Development of Seismic Fragility Curves For Hospital Equipment

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SUMMARY:
Safety and serviceability of hospitals exposed to earthquakes depend on many factors: structural integrity, non-structural and utility performance and response of medical facility and other contents to seismic motions. Among these factors, seismic vulnerability of medical equipment's and contents are crucial in assessing the functionality of hospital under seismic motions. In this study an analytical approach is proposed to estimate seismic vulnerability of hospital equipment's, using simulation on a virtual shaking table. The methodology examines performance of various types of contents in terms of sliding, overturning and impacts caused by seismic motions. The procedure involves using many horizontal and vertical strong ground motion records to incorporate uncertainties associated with ground motions. A virtual 3D shaking table software is used to model sliding and overturning performance of free standing equipment. In order to test the model, inventory of contents and equipment in a surgery theatre are collected and modeled three dimensionally in this study. These equipment are modeled on the virtual shaking table and their performance under many strong ground motion records are collected and further analyzed to estimate probabilistic distribution of damages caused by seismic motions. Graphs showing preliminary fragility curves are presented for these equipment's. The procedure presented in this paper can be extended to a variety of other contents and equipment used in different buildings.

Keywords: Equipment Fragility Curves, Seismic Risk, Virtual Shaking Table

1. INTRODUCTION

Observations during past earthquakes have demonstrated that in addition to structural damages, damage to non-structural components and equipment's could account for significant proportion of economic loss and expensive recovery and/or replacement costs. The damage costs of nonstructural components may account up to 65% to 85% of the total loss in commercial buildings. In certain buildings like hospitals, the indirect losses due to damaged equipment's, lost inventory and records and revenue can be two to three times greater than the cost of replacing collapsed buildings or repairing structures. Moreover, the survival of nonstructural components during an earthquake is important for maintaining the operation of emergency services and the continuing functionality of such buildings. The damage to nonstructural components may also pose life safety concerns to the occupants. However, even if a building remains structurally sound during an earthquake, it may be rendered unusable due to damaged nonstructural component. Therefore, to implement mitigation measures and improve life safety, it is necessary to estimate the expected damage that these elements may suffer when subjected to earthquake shaking. Such assessment in turn requires estimates of seismic vulnerability of non-structural elements under different levels of shaking intensities. Many researchers in recent decades have been studied seismic performance of equipment's to predict their responses under seismic motions.

Esfandiari *et al*. (2001) presented their modeling of rigid blocks under seismic loading using computer software tool SAP2000. In their work, the contact surface was modeled using SAP2000's Nllink element and the Fast Non-linear Analysis (FNA) module was utilized for the analysis. The FNA approach proved to be very accurate and extremely fast compared to more traditional non-linear time-history analysis techniques. As a benchmark to verify the accuracy of such methodology, the behavior of a rigid block under dynamic loading is used in the literature. This methodology can be adopted to accurately predict the sliding, rocking, or slide-rock behavior of unanchored rigid blocks.

Fierro and Perry (2004) used a program called “Working Model” to assess the overturning performance of unanchored rigid blocks situated at or near ground level and to see how the overturning potential varies with block size, aspect ratio, or seismic characteristics of ground motions. This study is based on a series of simulated experiments, that is, experiments conducted by running a large number of nonlinear time history computer analyses. The results show that if the aspect ratio is held constant, overturning is strongly dependent on the size of the blocks and on the size and shape of the displacement response spectra. In general, objects with widths that are relatively large compared to the displacement demand do not overturn independent of their height. Based on results of that study, some rules of thumb are provided that indicated the relative vulnerability to overturning for different types of rigid blocks subjected to earthquake ground motion.

Burningham and Mosqueda (2007) also applied the Working Model 2D software for evaluating the performance of non-structural components towards development of fragility curves. They compared fragility curves generated based on compatible time histories for AC156 and FEMA461 against fragility curves generated based on actual building time histories. They showed how these tools could be practically used to study seismic behavior of nonstructural components. Makris and Konstantindis (2005) conducted analytical and experimental studies on the seismic response of laboratory equipment using shaking table and Working Model program.

