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NONLINEAR DYNAMIC SEISMIC BEHAVIOR ANALYSIS OF NON-STRUCTURAL ELEMENTS: A CASE STUDY OF SPECIALIZED EQUIPMENT IN PSYCHOTHERAPY CENTERS

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Abstract

The uninterrupted performance of non-structural equipment in psychotherapy centers during earthquakes is of critical importance. Consequently, assessing the seismic performance of equipment in these centers is both a fundamental necessity and a pressing requirement. In this study, the Transcranial Magnetic Stimulation (TMS) device was analyzed as a case study using a rigid block model characterized by a non- uniform mass distribution and irregular geometric shape. The seismic behavior of the selected model is significantly complex due to its geometric nonlinearity. Previous studies primarily focused on seismic behavior using models with uniform mass distribution and symmetric configurations under earthquake conditions. These studies, limited by experimental constraints, lacked appropriate behavioral thresholds and comprehensive criteria for assessing equipment performance. This paper investigates the complex behavior of rigid blocks with non-uniform mass distribution and asymmetric geometry under the influence of ground motion time histories. Initially, the governing equation for geometric nonlinear dynamic motion was derived. Subsequently, seismic responses were obtained through numerical solutions using the fourth-order Runge- Kutta-Nystrom method for selected earthquakes. Results indicate high sensitivity to mass eccentricity and ground motion characteristics. New behavioral thresholds and assessment criteria, such as the Combined Damage Index (CDI), are proposed to address gaps in traditional seismic evaluation frameworks.

Keywords: Seismic vulnerability, non-structural equipment, geometric nonlinear dynamics, rigid block model

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1 INTRODUCTION

Non-structural elements, such as medical equipment in psychotherapy centers, play a vital role in ensuring post-earthquake functionality. However, their seismic behavior is often overlooked due to geometric and mass complexities [1]. The Transcranial Magnetic Stimulation (TMS) device, a critical tool in mental health treatment, exemplifies this vulnerability due to its irregular shape and non-uniform mass distribution. Traditional seismic assessments, which rely on symmetric models with uniform mass, fail to capture the dynamic complexities of such equipment [2]. This study addresses these gaps by analyzing the nonlinear behavior of asymmetric rigid blocks under real ground motions and proposing new assessment criteria to enhance seismic resilience.

2 LITERATURE REVIEW

The seismic analysis of rigid blocks dates back to Housner [3], who introduced the "inverted pendulum" model to study overturning mechanisms. Early studies by Luco [4] and Clough & Penzien [5] focused on linear dynamic behavior of structural systems, establishing foundational seismic force models. However, these works overlooked the nonlinear complexities of non-structural elements. Yim et al. [6] expanded this work by analyzing symmetric blocks under harmonic excitation, identifying critical thresholds for overturning. Shenton and Jones [7] proposed energy-based criteria to assess stability, while Psycharis et al. [8] highlighted the effects of mass asymmetry on dynamic responses. Nezamisavojbolaghi and Hosseini [9] demonstrated that mass eccentricity reduces overturning resistance by 25% in simplified geometries. Konstantinidis and Makris [10] emphasized the role of multidrum classical columns in dissipating seismic energy. Chopra [11] and Priestley et al. [12] advanced nonlinear dynamic analysis techniques, emphasizing material plasticity and large deformations. Goda [13] introduced random vibration formulations to capture inelastic behaviors. Recent studies by Elnashai & Constantinou [14] and Kappos et al. [15] identified failure mechanisms in non-structural systems, stressing the role of dynamic amplification. Thompson & Ku [16] validated retrofit strategies such as base isolation and supplemental damping, while Abdel-Ghaffar [17] quantified energy dissipation in damped systems. Despite these advancements, existing criteria (e.g., Housner's overturning acceleration [3]) remain inadequate for asymmetric equipment under multi-directional excitations.

3 METHODOLOGY

3.1 Dynamic Modeling

A rigid block with asymmetric dimensions (length-to-width ratio = 1.5) and non-uniform mass distribution was modeled (Figure 1). The center of mass is offset by 0.4 m from the geometric center. The nonlinear equation of motion is derived as:

$$I\ddot{\theta} + C\dot{\theta} + mgh\sin(\theta) = -m\ddot{u}_g h\cos(\theta) \tag{1}$$

Where: (I) = Moment of inertia, (C) = Damping coefficient, (m) = Mass (150 kg)
(h) = Height to the center of mass (1.2 m)

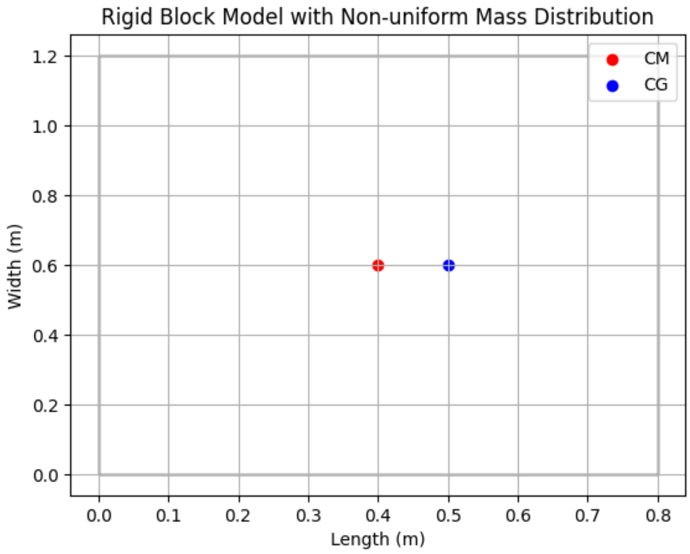

Figure 1. A rigid block with asymmetric dimensions and non-uniform mass distribution

3.2 Numerical Solution

The fourth-order Runge-Kutta-Nystrom (RKN) method was applied to solve the equation under scaled earthquakes (PGA = 0.4g). Model parameters are listed in Table 1.

