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Rocking of Rigid Bodies with Unilateral Constraints

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Abstract: - In the present research one addresses the problem of rocking of rigid blocks moving on a foundation base subjected to a horizontal ground motion.
To this purpose, one analyses and discusses basic reference models, thereafter, one tests the pure rocking response of rigid blocks from an experimental point of view by means of a shaking table; experiments are developed on rectangular aluminium blocks of various sizes and geometry ratios.

Key-Words: - dynamics, experimental tests, rigid blocks, rocking response, shaking table, laboratory data, unilateral constraints, non-linear behaviour

1 Introduction

1.1 Generalities

1 Introduction

The rocking response and the possibility of overturning of rigid bodies in earthquakes are central considerations in seismic safety problems.
As an example for understanding the importance of this phenomenon, one may cite the case of museums or archaeological sites, which are particularly subjected to this risk (in Figure 1 one reports some pictures of remnants from the S. Maria Capua Vetere site), since a broadly similar response can be observed, during earthquakes, in the behaviour of sculptures and remnants of ancient Greek and Roman stone temples, which may result in the damage of precious and ancient pieces. Actually the interest field of the specific subject is much wider. Generally speaking, the rocking and overturning of a variety of structures, such as electrical equipment (Figure 2), retaining walls, liquid storage tanks, tall rigid buildings, tombstones (Figure 3) and so on, and the need of understanding and predicting these failures in association with the attempt of estimating the related intensity levels of ground motion have motivated a number of studies on the rocking response of rigid blocks [1].
Although the starting interest in the modern theory of the dynamics of a rigid block mounted on a rigid oscillating surface is recent [2], the first investigations date back to Milne [3] and Perry [4], who estimated the intensity of ground shaking observing its effects on tombstones and monumental columns, whether they overturned or remained standing (Figure 4).

The first significant attempt to accurately describe the motion of rocking blocks was produced by Housner [2], who examined the free and forced vibration responses to rectangular and half-sine pulse excitations, and, using an energy approach, presented an approximate analysis of the dynamics of a rigid block subjected to a white-noise excitation [5].

Figure 1. Remnants from the S. Maria Capua Vetere archaeological site.

Figure 2. An electrical transformer at the Sylmar Converter Station, California, that overturned during the 1971 San Fernando earthquake.

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Figure 3. The rocking and overturning of tombstones.

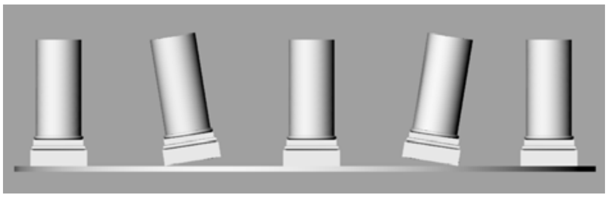


Figure 4. Schematics of rocking motion of columns.

Classification of basic motion components is due to Ishiyama [6], who individuated in slide, bounce and rock the fundamental response modes, and, finally, provided the combination of these three modes for the study of any motion of a rigid body in a plane, thus determining six different situations: (1) rest, (2) rotation, (3) slide, (4) slide and rotation, (5) slide and bounce, (6) rotation, slide and bounce (Figure 5).
When considering pure rocking of a rigid block, the rotation is assumed to continue smoothly from one base edge to the other.

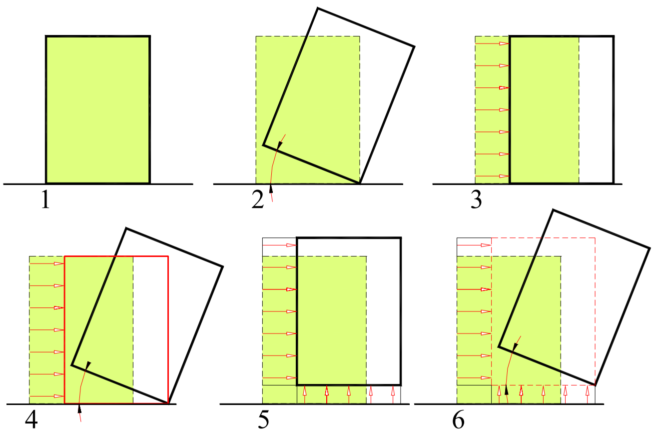


Figure 5. Response modes of rigid block moving in a plane: (1) rest, (2) rotation, (3) slide, (4) slide and rotation, (5) slide and bounce, (6) rotation, slide and bounce.

