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Response of structures to motions with fling step: Does fling matter?

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Abstract

: An essential signature of the near-fault motions is the fling-step, which contains a one-sided velocity pulse and ultimately results in permanent ground displacement. It is well-known that the standard processing of ground motion removes such fling. However, some researchers believe that dynamic action is hardly affected by such removal of permanent static displacement. So, such processed motions can be used to examine the effect of fling-step. In the current investigation, two mathematical analogues, rigid sliding and rigid rocking blocks are extensively studied under near-fault motions with fling-step. The response is computed using the processed motions (without explicit fling) and the processed motions with fling mathematically reintroduced. A comparison in response confirms that using motions without explicit fling is essentially deficient from a structural engineering perspective. The study has also noted the peculiarities in the dynamics of rocking oscillators, which may be of significance for assessing the consequences of the sequence of motions.

Keywords: Fling step, Rigid sliding, Rigid rocking, Nonlinear system, Resurrection

1. Introduction

In the proximity of a seismogenic fault, ground motions may contain a one-sided velocity pulse and result in a step-like non-zero static residual displacement. This permanent displacement, known as the fling step, 'inflict large irrecoverable deformations on structural and/or geotechnical systems' (Garini et al. 2015).

Even though the raw ground motion data can be specially processed to retain fling (Iwan et al., 1985; Boore, 2001), standard processing such as the one adopted in the database of the Pacific Earthquake Engineering Research (PEER) Centre effectively removes fling (Boore and Bommer, 2005). Keeping the (i) complexities of the special processing techniques and (ii) sensitivity to the parameters involved in view, several studies have been made on the mathematical simulation and parameterization of fling (e.g., Makris and Chang, 2000; Mavroeidis and Papageorgiou, 2003; Kamai et al., 2014; Burks and Baker, 2016; Yadav and Gupta, 2017). One of the simple and feasible alternatives is to reconstruct fling by artificially introducing fling-step on the processed motions (Kamai et al. 2014; Burks and Baker, 2016; Yadav and Gupta, 2017; Acharjya and Roy, 2022). It is important to note that the 'difference' between the acceleration histories without and with explicit fling-step is 'little discernible' (Boore and Bommer, 2005). Further, the 'peak-to-peak displacement' of standard PEER processed time history appears approximately similar to the properly processed fling records (Darragh et al. 2004; Ancheta et al. 2014), which implies a similar dynamic action. As such, the necessity of explicit consideration of the fling step deserves further scrutiny from a structural engineering perspective. Research on the consequences of fling to geotechnical and structural systems started primarily in the aftermath of the Chi-Chi, Taiwan and the Kocaeli, Turkey, earthquakes in 1999 and is expectedly scanty. Against this backdrop, the present paper considers two mathematical analogues: rigid sliding blocks and rocking blocks. Rigid sliding blocks representing a rigid-plastic constant-friction system may experience extreme inelastic behavior and are widely used in the analysis of embankments, earth dams, landslides and seismic isolation with low-friction bearings etc. Rigid rocking blocks assumed to experience pure rocking with no sliding (friction is relatively large), represent the dynamics of many free-standing slender bodies such as laboratory equipment, museum artefacts, household furniture, concrete radiation shields, electrical transformers etc., including the phenomenal existence of a number of statues and monuments over millennia (e.g., Makris and Kampas, 2016).

Ever since Newmark (1965) published his seminal work on the rigid sliding block, such idealized blocks have been adopted in numerous studies (e.g., Roy et al. 2016). Of particular interest are the studies (Gazetas et al. 2009; Garini et al. 2015) that epitomize the behaviour of sliding blocks employing natural motions with fling and idealized wavelets. Beginning with the enlightening contribution of Housner (1963), the dynamics of free-standing rocking blocks have been widely studied (e.g., Zhang and Makris, 2001; Pradhan et al. 2022). It is well-known and would be apparent afterwards that the behaviour of rocking blocks is highly nonlinear and hence expected to be far more sensitive. Also, to the authors' knowledge, the effects of fling are yet to be explored in the context of such rocking bodies.

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Based on the foregoing review, the goal of the present study is to decisively isolate the effect of the existence of explicit fling-step from structural engineering perspectives.

2 Descriptions of the idealized systems

In order to explore the implications of near-fault motions with a fling, two widely used mathematical analogous which can mimic a variety of geological, geotechnical and structural systems are chosen.