Response of free standing rigid and unanchored contents under ground excitation makes major concern in the seismic risk mitigation for many ordinary building contents and equipment. Such response is therefore, the primary topic being investigated by several researchers. The analytical formulation describing the fundamental equations of motion for rigid unattached bodies was presented by Shenton and Jones (1991). In a later work, Shenton (1996) investigate the criteria for sliding and rocking and sliding- rocking of rigid body modes. This work showed that a free standing rigid body on an accelerating foundation can undergo a wide range of motion in two dimensions, the behavior is describe by five modes of response :rest, slide, rock, slide-rock and free flight. It is demonstrated that a side-rock mode can also be initiated from rest. Criteria governing the initiation of the slide, rock and slide-rock modes are derived in that study. In addition to the analytical methods, computer software tools have been also used to model and evaluate seismic response of non-structural components and equipment’s.

2. SEISMIC BEHAVIOR MODELLING

During strong earthquakes, standing equipment’s may slide appreciably, slide-rock, rock, or even overturn depending on equipment property and ground motion characteristics. Rocking response is very sensitive to the equipment geometry and the nature of ground motion. Rocking is in principle an undesirable response for equipment’s since it often causes overturning and therefore, damage or total loss of the equipment’s. On the other hand, excessive sliding may cause inter-equipment impact and/or damage to the content and equipment’s.

In order to assess seismic performance of nonstructural component, mainly analytical and experimental evaluation methods are used. Experimental tests, using shaking table, could provide the best means to fully understand the behavior of nonstructural components and building contents and equipment subjected to seismic excitations. These instruments are capable of reproducing real or simulated earthquake strong ground motions allowing for controlled testing of structures subjected to earthquakes. However, performing such real tests is not always feasible due to availability of shaking table facilities and time and resource-consuming process.

In this study, computer software tools are used to simulate shaking performance of equipment under seismic ground motions. The Working Model 2D software is used for this purpose which is capable of stimulating shaking tables. Its ability to calculate mechanical interaction of rigid bodies under different constraints and temporal forces makes it suitable tool for this purpose. Makris and Konstantinidis (2007) verified seismic response of the equipment obtained from this program against those derived from real shaking table. To study seismic performance of equipment's in this study, the same virtual shaking table software is used here. This software applies sophisticated numerical techniques in order to solve differential equations representing mechanics laws of bodies subjected to force time history. It uses numerical methods such as Euler and Kutta-Merson (fifth order Range-Kutta). It is capable of simulation process under simultaneous vertical and horizontal seismic ground velocity. As input ground motions, one may use time histories representing free ground or response of structure if the bodies are placed on building floors.

