



FINITE ELEMENT MODELING OF A FREE-STANDING CYLINDRICAL COLUMN UNDER DYNAMIC EXCITATION

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Abstract

This paper presents a finite element (FE) model used to analyze the response of rocking objects and validates it against shake table tests of a free-standing cylindrical steel column. The rocking column was shake table-tested under a set of 100 bidirectional ground motions. During testing the column was allowed to slide and rock in all directions. An explicit finite element solver was used in the FE analysis. Since the stresses developed in the column were significantly below the yield stress and given that the steel's modulus of elasticity is high, the rocking object was analyzed as rigid body. The contact between the base of the column and the moving base was modeled using Coulomb friction for the tangential behavior, and stiff contact for the normal direction. Two energy dissipation mechanisms were modelled: a) Friction, as Coulomb friction and b) Radiation damping, using a spring and a dashpot system underneath the supporting slab. Rayleigh damping was set to zero.

The FE model results were statistically compared with the corresponding experimental ones using the cumulative distribution function (CDF) for the main response quantities (i.e., maximum displacement at the top of the column and residual displacement), demonstrating good agreement.

Moreover, this work examined the influence of the friction coefficient, through an extensive sensitivity analysis using non-linear time-history analyses. It was proved that the statistics of the response only smoothly depend on the exact value of the friction coefficient, even though the response to an individual ground motion seems chaotic.

Keywords: rocking columns; finite elements; statistical validation; sensitivity analysis; free-standing equipment

1. Introduction

Rocking structures are the ones that are allowed to uplift. Under ground motion, uplifting occurs when

$$\ddot{u}_g > g \tan \alpha \quad (1)$$

where the \ddot{u}_g is the ground acceleration, g is the gravity acceleration, and α is the slenderness of the block (Figure 1). It is assumed that the sliding surface is sufficiently rough to prevent sliding. This uplifting effect acts as a fuse, limiting the inertial forces transmitted to the superstructure. After uplift, a rocking oscillator demonstrates negative stiffness, making the description of such systems significantly different than the conventional ones.

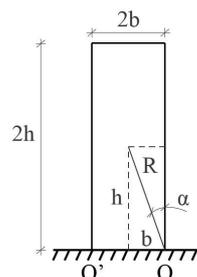


Fig. 1. Geometric properties of a rocking block.



The first analytical study of this phenomenon is dated back to 1885 [1,2]. However, rocking structures have been systematically studied after 1963, when Housner published his seminal paper [3] where two main properties of the rocking structures were elucidated: i) out of two geometrically similar rocking blocks (same α) the larger one (larger R) can survive an excitation which will topple the smaller one ii) longer period ground motions have a higher overturning potential [3].

The rocking oscillator has been used to describe the dynamic behavior of free-standing equipment [4-7], masonry structures [8-14] and ancient temples [15-19]. Rocking is also a promising seismic response modification technique, both for bridges and buildings, with practical applications in the former USSR and New Zealand [20,21]. Applications in buildings may comprise a soft-rocking-story mechanism [22-24], or a rocking wall [25, 26], whereas in bridges, rocking piers [27-35]. Several analytical studies investigated the response of rocking structures combined with external dampers or restraining tendons [36-38]. The influence of the flexibility of the rocking body was also studied, both analytically and experimentally [39-42].

The analytical model proposed by Housner describes the planar response of a rigid rocking body when subjected to one-directional excitation. However, under seismic excitation, rocking structures are subjected to bidirectional (or three-directional when the vertical acceleration is considered) excitation [43-46]. Under these conditions, an unanchored body may rock in 3D dimensions (wobble). When it is not restrained, it may also slide out of its initial position [47] or completely detach from the support.

This study aims at developing a practical three-dimensional finite element model to predict the response of free-standing cylindrical rocking columns. The validity of the proposed model is assessed by statistically comparing numerical and experimental results. The experimental results comprise 100 shake table tests, using a cylindrical steel column with a slenderness (α) of 0.15. The number of tests performed is large enough to allow such a statistical comparison. The specimen was subjected to two-dimensional excitation, and it was free to slide, rock and wobble in all directions. As the column is free to slide and wobble out of its original position, it serves for validation of numerical models used for the description of the seismic behavior of unanchored equipment, rather than of structures that use rocking as a seismic isolation strategy.

2. Statistical validation

Rocking is often characterized as “chaotic”, in the sense that the response of rocking objects is sensitive to the initial conditions, often making tests non-repeatable. Therefore, validating numerical models in a deterministic way does not even make sense.

