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Seismic response of slender rigid structures with foundation uplifting

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Abstract

The rocking of rigid structures uplifting from their support under strong earthquake shaking is investigated. The structure is resting on the surface of either a rigid base or a linearly elastic continuum. A large-displacement approach is adopted to extract the governing equations of motion allowing for a rigorous calculation of the nonlinear response even under near-overturning conditions. Directivity-affected near-fault ground motions, idealized as Ricker wavelets or trigonometric pulses, are used as excitation. The conditions under which uplifting leads to large angles of rotation and eventually to overturning are investigated. A profoundly nonlinear rocking behavior is revealed for both rigid and elastic soil conditions. This geometrically nonlinear response is further amplified by unfavorable sequences of long-duration pulses in the excitation. Moreover, through the overturning response of a toppled tombstone, it is concluded that the practice of estimating ground accelerations from overturning observations is rather misleading and meaningless.

Keywords: Rocking; Foundation uplift; Overturning; Soil–structure interaction; Nonlinear dynamics; Near-fault motions

1. Introduction

While slender structural systems with a shallow foundation are generally considered as bonded to the ground, during strong seismic shaking uplifting from the supporting soil is often practically unavoidable. Examples of structures that experienced uplifting from the supporting soil have been reported in numerous earthquakes, including that of Chile 1960, Alaska 1964, San Fernando 1971, Kocaeli 1999, and Athens 1999. It is well documented in the literature that uplifting changes the rocking behavior in a profoundly nonlinear sense and modifies the structural response in most cases favorably. Apart from civil structures, uplifting and overturning are some of the most familiar phenomena for free-standing bodies (such as appended equipment, furniture, etc.) during strong earthquakes.

Since the pioneering work of Milne and Perry in 1881 [1,2] the uplifting and overturning response of rigid bodies has attracted the interest of many earthquake engineers and seismologists for over a century [3]. Early analytical and experimental studies conducted mostly in Japan had been motivated by tombstones overturnings after large earthquakes (Sagisaka, Inouye, Kimoura, Ikegami among others [3]). Housner [4] investigated in detail the rocking behavior of rigid blocks subjected to base excitation. Using an energy approach he uncovered the role of the excitation frequency and of the block size on the overturning potential. Makris and his co-workers [5,6] focused on the transient response of rigid blocks under near-source ground shaking idealized as trigonometric pulses, and derived the acceleration amplitude needed for overturning. Ishiyama [7] studied the slide-rocking motion of a rigid body on rigid floor and established criteria for overturning. Psycharis [8] introduced the compliance of the supporting soil with a visco-elastic Winkler foundation, extracted the linearized equations of rocking motion, and addressed the structural response of an uplifting system. Koh et al. [9] extended Psycharis' work on the linearized rocking response on flexible foundation by introducing the flexibility of the superstructure. Huckelbridge and Clough [10] carried out $\frac{1}{3}$-scale shaking table tests with 9-story steel moment frames and confirmed the beneficial role of transient uplift on structural response.

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In the present study, two different systems of structures undergoing rocking motion with uplift are examined (Fig. 1):

- a rigid block supported on *undeformable ground*, which will be referred to herein as "*rigid foundation*";
- a rigid block founded on an elastically deformable continuum in the form of a *homogeneous halfspace* or a *stratum over rigid bedrock*.

The conditions under which uplifting of these simple systems leads to large angles of rotation and eventually to overturning are investigated, and minimum acceleration levels for overturning are derived. Ground motion is mainly represented with two drastically different records (despite their nearly identical *PGA*s and not very different strong motion duration) obtained in the Athens and Kocaeli earthquakes of 1999, as well as with idealized Ricker-wavelets and one-cycle sinusoidal pulses.

2. Uplifting and overturning on a rigid base

We consider first a rigid rectangular block with aspect ratio b/h (half width over half height ratio) simply supported on a rigid base, which is oscillating horizontally. The coefficient of friction is adequately large so that sliding is prevented. As long as the overturning moment (ma_gh) about the base edge (where a_g = the base acceleration) does not exceed the restoring moment (mgb), the block remains attached to the base and undergoes only horizontal oscillation. As soon as the restoring moment is exceeded uplifting occurs setting the block on rocking motion. The system configuration is illustrated in Fig. 1a. Under static conditions, once uplifting is initiated about the corner point, the body overturns. Thus, the critical uplifting acceleration of the base is identical with the minimum required to statically overturn the block in units of g (acceleration of gravity)