This constraint about rotation, in association with conservation of momentum, requires an energy loss (which depends on the slenderness of the block) during impact that emerges from the requirement that the block sustains rocking motion [2] as it will be shown in the following in more detail.

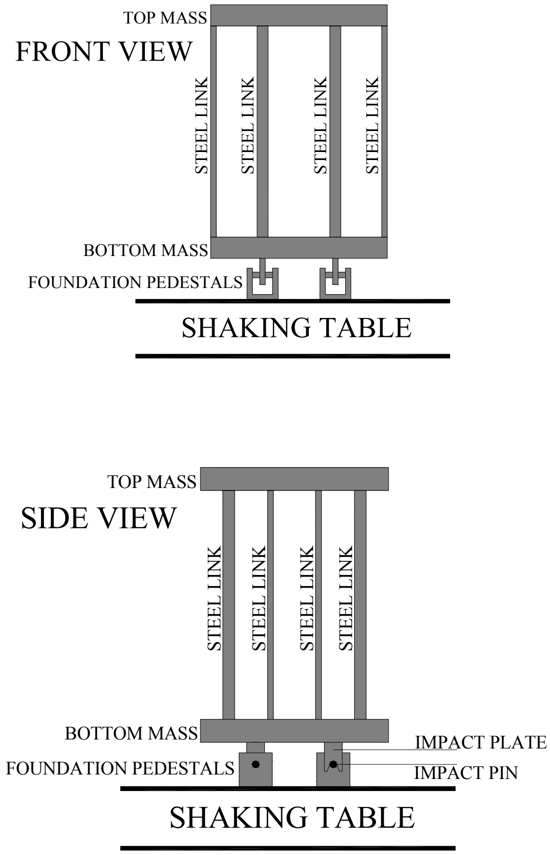


Figure 6. The Tso & Wong's prototype [9].

Up to now a number of papers are available in literature, aimed at demonstrating this and other features characterizing rocking motion of rigid blocks. Actually many authors, (in the following paragraph one summarizes some studies by Aslam et alii [8], Tso & Wong [9], Anooshehpoor & Brune [10]), executed experimental campaigns in order to confirm their numerical models, .
As an example one can mention the study by Tso & Wong [9], which consolidated many of the theoretical results on steady state rocking responses of rigid blocks, by realizing an experimental investigation on a rigid block prototype consisting of a rigid upper block pivoting on specially designed foundation pedestal (Figure 6). In the paper, after giving (subsequent section) a general overview and description, from a theoretical point of view, of the main features and studies on the rocking motion of rigid blocks, one reports the results of an experimental

investigation aimed at emphasizing basic behavior of rigid blocks under pure rocking, as obtained by laboratory tests developed on a unidirectional shaking table at the University of Naples.

2 Shaking Table Experiments

In the following one refers to experiments executed at the Laboratory of Materials and Structural Testing of the University of Naples "Federico II" [11].

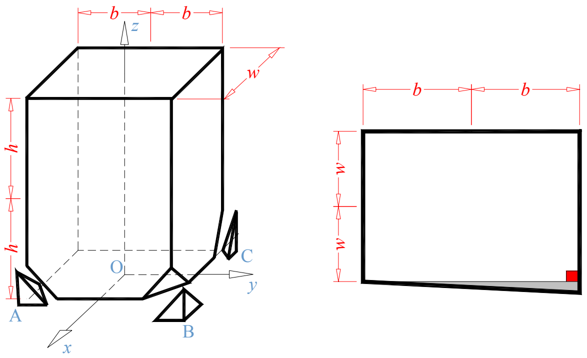
One uses a unidirectional shaking table whose motion is purely transactional in the horizontal direction. The dimensions of the table plane are 1.0m×1.0m.

In the first stage, experiments were developed on concrete blocks (YTONG), with different dimensions: one refers to two types of blocks with breadth of 24 cm., height of 30 cm. and thickness of 10 and 20 cm (Figure 7).

Experiments were executed by varying the frequency value of the sine-wave base acceleration between 1 Hz and 50 Hz and keeping a fixed span, measuring the dislocation of the shaking table in one direction, of 5 cm. The span multiplied times the pulsation of the base excitation clearly represents the amplitude of the ground acceleration.