Bachmann et al. [48] and Del Giudice et al. [49, 50] claimed that validating a numerical model using a single ground motion is a sufficient but not necessary validation procedure. The seismic response is inherently stochastic since the excitation is stochastic. Therefore, a statistical (and not a deterministic) validation of the numerical model is proposed. During this statistical validation, the statistical distributions of the main response quantities of the model and the experiments are compared. This procedure requires an experimental benchmark dataset, where the same (or identical specimens) are excited by an ensemble of ground motions. Afterwards, a numerical model is used to create another dataset, using the same ensemble of excitations. The validity of the numerical model is assessed by comparing the Cumulative Distribution Function (CDF) of these two datasets for the same response quantity (i.e., maximum top displacement). This validation test is weaker (and easier to pass), yet sufficient for earthquake engineering applications.

3. Numerical studies of rocking structures: results of a blind prediction contest

During the last decade, both FEM and DEM numerical models were developed to predict the rocking problem [51-54]. A recent blind prediction contest organized by ETH Zurich, the University of Bristol and the Pacific Earthquake Engineering Research (PEER) Center, shed light on the efficiency of numerical models used to describe the statistical response of a rocking podium structure [55]. Unlike the tests discussed in this paper, the tests of [55] concerned a rocking podium structure that was restrained not to slide or wobble out of its original position. Thirteen contestants participated, using FEM, DEM, and analytical rigid-body models [56-



57]. One of the important outcomes of this contest is that there is no basis for recommending FEM or DEM to model the response of wobbling structures; the accuracy of these models depends on the modeling assumptions. Moreover, it was proven that even though the winning models accurately captured the Cumulative Distribution Function of the maxima of the responses to each set of excitations, they were unable to accurately predict the response to each individual ground motion.

4. Experimental procedure

This section briefly presents an experimental investigation designed at ETH Zurich and carried out at EQUALS Lab, University of Bristol [58]. This investigation includes 115 shake table tests of cylindrical free-standing rocking bodies, which were free to slide and rock in all directions. More details about the tests can be found in [58]. From the various free-standing columns which were experimentally tested (Figure 2), the results of one cylindrical column were utilized to assess the efficiency of the proposed FE model (Figure 3, right). The selected cylindrical column was the one with the lowest slenderness ratio, thus, the one with the highest probability of overturning. The experimental results from [58] served as an experimental dataset, to assess the proposed FE model.

The rocking specimens tested in [58] were not chosen to represent specific free-standing rocking equipment; the results serve for model validation. They were designed to remain elastic after each test, so they could be excited with a large number of earthquake excitations to create a database suitable for a statistical validation. The specimens were made of round steel pipes, with different dimensions and slenderness.

The rocking response was induced by a di-directional dynamic excitation using a shake table. The applied ground motions were synthesized using a spectral version of the Rezaeian and Der Kiureghian stochastic ground motion model [59-60]. The 1989 Loma Prieta UCSC Lick Observatory ground motion record was used as a seed ground motion to generate an ensemble of 100 ground motions. The ground motions were scaled, with the frequency of ground motions increased by 2 without changing the amplitude. Therefore, in the prototype scale, the columns are 4 times larger.

5. Numerical model

The finite element software ABAQUS [61] was utilized to perform the analysis. The model comprised the cylindrical rocking bodies and a moving flat base slab. The base slab was modelled with 10mm-thickness steel shell elements, but their modelled thickness is insignificant because a rigid body constraint was imposed on all of them. Then, the base slab was vertically supported by a spring-dashpot system to simulate the vertical stiffness of the shake-table platform and the radiation/impact damping mechanism (Figure 3, Left). Its rotation was constrained and set equal to zero. This approach was previously used in [62] in an effort to model radiation/impact damping, and it was shown that that in the planar case it leads to Housner's solution, as long as the stiffness of the spring is relatively high. Therefore, the spring constant was set to 10^9 N/m so that the pre-uplift vertical eigenperiod of the system is 0.001 sec. All rotations of the base were fixed. To apply the ground motion, the base moved parallel to x and y axis.

A uniform mesh with a size of 5 mm was utilized in all analyses. A 4-node 3D rigid quadrilateral finite element was used both for the rocking column and the flat base. The motion of the specimens was monitored with a reference point at the top of the column. The contact surface was simulated using Coulomb friction for the tangential behavior and ABAQUS stiff contact [61] for the normal direction. An explicit scheme with a fixed time increment of 10^{-6} sec was used in all cases.

