

The Overturning Response of Rigid Blocks to Increasing Amplitudes of Sinusoidal Accelerations

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Abstract: Earthquakes are ground motions near the Earth's surface that can cause great damage to both structural and nonstructural elements of buildings. Free-standing nonstructural elements like shelves, cabinets, and furniture are susceptible to overturning during these events that can be costly to replace or repair. Additionally, these nonstructural elements can also pose a hazard to adjacent persons or patients in hospitals when these overturn or fall from high places. These account for a large proportion of earthquake-driven injuries. With this, the study assessed the overturning response of wooden rigid blocks of varying slenderness when subjected to incrementally increasing amplitudes of sinusoidal motions set at 2.75 Hz using shake table tests. IDA data sets and overturning fragility curves were created to observe the overturning probabilities of the blocks. The study found that blocks of slenderness ratios 2.0 and 2.5 exhibited no rocking motion and jumped immediately to overturning with only a 0.02 cm increase in the amplitude of the sine wave. However, the tallest block with a slenderness ratio of 3.0 exhibited rocking motions between amplitude values of 0.78-1.00 cm, before overturning to higher amplitudes. The fragility curves displayed increasing probabilities of overturning as the slenderness of the block increases. At 1.00 cm amplitude, the shortest block had an overturning probability of 16%, the middle block at 34%, and the tallest block at 57%. Overall, the study found that the responses of the rigid blocks were highly sensitive to the input motions since the responses of the blocks are uncertain in nature.

Key Words: Overturning response; Fragility curve; Rigid block; Sinusoidal motions; Shake table tests

1. INTRODUCTION

The Philippines, which is situated along the Pacific Ring of Fire, is prone to experiencing strong earthquakes due to the many active fault lines present. A few notable earthquakes that recently occurred in the Philippines include a 7.0 magnitude earthquake that hit Northern Luzon in July 2022 and a 6.7 magnitude earthquake in Surigao del Sur in December 2023. Both earthquakes scored a VII on the

Phivolcs Earthquake Intensity Scale. Recovery from such earthquakes takes much time, effort, and expenses, which could adversely affect the residing communities.

Nonstructural elements play a pivotal role in the functionality of a building, such as hospital beds and medical equipment in hospitals, tables and shelves in an office, or washing machines and refrigerators in a house. These elements are abundant in buildings and take up a large proportion of the entire building's value. However, they are also

vulnerable to rocking or overturning when subjected to ground motions, which can cause severe economic losses and can hinder the functionality of a building due to damage sustained by these elements. Additionally, nonstructural elements can pose a hazard and cause injuries to occupants inside buildings, which accounts for around 40% of injuries caused by earthquakes (Sato et al., 2006).

Although numerous studies have focused on the resilience and seismic response of nonstructural elements using numerical and other non-experimental analysis methods, there is still limited research that examines the real-life response and resilience of rigid blocks or nonstructural elements with varying slenderness when subjected to sinusoidal motions. Rigid blocks are an effective way to model the response of a nonstructural element when it is subjected to ground motions. The main objective of this study is to develop and evaluate fragility curves of the overturning response of rigid blocks with varying slenderness when subjected to sinusoidal motions of increasing amplitudes using shake table tests. The first assumption of this study is that the static and kinetic coefficients of friction are high enough to eliminate any form of sliding displacement. Secondly, the motions used are unidirectional. And lastly, all blocks possess uniform weight distribution.

Wittich and Hutchinson (2015) investigated the vulnerability of rigid structures with the use of shake table tests and found that taller and larger structures experience only a slight increase in rocking but show a significant rise in sliding while shorter and smaller structures tend to exhibit a greater increase in rocking, making them more susceptible to overturning, with a lower slide tendency. Marotta et al. (2021) investigated the damage of an earthquake in Central Italy, assessing the vulnerability of the structures using seismic fragility curves. The study found that the curves were accurate and precise in predicting damage, as they closely aligned with actual data collected from the seismic event. Liu et al. (2023) observed the behavior of wheeled nonstructural elements such as a ventilator and anesthesia machine. Using incremental dynamic analysis and seismic fragility curves, the study found that the specimens experienced more displacement due to the uneven friction, increasing the risk of damage.