2.1 Rigid sliding blocks

The mathematical framework of the idealized rigid-plastic blocks, as shown in Figure 1a, can be derived from the basic principles of mechanics. For a rigid sliding block of mass *m* resting on a horizontal base, assuming a constant coefficient of friction (μ) at the interface (Coulomb), sliding initiates beyond the yield capacity of $F = \pm\mu mg$ (Figure 1b) and the equation of motion for the base excitation ($\ddot{u}_g(t)$) can be derived by Newton's law of motion as follows:

$$m\ddot{x}(t) + m\ddot{u}_g(t) = -\mu mg \quad for\ \dot{x}(t) > 0 \qquad \ldots(1a)$$

$$m\ddot{x}(t) + m\ddot{u}_g(t) = \mu mg \quad for\ \dot{x}(t) < 0 \qquad \ldots(1b)$$

Equations (1a) and (1b) can be expressed in the compact form

$$m\ddot{x}(t) + m\ddot{u}_g(t) = -sign(\dot{x}(t))\mu mg \qquad \ldots(1c)$$

in which g is the acceleration due to gravity and $sign(\dot{x}(t))$ is the signum function, i.e., +1 and -1 respectively for $\dot{x} > 0$ or $\dot{x} < 0$.

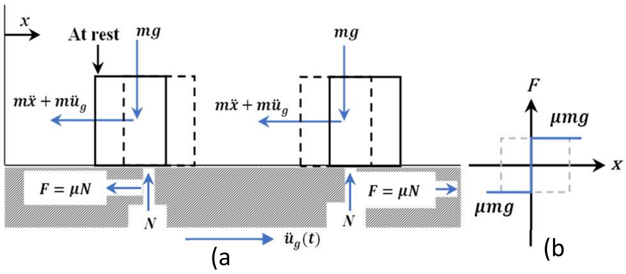


Fig. 1 Rigid sliding block (a) free body diagram (b) yield capacity curve.

2.2 Rigid rocking blocks

The dynamics of slender, rigid blocks (dimension $2b\times2h$) resting on a plane inclined at an angle of η with the horizontal is studied herein (Figure 2a). Clearly, the body, without slipping, may uplift if $\ddot{u}_g(t) \geq gtan(\alpha-\eta)$, in which slenderness of the block tanα =b/h. From the rudimentary mechanics, it is straightforward that, for a ground excitation acting rightward, the block initially rotates to the left, i.e., angle of rotation, θ < - η and may overturn without impact under a sufficiently strong excitation. If the block does not overturn, θ is to assume a positive rotation (θ > - η) and the first impact occurs at pivot O. This rocking motion continues until the block overturns or the excitation expires. In case of rocking, this is followed by the free-vibration even after the motion expires (Makris and Roussos, 2000). Assuming no bouncing, equations of motions resting on the horizontal plane can be derived as follows:

$$\ddot{\theta}(t) = -p^2\left\{\sin[-\alpha-\theta(t)] + \frac{\ddot{u}_g(t)}{g}\cos[-\alpha-\theta(t)]\right\} for\ \ \theta(t) > -\eta \qquad (2a)$$

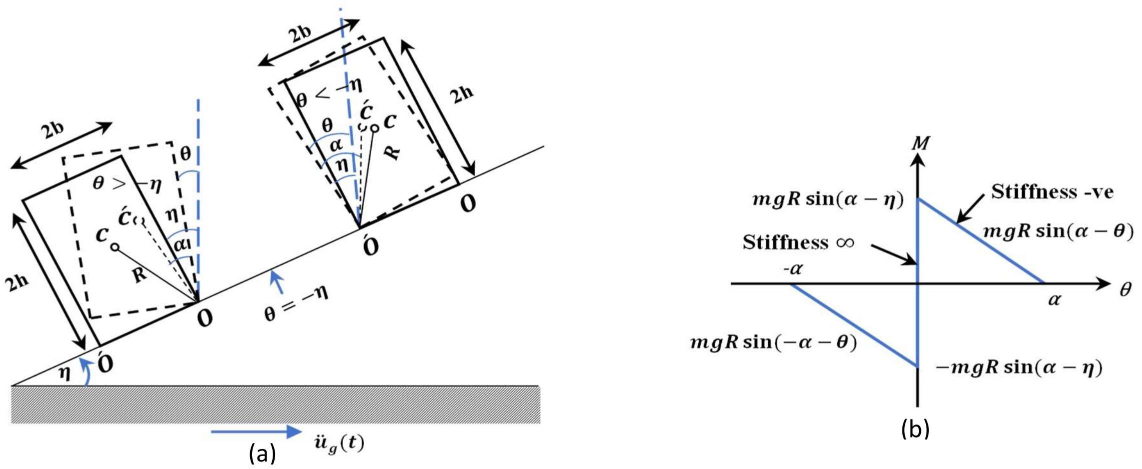


Fig. 2 Rigid rocking block (a) description of basic parameters (b) Moment-rotation curve.