The developed numerical model considers two main damping mechanisms; friction and radiation/impact damping. Inherent Rayleigh damping is set to zero since this energy dissipation mechanism is inconsistent with the physical problem. Energy dissipation through friction is considered through the friction coefficient, whereas radiation damping through the utilized dashpot. Neither the friction (μ) nor the dashpot (ζ) coefficient was known a priori; the influence of the friction coefficient was assessed through an extensive parametric analysis employing non-linear time history analysis.



Fig. 2. Free-standing rocking column specimens on the shake table at EQUALS lab, University of Bristol.

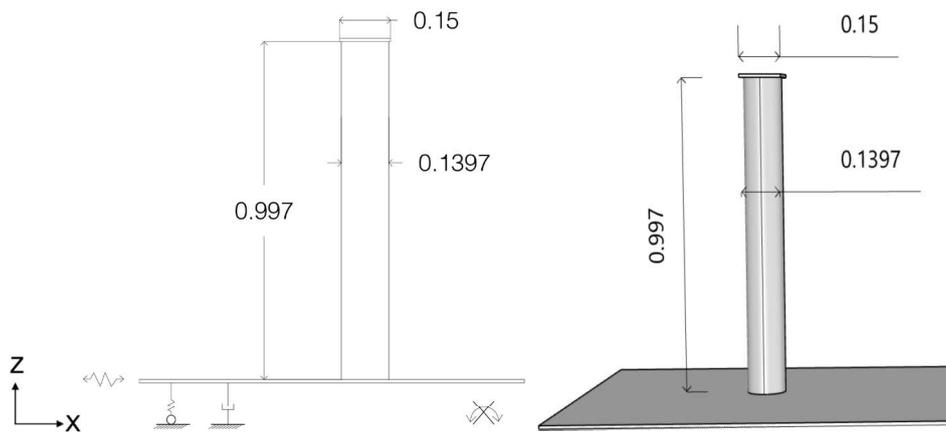


Fig. 3. Left: Schematic representation of the rocking column, the constraint of the flat base and the spring-dashpot system below the base; Right: Dimensions (in m) of the tested specimens

In this parametric analysis, the coefficient of friction μ was varied from 0.3 to 2. Not all the above values are realistic, but the analysis explores the influence of extreme values of the modelling parameters on the rocking response. The damping ratio ζ corresponding to the vertical vibration mode (i.e. radiation damping) was set to $\zeta=1\%$. This damping should not be confused with Rayleigh, which was equal to zero in all tests.

6. Results

6.1 Deterministic comparison

Figure 4 presents a comparison between experimental and numerical results for the different values of the critical modeling parameter (i.e., friction coefficient). The investigated response parameter is the maximum displacement (u_{\max}) at the top of the rocking column, and the residual displacement after the end of the excitation (u_{res}), both measured in meters. In the following plots, “OT” denotes overturning of the specimen.



In all scatter plots, the horizontal axis corresponds to the experimental results, whereas the vertical to the numerical ones.

It is evident that the numerical results are moderately correlated to the experimental ones. Moreover, similarly to previous studies [48], the numerical model often fails to predict overturning. However, the relevant question in earthquake engineering is not whether the model is accurate but whether it is biased and whether it induces more uncertainty than the ground motion. Comparing the results of individual ground motions, it is not possible to identify clear patterns of the influence of the coefficient of friction on the maximum response of the body. Most importantly, minor changes in the coefficient of friction, lead to very large changes in the maximum response.

6.2 Statistical comparison

When the numerical results are statistically assessed, clear trends emerge (Figure 5), similarly to what was observed for the planar rocking model by Yim et al [63] as early as in 1980. An increase of the friction coefficient leads to an increase of the maximum displacement of the rocking column (Figure 5, left). The