Figure 7. First experiments executed on YTONG blocks placed on the shaking table.

During experiments on concrete blocks, some difficulties arised, since, when the blocks began rocking and frequencies increased, corners presented a 45° crack on their base edges and, for high intensity frequencies, pieces of concrete detached, making the impact point uncertain (Figure 8a).



a) b)

Figure 8. Experiments on concrete blocks: a) detachment of the corners at the base edges; b) possible imperfections in the block geometry (plant) due to construction problems.

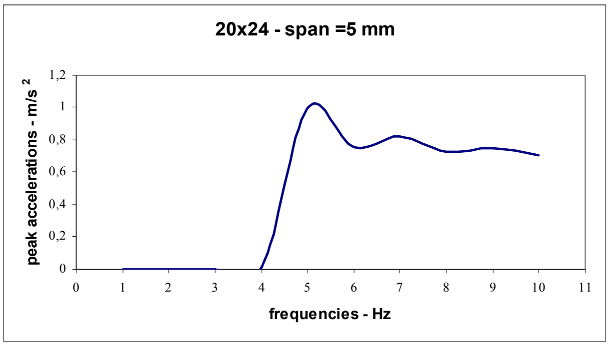


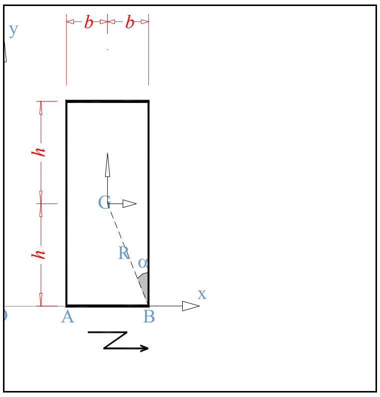
Figure 9. Graphic of the 20x24x10 concrete block.

In Figure 9 one reports one of the diagrams obtained for one of the concrete blocks.

In this way it was not possible to complete an experimental cycle on the same block, because the block changed its characteristics while increasing the frequencies.

Moreover, some small imperfections (not perfectly square shape) in the block's geometry (Figure 8 b), due to construction problems, implied that the block rotated around z–axis and sledded on the surface making impossible to refer to the reported two – dimensional schematic for analyzing pure rocking of the blocks (Figure 10).

Actually one could appreciate that effects of small geometrical imperfections, such as a not-perfectly leveled base and a not perfectly vertical block, tend to cumulate and may become significant.



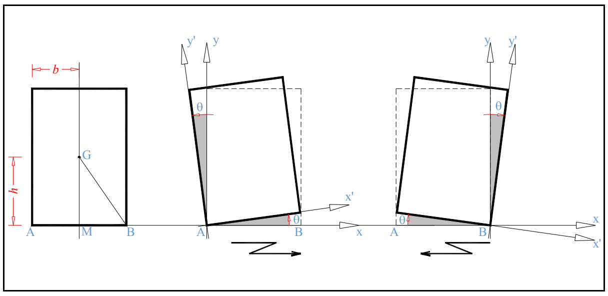


Figure 10. Schematics of a free-standing 2-D block in rocking motion when subjected to a single horizontal component of a ground shaking.

In order to avoid the problem of material detachment, responsible of change characteristics during experiments, one decided to use aluminum blocks and a special device was studied for avoiding rotation around z–axis and sliding on the shaking table surface.

Figure 11. The device placed on the shaking table for avoiding block's rotation around the vertical z-axis and sliding.

As illustrated in Figure 11, the device, placed on the shaking table plane, consisted of two fixed longitudinal iron tracks along the direction of the motion, for blocking rotations around z–axis, and two transversal iron sticks along the direction orthogonal to the motion, for avoiding sliding on the table plane. The position of the transversal sticks on the table could be regulated in such a way to fit the varying transversal dimensions (thickness) of the blocks (all the considered blocks were characterized in dimension by same height and longitudinal base length).

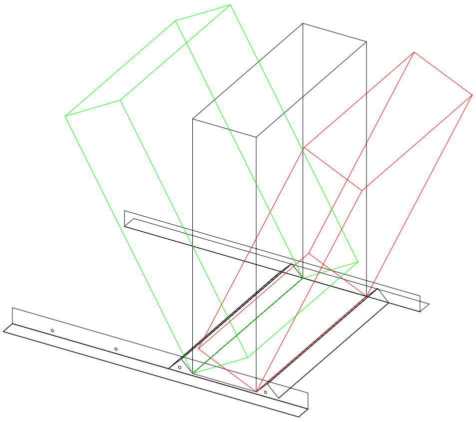


Figure 12. Pure rocking motion of the blocks during experiments: only rotations around the base edges are permitted.