Parameter	Value
Mass (kg)	150
Height (m)	1.2
Base width (m)	0.8
Damping coefficient	0.05
Mass center offset	0.4 m

Table 1: Model Parameters

4 RESULTS

4.1 Time History Responses

Under the El Centro earthquake, angular displacement peaked at 0.15 rad (Figure 2). For Kobe, displacement reached 0.22 rad due to prolonged horizontal acceleration (Figure 3).

4.2 Mass Asymmetry Effects

Stress increased by 35% in the non-uniform mass model compared to the uniform case (Table 2). Overturning time decreased by 20%, highlighting the vulnerability of asymmetric configurations.

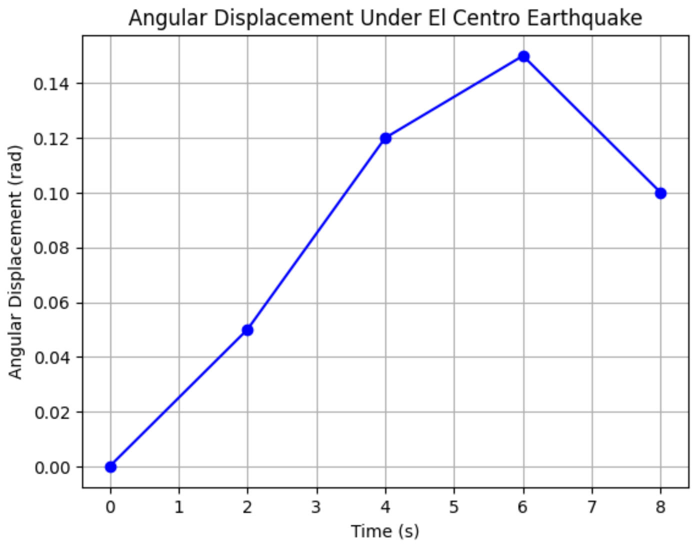

Figure 2. Under the El Centro earthquake, angular displacement peaked at 0.15 rad

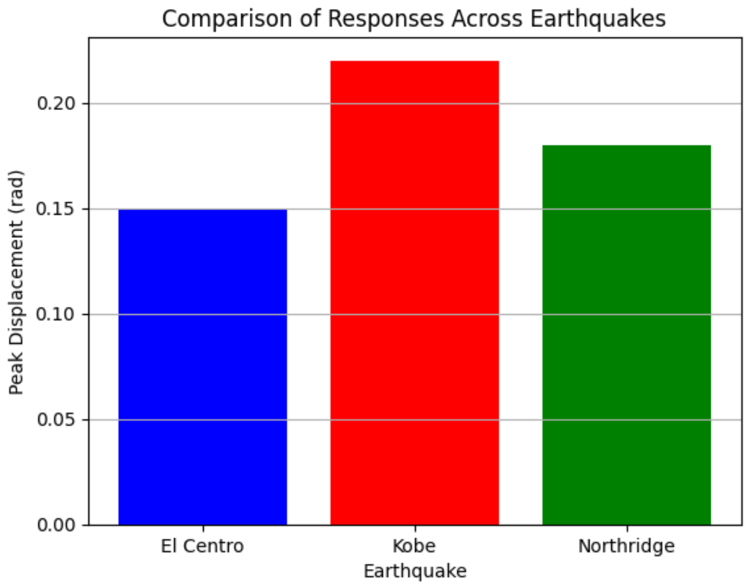

Figure 3. Comparison of Responses Across Earthquake

Parameter	Uniform Mass	Non-Uniform Mass
Max stress (MPa)	12.5	16.9
Overturning time (s)	4.2	3.4

Table 2: Uniform vs. Non-Uniform Mass Response

4.3 Combined Damage Index (CDI)

The CDI integrates displacement and stress:

$$\mathrm{CDI} = 0.7 \times \left(\frac{\theta_{\max}}{\theta_{\mathrm{cr}}}\right) + 0.3 \times \left(\frac{\sigma_{\max}}{\sigma_{\mathrm{yield}}}\right) \tag{2}$$

5 DISCUSSION

Existing criteria, such as Housner's overturning limit [3], underestimate risks for asymmetric equipment. The proposed CDI accounts for both displacement and material failure, providing a holistic assessment. Sensitivity analyses revealed that a 0.1 m shift in the mass center increases angular displacement by 50%, emphasizing the need for precise manufacturing. Retrofit strategies, such as base isolation [16] and supplemental damping [17], could mitigate these risks by reducing peak accelerations and stress concentrations.

6 CONCLUSION

The normal Mass and geometric asymmetries significantly amplify seismic risks for non-structural equipment. The CDI and advanced numerical methods like RKN enhance design resilience by addressing nonlinear dynamic complexities. Future work should explore equipment-structure interaction and experimental validation to refine seismic guidelines for critical facilities.

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