3. CASE STUDY: SURGERY ROOM EQUIPMENT 'S

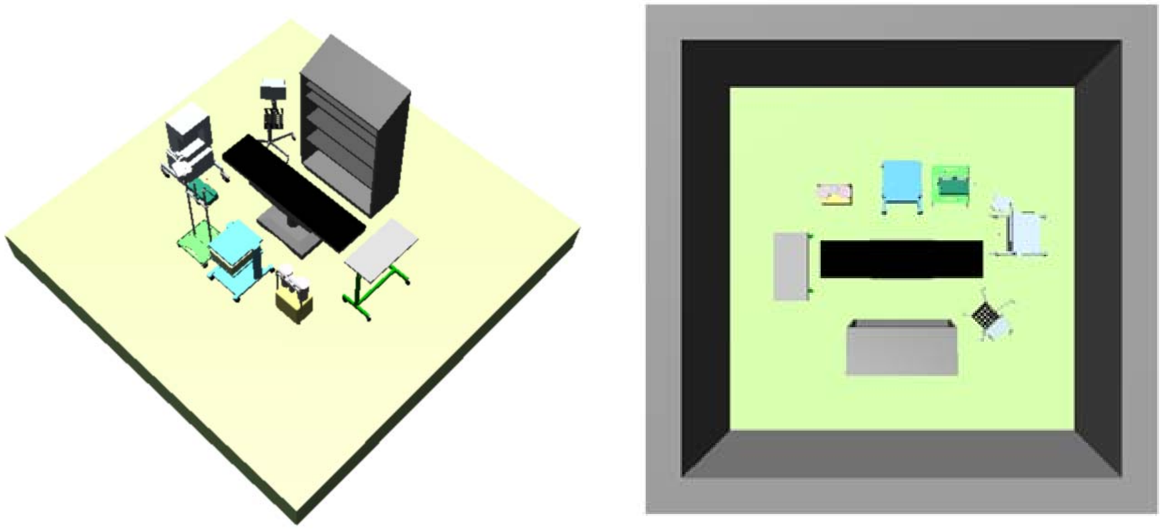
The analytical approach and procedure used to derive overturning and sliding fragility curves are further explained in this section using data from a real case study on the equipment's in a normal surgery theater. For this purpose a hospital surgery room was visited and inventory of equipment and contents such as suction machine, cutting and anesthesia machines, injection pump, monitor, trolley table, cabinet and bed were collected (Figure 1). The inventory contains geometry as well as other mechanical property of each instrument/content. In order to analyse these equipment, their 3D geometries were modelled graphically first. Figures 2a and 2b show view of modeled equipment on the virtual shaking table. Other characteristics such as weight, friction coefficient and coefficient of restitution were also imported to the software. Weights and dimension are taken from equipment documents. For equipment without wheels or those with locking wheel, friction factors of 0.5 are considered to represent surface-equipment friction. For equipment with unlock wheels, negligible friction factors of 0.001 are used. The coefficient of restitution for the interaction between the surface and the equipment has been also considered as 0.5.

Figure 1. View of a normal hospital surgery room and related equipment and contents

These equipment/contents were subjected to ground shaking on the virtual shaking table simultaneously in order to take into account their interactive behavior. To stimulate the equipment-wall interaction and impact, solid and stable walls are also modeled on the shaking table (Figure 2b). A selection of 20 strong ground motion records were selected from PEER strong motion database. The following criteria are considered:

1. Earthquake magnitude of Mw6.0 to Mw7.3
2. Source-to-site distance of 20 to 80 km
3. Soil type: B according to the USGS soil classification

Comparison on the graphs of Areas Intensity are also made for this selection in order to choose records with comparable energy contents. Both vertical and horizontal records are used. These records are scaled from 0.1*g* to 1.0*g* with 0.1*g* increments. As input to the software, velocity components of the scaled records were used. Response of equipment's are modelled in this way under each scaled strong ground motion record. Figure 3 for example shows the sliding response time history of the suction machine subjected to one of the selected records. This procedure is carried out for 20 strong ground motion records scaled by 11 *PGA* values, in total 220 simulations. Figure 4 shows sliding response of the suction machine under 20 records scaled with various *PGA's*. This figure shows the maximum sliding displacement of suction machine under *PGA* values.



a) b)

Figure 2. Graphic representation of hospital surgery room and equipment modelled in the virtual shaking table software

For overturning damage state, overturning probability *P(OT)* is estimated based on the number of times equipment is overturned during simulations and at a given *PGA* value:

$$P(O_T) = \frac{n(O_T)}{N} \tag{3.1}$$

In which *P(OT)* is overturning probability, *n(OT)* is the number of time equipment overturns at a specified *PGA*, and *N* is total number of simulation at a given *PGA* value. Table 1 shows such statistics for the suction machine. Figure 5 shows states of equipment's on the shaking table under large *PGA* value, illustrating overturning situation for most equipment's.

Input Strong Ground Motion Equipment Response Time History

Figure 3. Sliding responses of the suction machine subjected to strong ground motion records.