2. METHODOLOGY

2.1 Specimen Design and Motion Inputs

As for the selection of rigid blocks, the study made use of three wooden blocks of varying heights with a fixed size for the base. Table 1 below shows the specifications of each block.

Table 1. Wooden block specimens' specifications.

Block	Height (in)	Base (in)	Slenderness (h/b)	Slenderness Angle (°)	Mass (g)
B1	5	2.5	2.0	26.6	241.16
B2	6.25	2.5	2.5	21.8	320.63
B3	7.5	2.5	3.0	18.4	462.40

For the input acceleration, a sine wave function was used, utilizing amplitudes from 0.0 to 2.0 cm with 0.02 cm increments, all set to 2.75 Hz. This led to a total of 100 unique motion inputs and 300 test cases overall.

2.2 Experimental Setup

To perform shake table tests, the Quanser Shake Table II was used. For the layout of the setup, sandpaper was placed on the base of the shake table to prevent sliding displacement of the specimens. On top of the sandpaper, a bracing made of wood and acrylic was installed to keep the horizontal axis of the block parallel to the direction of motion. Then, a 240 fps HD camera was placed in front of the shake table using a tripod close enough to keep the full block in view throughout the whole range of motion. Green markers were also attached to the block for the video analysis.

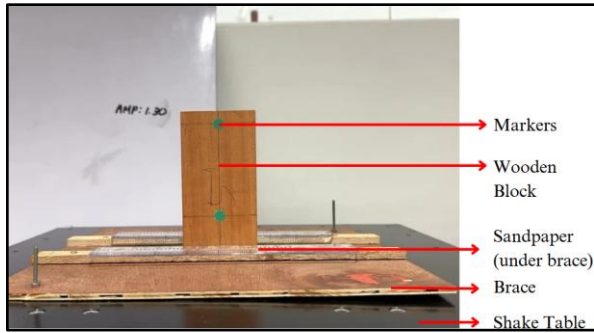


Fig. 1. Experimental setup design.

To extract the data from the trials, the videos were processed using Python to obtain the maximum angle displacement experienced by the block. Additionally, each trial was classified as either 0 if the block did not overturn or 1, if it did. This binary classification, along with the rest of the data, was later used to develop the fragility curves for each block.

2.3 Fragility Curve Development

To develop fragility curves, the study adopted a method used in Liu et al. (2022) wherein the IDA data sets are used to create a logistic regression model that predicts the overturning probability of the block. The overturning probability is then written as a function of amplitude.

$$P(|\theta|_{max} \geq \alpha|A) = \frac{1}{1 + \exp[-(b_0 + b_1 \times A)]} \quad (\text{Eq. 1})$$

where:

- b_0 = the intercept coefficient of the function
- b_1 = the slope coefficient of the function
- A = amplitude (cm)

3. RESULTS AND DISCUSSION

3.1 IDA Datasets of Blocks

From the data sets, it is observed that blocks B1 and B2, seen in Figs 2.1 and 2.2, were not prone to rocking as they had shifted from displacement values 0 to 4 degrees then immediately jumped to 90 degrees in which they had overturned. However, for B3, seen in Fig 2.3, the response was different from the first two as it displayed rocking motions between amplitude values of 0.75 to 1.00 cm, this may be due to the block having the highest slenderness ratio (3.0). Additionally, this aligns with Housner (1963) stating that tall, slender blocks are more prone to rocking, which can attribute to its ability to resist overturning.

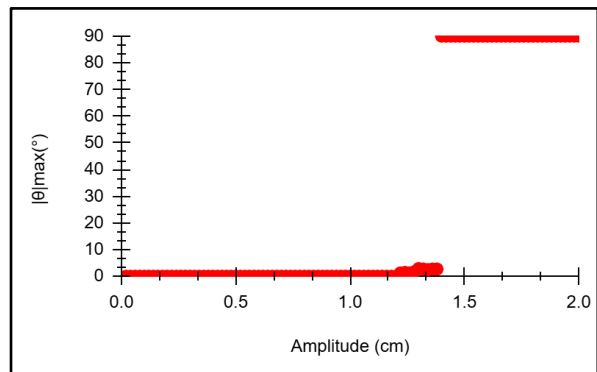


Fig. 2.1. IDA data set for B1.

