | n/a |
| Hospital Bed | 0.57, 0.37 | 1.03, 0.29 | 1.22, 0.30 | n/a | n/a |
| Operating Table | 0.68, 0.20 | 1.03, 0.32 | 1.23, 0.27 | 1.13, 0.30 | n/a |
| IV Pole | 0.10, 0.30 | 0.20, 0.44 | 0.29, 0.41 | n/a | n/a |
| Trolley Cart | 0.11, 0.32 | 0.21, 0.44 | 0.30, 0.40 | n/a | n/a |

The equipment that exhibited the most notable sliding behavior are the unlocked wheeled equipment while the least notable are the unwheeled equipment. On the other hand, the equipment most prone to overturning are the unwheeled equipment. Some locked wheeled equipment were not observed to overturn due to high b/h ratios and sliding behavior, while all the unlocked wheeled equipment did not exhibit rocking behaviors due to very low friction.

### *3.2 Case Study on Hospital Rooms*

For the patient room, only the IV pole exhibited a significant sliding behavior and exceeded the 10 cm limit state. Other equipment only has a maximum sliding displacement of less than 0.1 cm. No rocking and collisions were observed.

For the ward room, collisions were observed with the majority of collisions having absolute momentums less than 1 kg·m/s. The major collisions, however, have absolute momentums greater than 4 kg·m/s. These collisions are primarily IV pole to bedside cabinet, IV pole to a hospital bed, and IV pole to IV pole. The IV poles are the only equipment to exceed the sliding limit state. When the IV bag attached to the pole is connected to the patient, possible risks are injuries. Furthermore, equipment collisions post economic risk due to damages. No significant rocking was observed.

For the operating room, only the trolley cart exhibited a significant sliding behavior and exceeded the 10 cm limit state. Other equipment only have maximum sliding displacements less than 0.1 cm. No rocking and collisions were observed. Some surgical equipment atop the trolley cart may fall, which may get damaged and contaminated. Thus, the risks posed are impeded medical operations.

## 4. CONCLUSIONS

The simulations showed that the hospital equipment excluding those with unlocked wheels exhibited a high probability of sliding and overturning at high PGA's. Among the selected equipment, the IV pole (unlocked wheel) and trolley cart (unlocked wheel) were most susceptible to sliding compared to the other equipment. The presence of wheels minimized the effect of the b/h ratio to overturning as seen in the IV pole. On the other hand, the storage cabinet and wardrobe equipment showed a higher probability of overturning. These are the equipment with low b/h ratio with no wheels.

For the room damage assessments using the Surigao 2017 earthquake, the major hazards in rooms are the unlocked wheeled equipment as they have increased the chance of colliding with walls and other equipment due to notable sliding behavior.

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