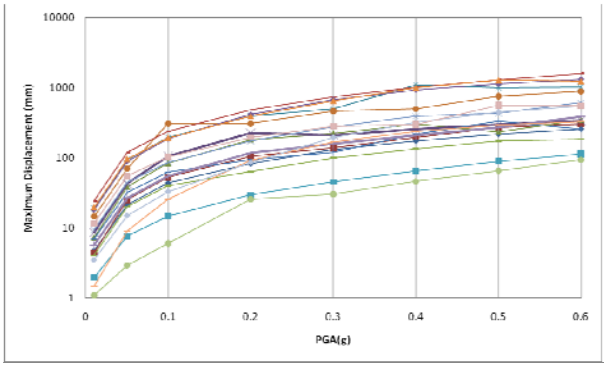


Figure 4. Sliding responses of the suction machine under 20 records scaled with various *PGA's*

Table 1. Overturning frequency for suction machine under various *PGA* values

PGA (g)	0.01	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Overturning Frequency, $n(O_T)$	0	0	0	0	0	2	5	7	9	9	9

4. DEVELOPMENT OF FRAGILITY CURVES FOR EQUIPMENTS

Fragility curve describes the probability of reaching or exceeding a damage (or limit) state as a function of the level of excitation or demand. These functions represent conditional probability of failure expressed as functions of the ground motion intensity and are used for any systematic damage or loss assessment process. In this study, the methodology proposed by ATC58 (Applied Technology Council, 2009) is used to develop fragility curves for selected equipment/contents.

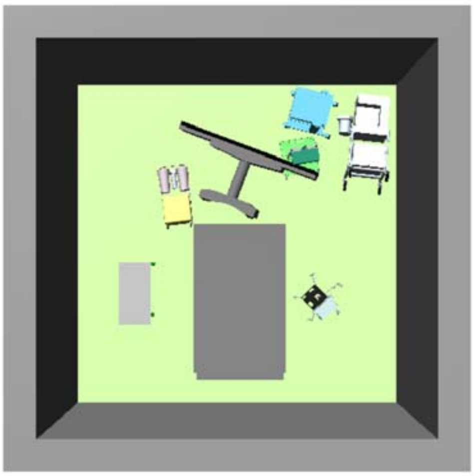


Figure 5. Overturned equipment under sever seismic ground motion

Simulation of the equipment on the virtual shaking table under various records and various *PGA's* resulted in a family of response curves as shown in Figure 4. Such figure shows the variability of maximum response of an equipment/content under a given *PGA* value. In this study and according to the ATC58 recommendation, log-normal distribution is used to model such variability at each *PGA* level:

$$F_i(D) = 1 - \phi\left(\frac{\ln(D/\theta_i)}{\beta_i}\right) \tag{4.1}$$

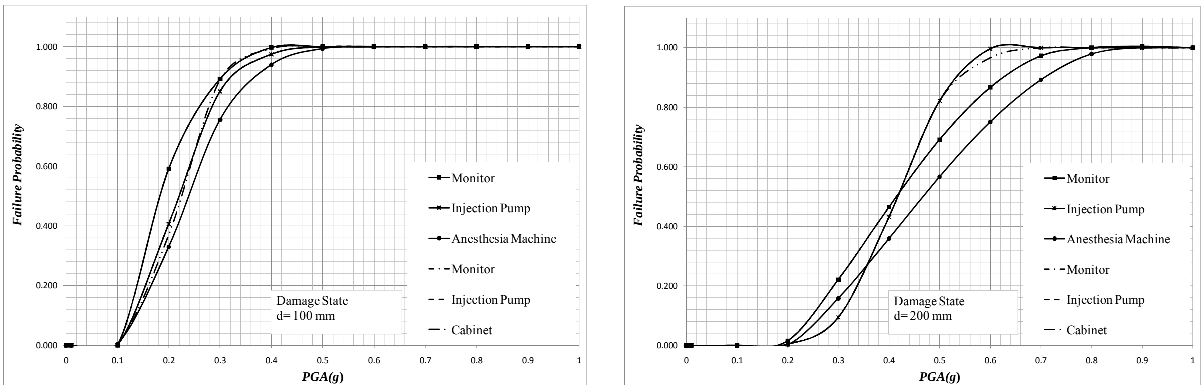
In which *Fi(D)* is the conditional probability that the equipment experience damage equal or larger than damage state *i* as a function of demand parameter, *D*; *Φ* denotes the standard normal (Gaussian) cumulative distribution function, *θi* denotes the median value of the maximum response of component and *βi* denotes the logarithmic standard deviation value of the maximum response of equipment. In this paper as representative damage states, sliding (displacements) of 100mm and 200mm are used. Median and standard deviation of equipment response are estimated using the results of shaking table for each range of *PGA* values using the following equation:

