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Experimental and numerical analyses of variability in the responses of imperfect slender free rigid blocks under random dynamic excitations

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ABSTRACT

Due to the well-known sensitivity of the behaviors of free structures under seismic excitations, the question of the aptitude of a numerical model to accurately represent them arise. To contribute to the answer to this question, this article presents experiments which were carried out on the shaking table of CEA/Saclay in France, on three rigid blocks with geometrical defects, inevitably due to the manufacturing process, subjected to 100 realizations of a random process. These tests were analyzed using specifically-developed indicators, and compared with the results yielded by two numerical models, one with a symmetrical geometry and the other with a non-symmetrical geometry, calibrated to reproduce out-of-plane behavior identified through release tests. Counter-intuitively, this article shows that a numerical model can predict motion over a longer period than an experiment performed on a supposedly identical block. From a statistical point of view, despite experimental uncertainties this article shows a good agreement between numerical and experimental results. Finally, a numerical study, performed using artificial seismic signals, showed that the assumption of perfect geometry can lead to an underestimation of the risk of overturning. Moreover, it is showed that a symmetrical model with a realistic slenderness correction can provide an overestimation of this risk under 1D excitation, but not in 2D.

1. Introduction

A free structure, placed on the ground without any anchoring, is likely to rock or overturn during an earthquake. The slenderer the structure is, the greater the risk of overturning. Thus, columns of ancient temples or stacking containers are all structures that may be concerned by this type of risk. The numerical modeling of the rocking behavior of structures under seismic motion is quite the challenging task, since this problem includes several difficulties, due to the large displacements, large rotations, and also impact and friction nonlinearities, all of which cause the responses of these structures to be extremely sensitive to small perturbations [1]. Yim et al. [2] demonstrated numerically that it was not recommended to study the seismic behavior of such a structure using only a single excitation instance. A statistical study is necessary to understand the behavior of a rigid body under dynamic excitation. This sensitivity is not only numerical; it is also experimental. Nevertheless, various studies have shown that, depending on the type of solicitation and the nature of the bodies in contact, it is possible to observe a certain degree of repeatability in behavior. For example, Wong and Tso [3] studied in detail the behavior of a rigid slender structure under 1D sinusoidal excitation. Several steady states were experimentally observed and compared, more or less successfully, with the results of numerical simulations. Considering rectangular-based solid blocks composed of different materials, ElGawady et al. [4] showed that free rocking or release tests, performed on various types of supports, could demonstrate a certain repeatability in the main motion axis, although only when the foundation was rigid. More recently, Mathey et al. [5] showed, for release tests on a rigid foundation using a slender rectangular cuboid block with small geometrical defects, that both in-plane and out-of-plane movements exhibited some repeatability over a limited period. Conversely, Mouzakis et al. [6] showed that the out-of-plane movement of a cylindrical structure with a circular base subjected to 1D seismic tests was barely repeatable. Peña et al. [7] obtained experimental movement repeatability over a relatively long period during rocking tests performed on rectangular-based blocks under harmonic acceleration, with poorer repeatability when under random acceleration.

In the present article, because of the extreme sensitivity of the responses of free structures to small perturbations under seismic excitations, the authors are concerned with assessing the aptitude of a

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numerical model to represent, over time, the dynamic behavior of an imperfect slender rigid block subjected to random excitations. This work follows directly from article [5], in which the authors studied the influence of small geometric defects, inevitably due to the manufacturing process, on the seismic behavior of rigid blocks. To this end, they proposed a numerical model of an asymmetrical block which was propped up to reproduce out-of-plane behavior identified through release tests. So, in the present work, in order to assess the representativity of this model, from both a deterministic and a statistical point of view with respect to time, a series of experiments was carried out on four experimental blocks, using a 1D shaking table. First, the experimental blocks, arranged on the same shaking table, were subjected to 100 realizations of 30 s of a zero-mean stationary Gaussian process. Although they are not representative of real seismic ground motions, this choice ensures that a variation over time in the statistical characteristics of a block's response cannot be linked to a variation in the statistical characteristics of the excitation, but must be imputed to the structure itself, whether it be numerical or experimental. Next, repeatability tests were performed, *i.e.* the experimental blocks were subjected to 100 times the same realization of the stationary process. Theoretically, this type of test is more discriminating for the model since, by minimizing the excitation variability, it becomes possible to assess more specifically the "intrinsic quality" of the model as regards its aptitude to represent a given real behavior. In practice, these tests showed a repeatability level comparable to that obtained during tests performed by Peña et al. [7].