The whole prototype was thought in such a way as to have the impact or pivotal points between the block and the base plane at well defined positions, which resulted in the two requirements that no sliding of the model should occur on the base and the blocks should be sufficiently stiff such to be considered rigid.
Under these assumptions, only rotations around the two base edges of the blocks were permitted (Figure 12) according to the motion of the shaking table.
Experiments were executed on three aluminum parallelepipeds of various sizes and aspect ratios (width/height): breadth of 30 cm., height of 40 cm. and thickness of 10, 20 and 30 cm (Figure 13).
The input signal driven by the shaking table consisted of an horizontal sine acceleration with fixed intensity and frequency.

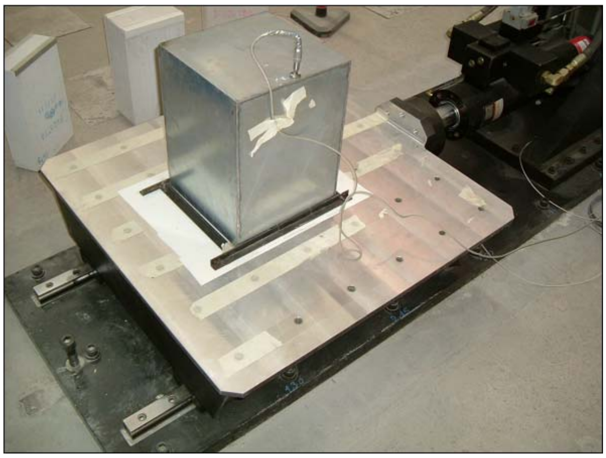


Figure 13. The 30×30×40 aluminum parallelepiped placed on the shaking table.

The monitoring equipment simply consisted of an accelerometer placed on the top of the blocks in order to read their accelerations.
The experiments were executed keeping a fixed span and varying the frequency value of the sine base-excitation inferred by the shaking table between 1 Hz and 50 Hz with intervals of 1 Hz. One used 5 different span values: 1, 3, 5, 7 and 10 mm.
Experimental results are reported in the Figures 14-16, representing peak accelerations (m/s^2) of the blocks versus frequencies (of the unidirectional base acceleration) (Hz) for various span levels.
The behavior of the single rigid block was investigated with respect to the considered span values and every graphic presents five curves relevant to the adopted span values: 1, 3, 5, 7, and 10mm.
One can notice that the rocking motion begins after a frequency of 4 – 6 Hz.

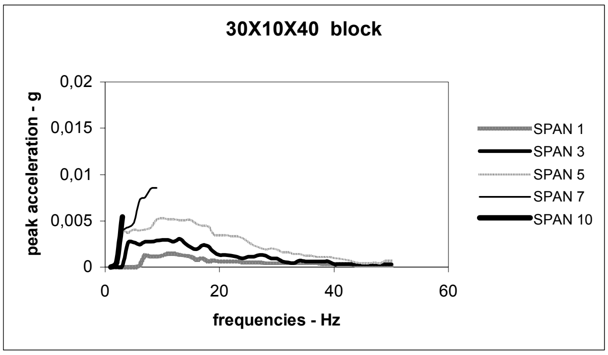


Figure 14. Graphic of the 30×10×40 block.

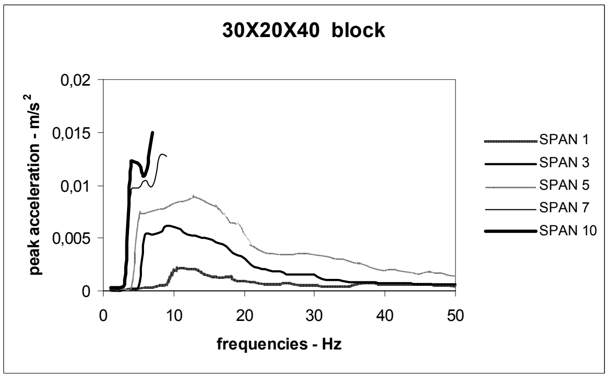


Figure 15. Graphic of the 30×20×40 block.