$$\theta = e^{\left(\frac{1}{M}\sum_{i=1}^{M}\ln d_i\right)} \tag{4.2}$$

In which *M* is the total number of sample points at a given *PGA* range and di is damage level *i* demand in test *i* at which the damage state was first observed to occur. Standard deviation is also estimated using the following equation:

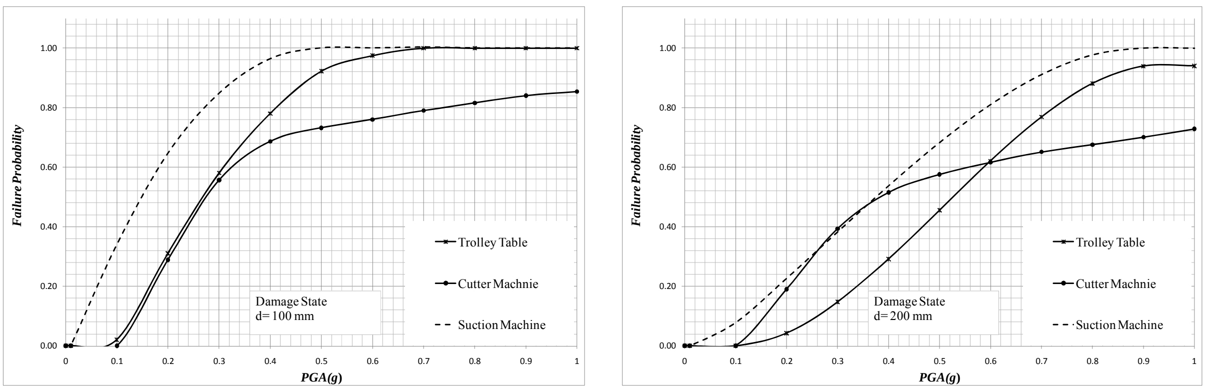
$$\beta = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}\left(\ln\left(\frac{d_i}{\theta}\right)\right)^2} \tag{4.3}$$

Following this procedure, fragility curves are estimated for selected surgical equipment's and contents. Figure 6a and 6b show such curves for damage stage of minimum 100 and 200 mm sliding (displacement) respectively and for equipment with friction coefficient of 0.5 (no or locked wheels). The same results are shown for equipment with unlocked wheels (friction coefficient of 0.001) in Figure 7a and 7b.



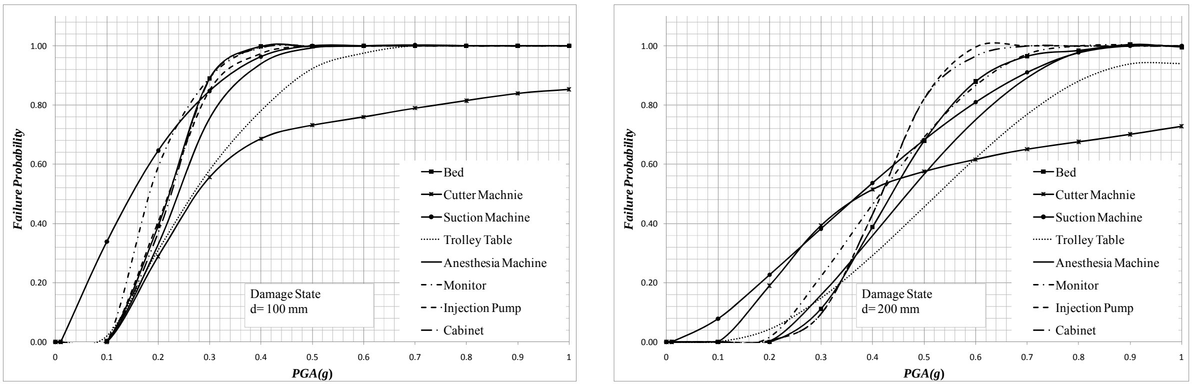
b) b)