This paper comprises 9 sections. In Section 2, the experimental campaign is presented in detail. In Section 3, various specifically-developed indicators of comparison are presented. Numerical models are presented in Section 4, and are compared with experimental results in Sections 5 and 6. These results are discussed in Section 7, leading to the proposition of an upper-bound model in order to obtain a conservative assessment of overturning occurrences. Then, Section 8 presents an extensive numerical study which aims to confirm the previous statistical results at a larger scale with synthetic accelerograms which are more "representative" of real earthquakes. Finally, the conclusion is presented in Section 9.

2. Experimental campaign

2.1. Experimental setup

The tests carried out in this study were performed using four solid steel blocks of about 54 kg, identical within manufacturing tolerances. Fig. 1 shows the four specimens placed on the shaking table in order to perform dynamic tests.

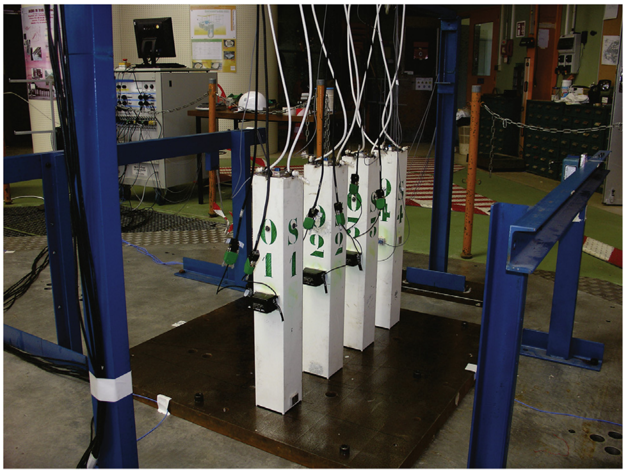

Fig. 1. The four tested blocks placed on the shaking table.

As shown in Fig. 1, the blocks are rectangular cuboids of slenderness 6.9, each with four cuboid feet carved out of the solid steel. Their dimensions are given in Fig. 2a.

As in reference [5], the blocks were only equipped with angular velocity sensors in the convected frame which follows the rotation of the block. These sensors have a measurement range of $\pm$ 200 deg/s and an accuracy of $\pm$ 0.01 deg/s. The acquisition of acceleration and angular velocity measurements was performed at 1000 Hz, with an anti-aliasing filter set to 500 Hz.

It is worth noting that angular velocities are the direct output of the algorithm used, both in this work and in reference [5], to solve numerically the equations of motion in the case of large rotations (see Section 4). Therefore, the comparison between analytical and experimental results will be made on the basis of these quantities. Given the input excitation, the numerical models actually compute the rotations and displacements of the body which are not constrained during the tests, as it can be seen in Fig. 1. The identification of the parameters of the models has been done comparing the experimental rotations with those obtained from the numerical models (see Section 2.2). Displacements have not been taken into account for this identification, because (i) they were not measured and (ii) during the tests, the bodies were mainly observed to be rocking. Nevertheless, though rotations do not determine the motion only, if amongst several physically-plausible scenarios there is one which matches the rotational records much better than the others, then this scenario could be retained as a credible explanation. This is the case for the models with defects used both in this work and in reference [5]. In doing this, it must be recognized that the set of parameters thus determined may not necessarily be the only set of parameters that would predict the motion of the body, especially given the lack of measurement of translational motions.

Note that for the sake of brevity, only the results concerning the first two blocks will be detailed in this paper.

2.2. Release tests

Before performing the dynamic tests on the shaking table, release tests were carried out on each block. These tests consisted in positioning and keeping the blocks still, balanced on two feet (in an unstable state), then releasing them to allow a free rocking movement. These tests demonstrate reproducible movement from one test to another, in the same experimental conditions, which enables the determination of the values of the models' parameters, through an optimization procedure using an evolutionary algorithm (see [5,8]). For the sake of brevity, the results of these tests are not presented in this article. Nevertheless, Section 4 presents the values obtained for the numerical model parameters.

2.3. Shaking table tests

To assess the representativity of the numerical models, both from a deterministic point of view and one of statistical analysis under dynamic excitation, two series of 100 tests were performed simultaneously on the four blocks, placed on the 1D shaking table, as shown in Fig. 1. In the first series of tests, the blocks were subjected to 100 different acceleration signals, each one generated by the process defined in the next paragraph. In the rest of this paper, this series of tests will be designated by the symbol $\neq$. As mentioned in the introduction, in the second test series, the blocks were subjected 100 times to the same signal, randomly selected among those previously used. These repeatability tests are more discriminating for the numerical models, since they minimize excitation variability (which is, in theory, null). In this study, we will designate this series by the symbol $\approx$. Note that before each test the blocks were repositioned manually along a line marked on the shaking table, in order to guarantee the closest possible angular conditions and initial position from one test to another (see Fig. 3).

Dynamic excitation characteristics. In order to study the behavior of a