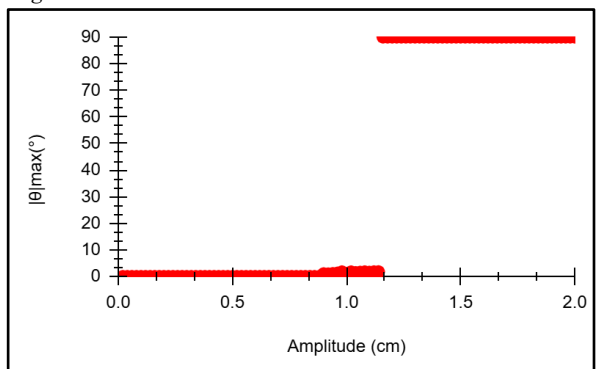


Fig. 2.2. IDA data set for B2.

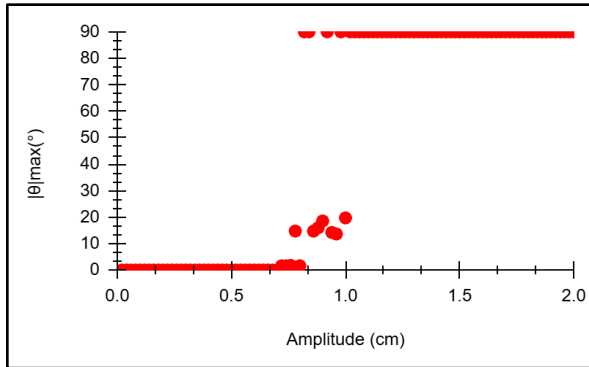


Fig. 2.3. IDA data set for B3.

3.2 Overturning Fragility Curves of Blocks

From the fragility curves, it is observed that the probability of overturning increases as slenderness increases. For example, at 1.00 cm amplitude, B1 has a 16% probability of overturning, B2 has 34%, and B3 at 57%, seen in Fig. 3. This shows that even though B3 possesses some capability to resist overturning (shown in the IDA data sets), it ultimately overturns to amplitudes lower than ones B1 and B2 overturn to.

Table 2. Fragility curve parameters for blocks B1-B3.

Block	b_0	b_1
B1	-5.71	4.05
B2	-4.84	4.19
B3	-3.79	4.09

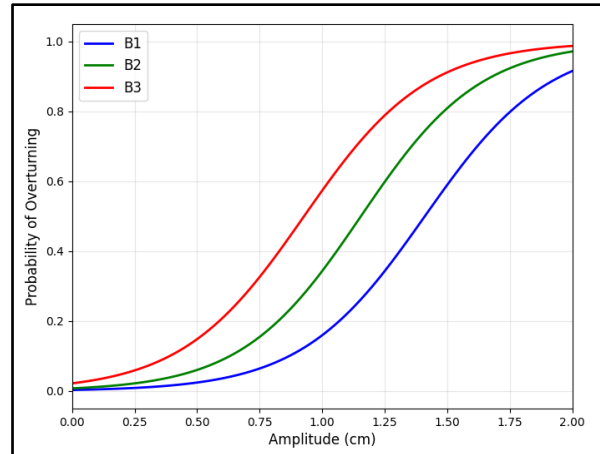


Fig. 3. Overturning fragility curves for blocks B1-B3.

4. CONCLUSIONS

The study found that B1 and B2 did not exhibit significant rocking motion, as they would go from slight angle displacements below 4 degrees to overturning from only a 0.02 cm increase in amplitude. For B3 however, it exhibited significant rocking motion between amplitudes 0.78-1.00 cm. This characteristic aligns with Housner's model of the rocking block stating that tall, slender structures have the ability to resist overturning since they are prone to rocking.

Overall, the study concludes that the overturning response of rigid blocks of varying slenderness is highly sensitive to input motions, as shown in the data sets, wherein cases of no rocking can change to overturning with a difference of only 0.02 cm in amplitude. Of the overturning fragility curves, a higher probability of overturning is generally associated with higher slenderness ratios, since blocks B1-B3 displayed increasing probabilities of overturning at the same amplitudes, respectively.

As a recommendation, the study suggests that the data from this research be used for future studies in order to validate and check to see if novel methods of response prediction of rigid blocks (such as artificial intelligence or machine learning) agree well with practical experimental data.

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