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Vulnerability assessment methods for rocking and overturning of free standing elements

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ABSTRACT

This paper presents a comparison between different methods for assessing the probability of rocking and overturning of free standing elements, under the action of ground motions of given intensities. The classical Ishiyama criterion is considered and compared with both kinematic linear and non linear analyses recommended by the Italian Standard (i.e. KL and KNL respectively) and with the displacement based approach proposed by Lam-Gad. The main differences among these methods are highlighted and validated on the basis of experimental tests available in literature, by using real seismic records. Then, the different stability criteria are used to obtain overturning stability charts, based on conventional spectra assumed by Eurocode 8 and some considerations concerning the applicability conditions of each method are given.

1. Introduction

In seismic areas a number of non-structural components (e.g. art objects in museums, equipment components, susceptible devices in hospitals) are prone to fail during an earthquake, causing significant financial and cultural losses and, in some cases, fatal collapses, even when the host building suffers only limited structural damages.

These objects can usually be modelled as freestanding rigid bodies, which can rock and overturn. As a consequence, even in the last decade, a great number of researchers paid attention on rocking/overturning behaviour of freestanding rigid blocks, e.g. [1,2]. A lot of these approaches use the formulation of rocking motion derived in the fundamental work of Housner [3], where the rocking response of rigid body was studied and overturning criteria were suggested for freestanding blocks.

Recently, the probabilistic approach to determine the overturning probability of blocks under earthquake excitations become widely used, based on the studies of Yim et al. [4]. Among others, the research carried out by Purvance [5], deals with the definition of suitable relationships for overturning fragilities as a function of the main earthquake parameters (i.e. peak ground acceleration, peak ground velocity and spectral acceleration), also by comparing the obtained results with an experimental campaign, [6]. Moreover in [7] it was demonstrated that the overturning risk is well correlated with the peak displacement demand (PDD) of a ground shaking.

Similar approaches were developed within the framework of the out-of-plane (OOP) seismic behaviour of masonry structures, as extensively discussed in the works of Lagomarsino [8] and Sorrentino et al. [9], which represent fundamental reference papers on this topic. Lagomarsino [8] proposes a displacement-based approach for rocking masonry structures, based on the use of overdamped elastic acceleration displacement response spectra, which is compatible with the PERPETUATE assessment procedure [10], developed for cultural heritage assets. Sorrentino et al. [9] presents an outline of main research works on Force-Based Assessment and Displacement-Based Assessment strategies and of their implementation in international codes.

In this paper, different methodologies for assessing the vulnerability to rocking and overturning of free standing elements, under the action of ground motions of given intensities, are presented and compared with experimental tests available in literature. It is worth noting that, in these tests, the input motions were free field records, consequently the applicability of the results for objects located at higher levels of building must be carefully considered due to the filter-effect. A critical evaluation of the effect of using conventional Eurocode spectra [11] on the different strategy assessments is also provided. In particular, the following strategies are analysed: the classical Ishiyama criterion [12,13] the Lam Gad overturning of non structural components (Lam-Gad, or LG) [14,15], and both kinematic non linear and linear analyses recommended by the Italian Standards [16,17], currently the only ones that account for both Force-Based Assessment and Displacement-Based Assessment strategies, [9]. These methods are validated on the basis of experimental tests performed by Purvance et al. [6] and Kafle et al. [7], by using real seismic records and then used to obtain overturning stability charts, based on conventional spectral shape assumed by

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Eurocode 8, [11]. Finally, some considerations concerning the applicability of each criterion for the vulnerability prediction of freestanding object are given with reference to the experimental data reported in [7]. It is to note that the paper focuses on the comparison of different overturning criteria for freestanding blocks, for this reason it is assumed that the friction coefficient is sufficiently large to guarantee that no sliding between the block and the base may occur.

2. Seismic stability criteria of free standing elements

The dynamic behaviour of objects that can be assimilated to rigid bodies, freestanding on a horizontal plane and subjected to horizontal seismic action, was among the first investigated by Housner [3], which proposed the formulation of the inverted pendulum. He studied the free oscillations of a rocking block, by assuming that no sliding may occur.

According to his results, in case of rectangular pulse and half-cycle sine-wave pulse, the overturning of the block may occur if the rocking condition is fulfilled and if the acceleration acts for a length of time sufficient to generate the velocity necessary to lead the overturning of the block. It is worth noting that for half-cycle sine-wave pulse an interesting contribution to the Housner's study was given by Shi et al. [18].