Figure 6. Sliding fragility curves of equipment with no or locked wheels (μ=0.5) for damage stage of minimum a) 100 mm, b) 200mm



a) b)

Figure 7. Sliding fragility curves of equipment with unlocked wheels (*μ*=0.001) for damage stage of minimum a) 100 mm, b) 200mm



a) b)

Figure 8. Sliding fragility curve of all equipment; a:limit state=100mm, b:limit state=200mm

For overturning failure criterion, if the equipment deviates from vertical direction, it is out of performance level and is considered damaged, even if it doesn't end in horizontal direction and relies on the other equipment. To derive fragility curves for overturning damage state, probability of overturning $P(O_T)$ is presented as a function of earthquake *PGA*. Figure 9 shows fragility curves for surgical equipment's/contents in terms of probability of overturning against various *PGA* values. Equipment with large height to base aspect ratios such as cabinet shows higher probability of overturning for a given *PGA* value compare to those with lower height and stable items. In this graph items such as bed shows the lowest overturning potential which is due to either smaller aspect ratio and/or concentration of equipment weight at bases of such equipment's.

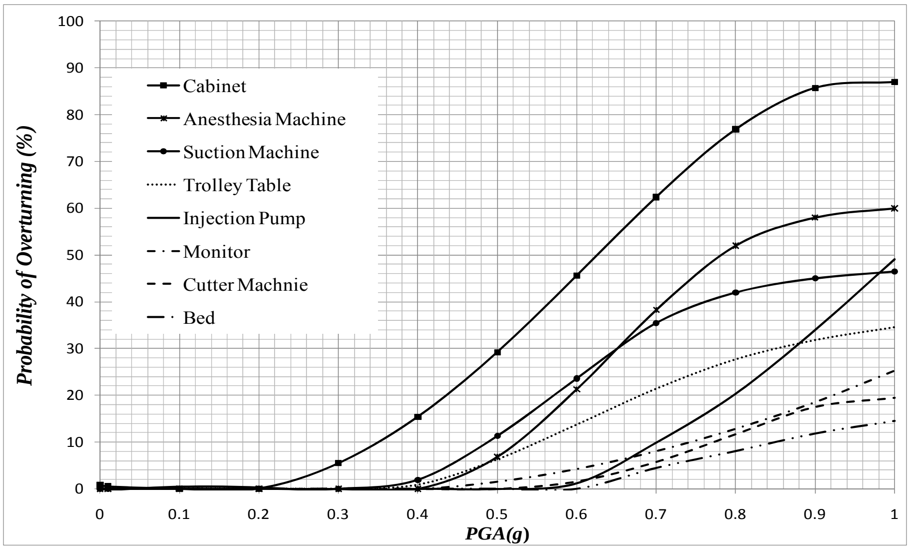


Figure 9. Fragility curves showing probability of overturning as a function of earthquake PGA

CONCLUSIONS

In this study, a methodology and procedure for assessment of fragility curves for equipment's/contents are presented. Response of modelled equipment's on a virtual shaking table are investigates using a simulation computer tool. Sliding and overturning potential for various surgical equipment's are studied based on their 3D geometry and other mechanical and dynamic characteristics. A range of real earthquake strong ground motion records are selected and scaled by various *PGA* values in order to use as input motion to the virtual shaking table. Record-to-record variability is the only source of uncertainties used in this study, however, the approach is capable of incorporating other sources of uncertainties associates with equipment and their characteristics. Fragility curves are developed by fitting a log-normal distribution on the variability of response by each equipment and under each *PGA* value. The approach provides a feasible procedure for development of fragility curves for other non-structural elements and contents and therefore further study and investigation are recommended using these tools.

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