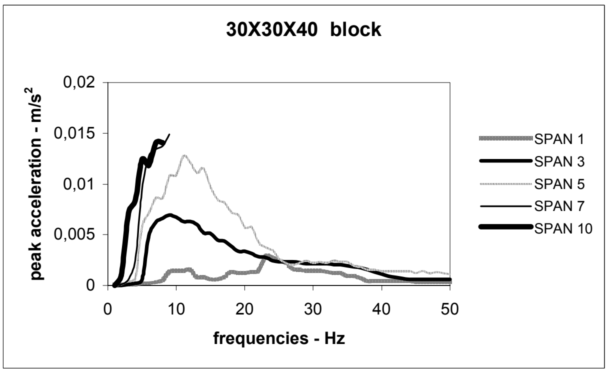


Figure 16. Graphic of the 30×30×40 block.

For high span, the peak acceleration values were higher and, in particular, for a span of 10 mm, the block with thickness of 10 cm overturned at a frequency of 4 Hz while the block 20 cm thick overturned after a frequency of 7 Hz and the block 30 cm thick at a frequency of 8 Hz approximately. For a span of 7 mm, the three blocks overturned approximately at 9 Hz.
Using any other lower span the blocks rocked without overturning at any frequency.
Generally speaking, peak accelerations were higher on stockier, and apparently more stable blocks, showing an unexpected effect which made

the larger of two geometrically similar blocks less stable than the smaller one.

It was also shown that the stability of a slender block subjected to a sine – wave base acceleration is much greater than the one that should be inferred from its stability against a constant horizontal force. In the light of these facts, the occasional survival of a slender structure that is apparently highly unstable is not surprising.

3 Conclusion

In the paper one focuses on dynamic response of rigid bodies with unilateral constraints. To this purpose, one starts by giving a description of some simplified models available in literature, by discussing their main features and adherence with laboratory tests.

Thereafter, one reports some results obtained from an experimental investigation devoted to focus on the main features exhibited by the dynamic rocking response of rigid blocks. In details one analyses the rocking motion and overturning of free-standing blocks subjected to pulse ground acceleration inferred by means of laboratory facilities.

Shaking table tests are developed for investigating rocking of 3 aluminum rectangular blocks with different dimensions and subjected to sine base accelerations acting at given frequencies and with fixed amplitudes.

The response results show that the response of the block is very sensitive to small changes in its size and slenderness ratio.

References:

[1] Hogan SJ, The many steady state responses of a rigid block under harmonic forcing, Journal of Engineering and Structural Dynamics 1990; 9: 1057-1071.

[2] Housner GW, The behavior of inverted pendulum structures during Earthquakes, Bull. Seism. Soc. Am., 1963; 53(2): 404-417.

[3] Milne J, Experiments in observational seismology, Trans. Seism. Soc. Japan 1881; 8: 12-64.

[4] Perry J, Note on the rocking of a column, Trans. Seism. Soc. Japan, 1881; 3: 103-106.

[5] Zhang J, Makris N, Rocking response of free-standing blocks under cycloidal pulses, Journal of Engineering Mechanics, 2001; 127(5)L 47383, ASCE.

[6] Ishiyama Y, Motions of rigid bodies and criteria for overturning by earthquake excitations, Journal of Engineering and Structural Dynamics 1982; 10: 35-650.

[7] Yim CS, Chopra AK, Penzien J, Rocking response of rigid blocks to earthquakes, Journal of Engineering and Structural Dynamics, 1980; 8(6): 565-587.

[8] Aslam M, Godden WG, Scalise DT, Earthquake rocking response of rigid bodies, Journal of Engineering Mechanics Division ASCE, 1980; 106(2): 377-392.

[9] Tso WK, Wong CM, Steady state rocking response of rigid blocks. Part 2: Experiment, Journal of Engineering and Structural Dynamics, 1989; 18: 107-120.

[10] Anooshehpoor A, Heaton TH, Shi B, Brune JN, Estimates of the ground acceleration at Point Reyes station during the 1906 San Francisco earthquake, Bull. Seism. Soc. Am., 1999; 89(4): 843-853.

[11] Corbi I, Orefice R, Study of rocking rigid blocks using shaking table experiments, *Proceedings of the 4th International Conference on Engineering Computational Technology*, Lisbon, 2004.