In case of seismic input, Housner proposed an "*ingenious, approximate analysis of overturning of blocks*", as stated in [4]. In this case, based on energy concepts, the requirement for overturning, respectively for generic block and for slender block, is given by:

$$\theta_c = \frac{S_v}{\sqrt{gr}}\sqrt{\frac{Mr^2}{I_0}} \tag{1}$$

$$\theta_c = \frac{S_v}{\sqrt{gr}} \tag{2}$$

where S_v represents the pseudo-velocity spectrum value, M is the mass of the object, g is the gravity acceleration, r is the radial distance between the centre of rotation O and the centre of gravity G, I_0 is mass moment of inertia of the block about O or O' and θ_c is the critical angle, Fig. 1. For a given pseudo-velocity spectrum value, a block having an angle θ_c will have approximately a 50% probability of overturning.

Eq. (2) evidences the presence of a scale effect in rigid body motion, which makes the larger of two blocks with same slenderness ratio (h/b) more stable than the smaller one. Moreover, for a block of fixed r and slenderness ratio, this equation suggests that the overturning probability increases with intensity of seismic input, Yim et al. [4].

The equations for dynamic equilibrium of rigid block under seismic excitation were solved by numerical integration by various researchers and, in some cases, investigated by experimental testing. Among others, the works of Purvance et al. [6] and Kafle et al. [7] present significant experimental campaigns on shake table to test the dynamic behaviour of specimens of different sizes and slenderness ratios. Concerning the out of plane behaviour of masonry structures, it is worth noting that a lot of analytical/numerical as well as experimental studies have been performed in last years, as properly summarized e.g. in [8,9].

Moreover, a number of simplified approaches is proposed in literature, which establish criteria for rocking activation, based on PGA,

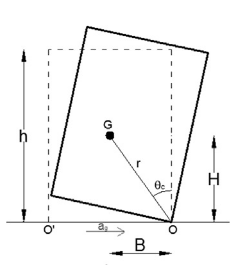

Fig. 1. Geometric parameters for the rigid body.

and for overturning, based on different seismic Intensity Measure. In this work, as previously stated, the overturning method of Ishiyama [12,13] which is mainly based on PGA and PGV criteria, is presented and compared with two displacement based approaches, i.e. Lam-Gad [14] and Non Linear Kinematic Analysis, recommended by the Italian Standard (KNL-NTC), and with Linear Kinematic Analysis (KL-NTC) suggested by the same Standard ([16,17]).

In the following, we focus our attention on the two-sided motion of freestanding single rigid block subjected to horizontal seismic excitation.

2.1. Ishiyama Criterion

Through an extensive and deep series of numerical analyses, Ishiyama [12,13] has investigated the response of rigid body subjected to a seismic action applied at the base and has formulated an overturning criterion based essentially on two seismic intensity measures (IM): horizontal acceleration and velocity. The lower limit of the maximum acceleration that can trigger the overturning motion is $a_{g,c}$, defined by the rocking condition:

$$a_{g,c} = \frac{B}{H}g \tag{3}$$

where H represents the height of the centre of gravity G of the block, and B represents the minimum value of the distance between the base edges around which the oscillation occurs and the projection of G. Only in case of symmetric body $B=b/2$ where b is the entire width of the base, and $a_{g,c}$ is the critical acceleration inducing oscillation about either of the base edges, Fig. 1.

Concerning the velocity, Ishiyama criterion states that the lower limit of the maximum velocity that may induce overturning is equal to v_c evaluated as:

$$v_c = 0.4\sqrt{2g\frac{I_0}{M}(1-cos\theta_c)\frac{1}{rcos^2\theta_c}} \tag{4}$$

where $I_0/M=i^2+r^2$, with i the barycentric radius of gyration of the body in the rotation plane. By introducing the geometrical parameter p:

$$p^2 = \frac{rMg}{I_0} \tag{5}$$

the Eq. (4) can be expressed as

$$v_c = 0.4\sqrt{\frac{2g^2}{p^2}\frac{(1-cos\theta_c)}{cos^2\theta_c}} = \frac{0.4g}{p}\frac{2\sin(\theta_c/2)}{\cos\theta_c} \tag{6}$$

that, in case of slender body ($\sin(\theta_c/2)\cong(\theta_c/2)$ and $\cos\theta_c\cong 1$), becomes:

$$v_c = \frac{0.4g\theta_c}{p} \tag{7}$$

If the body is rectangular and slender the relations (4) and (7) can be simplified in the usually adopted form:

$$v_c = 0.4\sqrt{\frac{4}{3}\frac{gB^2}{H}} \cong 14.46\frac{B}{\sqrt{H}}(cm,\ s) \tag{8}$$

which will be used in the following analyses. The extension to non-symmetrical cases for shape and/or mass distribution is possible by introducing in (8), instead of H, an equivalent height H' defined as [19]:

$$H' = \frac{4}{3}\frac{H^3}{i^2+r^2} \tag{9}$$

It is interesting to note that, in case of application of a horizontal sinusoidal input, in addition to the criteria expressed by (3) and (4), Ishiyama has introduced a lower limit of the maximum input displacement (i.e. PGD) equal to:

$$d_0 = v_c^2/a_{g,c} \tag{10}$$