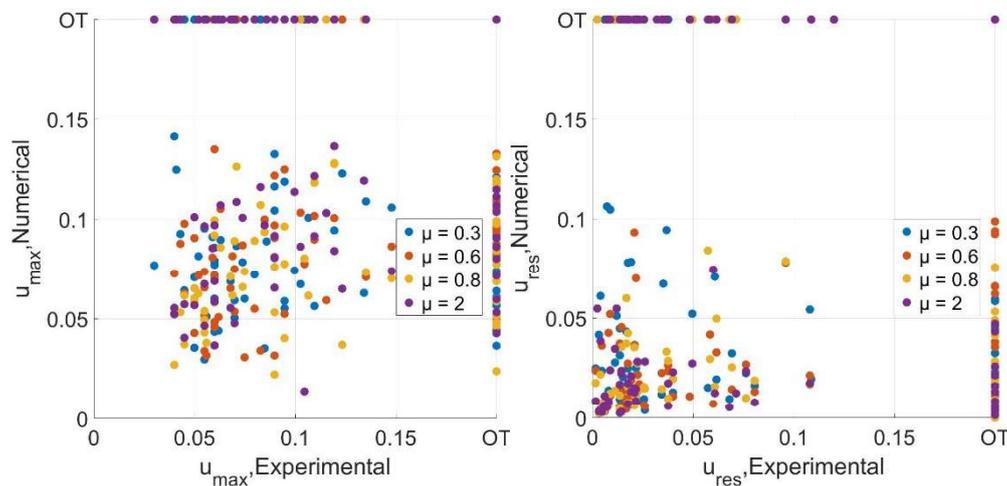


Fig. 4. Deterministic comparison for experimental and numerical results of the columns. Sensitivity analysis for friction coefficient. Left: Maximum Displacement, Right: Residual Displacement

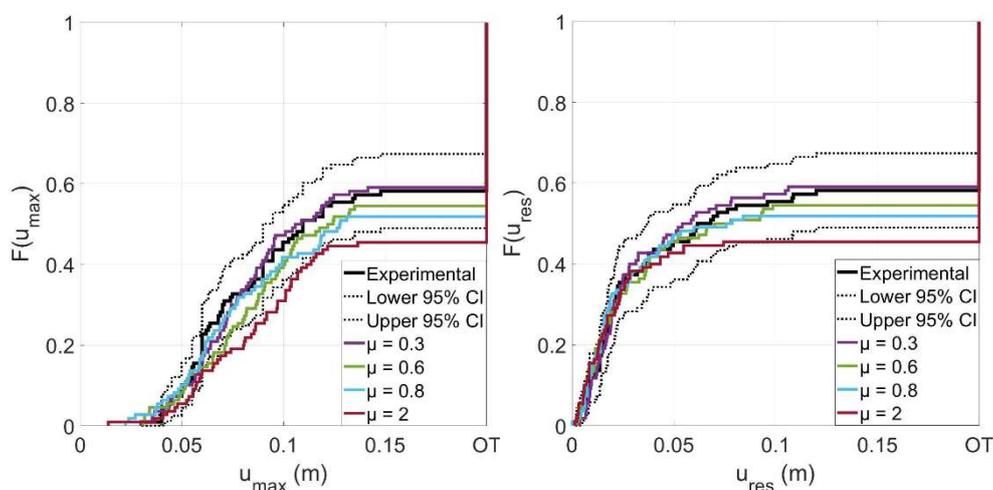


Fig. 5. Statistical comparison for experimental and numerical results of the columns. Sensitivity analysis for friction coefficient. Left: Maximum Displacement, Right: Residual Displacement



residual displacement does not seem to depend on the coefficient of friction, provided that there is no overturn. Hence, neglecting sliding (i.e. using a very high value for μ) is a conservative modelling approach, at least in terms of maximum displacement and prediction of overturning probability. It is worth noting that, varying μ from 0.3 to 0.8 leads to a statistical response which is inside the range of the 95% confidence interval (CI) of the experimental tests.

7. Conclusions

The presented numerical model simulates the response of α free-standing cylindrical column. The column had a slenderness ratio of $\alpha = 0.15$, and, during testing, it was free to slide and rock in all directions. It is shown that the model performs poorly when it is assessed based on its ability to predict the maximum displacement at the top of a column excited by an individual ground motion. However, it can perform well, when it is evaluated based on its ability to predict the CDF of the maxima of the responses to a set of ground motions.

The friction coefficient between the rocking block and the supporting surface was varied numerically and its influence was assessed with a large number of non-linear time-history analyses. Even though the exact value of the friction coefficient significantly influences the deterministic response, it affects the statistical response only moderately. The CDF curves show that an increase of the friction coefficient amplifies uplifting and leads to larger maximum rocking displacements, thus making the model more conservative. A friction coefficient equal to $\mu = 0.3$ and a radiation damping equal to $\zeta = 1\%$ leads to the optimal match between experimental and numerical results.

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