$$a_{\text{over,stat}} = a_c = \frac{b}{h}. \tag{1}$$

However, under dynamic base excitation the inertia force "quickly" changes direction as the acceleration changes sign, and overturning is avoided. Rocking oscillation takes place with the two corner points, O and O′, being alternately the pivot points. Between two successive impacts the governing equation of rocking motion can be expressed in the compact form

$$\ddot{\theta}(t) = -p^2(\sin[\theta_c \text{sgn}\theta(t) - \theta(t)] + a_g \cos[\theta_c \text{sgn}\theta(t) - \theta(t)]), \tag{2}$$

where $\theta(t) < 0 (or > 0)$ denotes the angle of rotation about O (or, respectively, about O′); $\theta_c = \arctan(b/h)$ is the angle shown in Fig. 1a; and $p = \sqrt{mgR/I_o}$ is a characteristic *frequency parameter* of the block; R is half the diagonal of the block. For a solid rectangular block the moment of inertia about its pivot point is $I_o = (4/3)mR^2$, and therefore $p = \sqrt{3g/4R}$.

In the free rocking regime the frequency of vibration depends strongly on the amplitude of rotation. Hence, the above frequency parameter p is not the eigenfrequency of the system, but merely a measure of the dynamic characteristics of the block. Table 1 summarizes the most important parameters of the problem and explains their symbols.

When a rigid body is rocking back and forth about its pivot points, it impacts on the ground and loses a part of its kinetic energy, even in a purely elastic impact. Its angular velocity right after the impact (at time t_o^+) is a fraction of that just prior to impact (at time t_o^-)

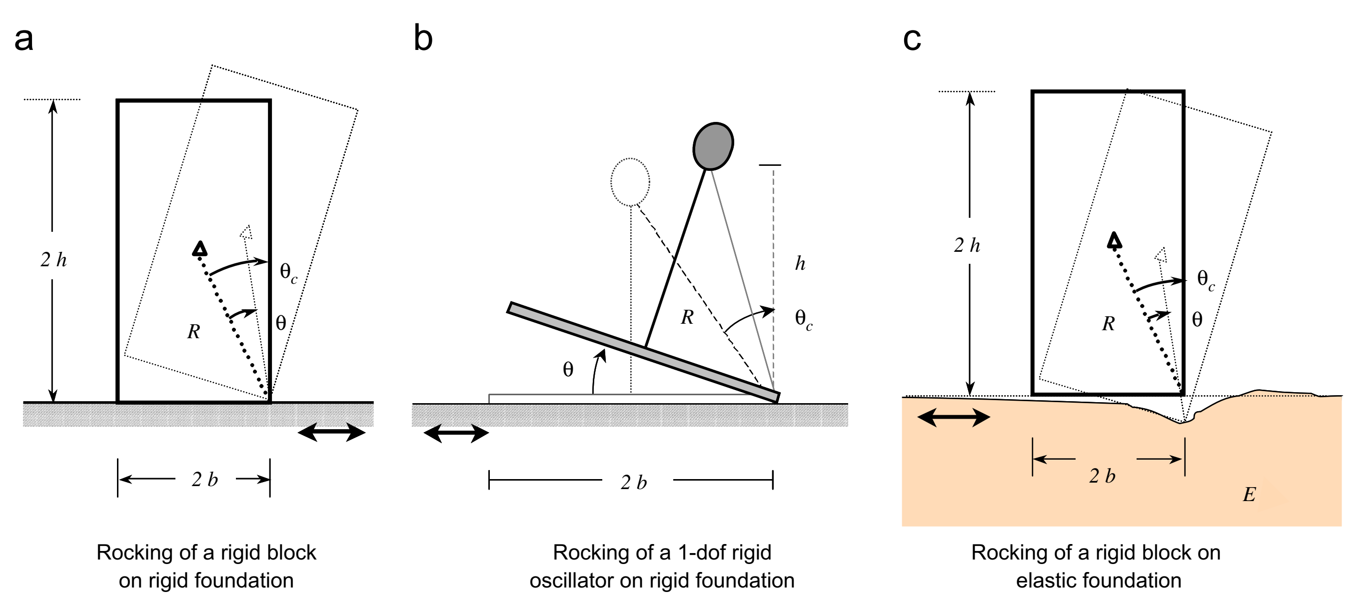

Fig. 1. The rocking systems considered in this paper. (a) Rocking of a rigid block on rigid foundation (b) Rocking of a 1-dof rigid oscillator on rigid foundation (c) Rocking of a rigid block on elastic foundation.