Table 1 Details of selected near fault motions with fling-step

Sl. No.	Event	Station	Record Identifier	Compo-nent ID	V_s30 (m/s)	M_w	r (km)	Ground-motion & fling parameters				
								PGA (m/s²)	T_m (s)	t_1 (s)	T_f (s)	D_f (cm)
1	Chi-Chi_Taiwan (9/20/1999)*1	TCU051	*RSN1491_CHICHI_TCU051-N*	Y-CT51	350	7.6	7.6	2.31	0.83	28.21	8.69	-66
2		TCU067	*RSN1504_CHICHI_TCU067-N*	Y-CT67	433	7.6	1.0	3.13	0.76	28.64	9.63	-81
3		TCU072	*RSN1508_CHICHI_TCU072-N*	Y-CT72	468	7.6	7.8	3.55	0.60	32.53	7.82	157

***1: mm/dd/yy; M_w** - Moment magnitude, **r** - closest site-to-fault-rupture distance, **V_s30** - Average shear wave velocity over a depth of 30m, **PGA**- peak ground acceleration, **T_m**- mean period, t_1-the instant for the of fling step, T_f - period of the basis sine-wave D_f -amplitude of permanent displacement (Acharjya and Roy, 2022)

$$\ddot{\theta}(t) = -p^2 \left\{ \sin[\alpha - \theta(t)] + \frac{\ddot{u}_g(t)}{g} \cos[\alpha - \theta(t)] \right\} for \quad \theta(t) < -\eta \quad \text{...(2b)}$$

Equations (2a) and (2b) may be combined as:

$$\ddot{\theta}(t) = -p^2 \left\{ \sin[-\alpha sign(\theta(t)) - \theta(t)] + \frac{\ddot{u}_g(t)}{g} \cos[-\alpha sign(\theta(t)) - \theta(t)] \right\}$$

…(2)

in which $I_0 = 4mR^2/3$, $p = \sqrt{3g/_{4R}}$ where I_o is the mass moment of inertia about the point of rotation, O, $R = \sqrt{b^2 + h^2}$ represents the size of the block and p may be taken as a measure of frequency (in unit of rad/s).

It follows from equations (2a) and (2b) that the system possesses infinite stiffness up to the magnitude of the applied moment $M = \pm mgRsin(\alpha\text{-}\eta)$ and, upon the initiation of rocking, this stiffness monotonically decreases (negative stiffness) and becomes zero for θ equals to α (Figure 2b). During rocking, this moment–rotation curve is followed without loss of energy (enclosing any area) during impact.

Clearly, a proper representation of the impact phenomenon is essential for the complete solution. For the consideration of a smooth rotation between O and O′ and no-loss of energy during impact, it can be shown that the coefficient of restitution (r) can be expressed as under.

$$r = 1 - 1.5\,(\sin\alpha)^2 \quad (3)$$

It is evident that the equation of motion for the rocking blocks is highly nonlinear and hence may be sensitive to initial state variables. In the parametric study, the effect of small inclination η is studied, and this explains why the base is taken inclined in the basic formulation. In the case of the horizontal base, equation of motion is same as (2) (taking η = 0).

3 Ground motions and methodology

3.1 Selection of records and Introduction of fling

Ground motions are collected from the NGA-WEST2 database of the Pacific Earthquake Engineering Research (PEER) Centre (Ancheta et al., 2014). In the limited case studies, motions recorded at three stations during the 1999 Chi-Chi earthquake are used.

As already pointed out, static residual displacement is removed from the PEER processed data. Hence, fling has been artificially introduced as per the procedure outlined elsewhere (Kamai et al. 2014; Yadav and Gupta, 2017). Relevant data for the introduction of fling to processed motions, such as displacement histories are taken from the works of Burks and Baker (2016) (available at:

http://purl.stanford.edu/pz055cs5875). A summary of the related parameters, viz., t_1, T_f and D_f, respectively representing the instant for the onset of fling-step, period of the basis sine-wave and the amplitude of permanent displacement are summarized in Table 1. Further details in this regard are available elsewhere (Acharjya and Roy, 2022).

3.2 Methodology

For the rigid sliding blocks, the responses are computed in the Simulink environment, which is in-built into Matlab V.9.5 (2018). Response of the rocking rigid blocks to ground motions is computed, in Matlab V.9.5 (2018) platform, per ode45 (Domand-Prince) solver choosing maximum step size as 0.005 (Ground motion time step). For the solver, options selected include absolute and relative tolerance of 10^{-14}, 10^{-12}, respectively.

4 Results and discussions

4.1 Response of sliding blocks

The response of rigid blocks resting on a horizontal surface assuming is presented for three selected motions in Figure 3, taking μ = 0.1. Displacements of the block are

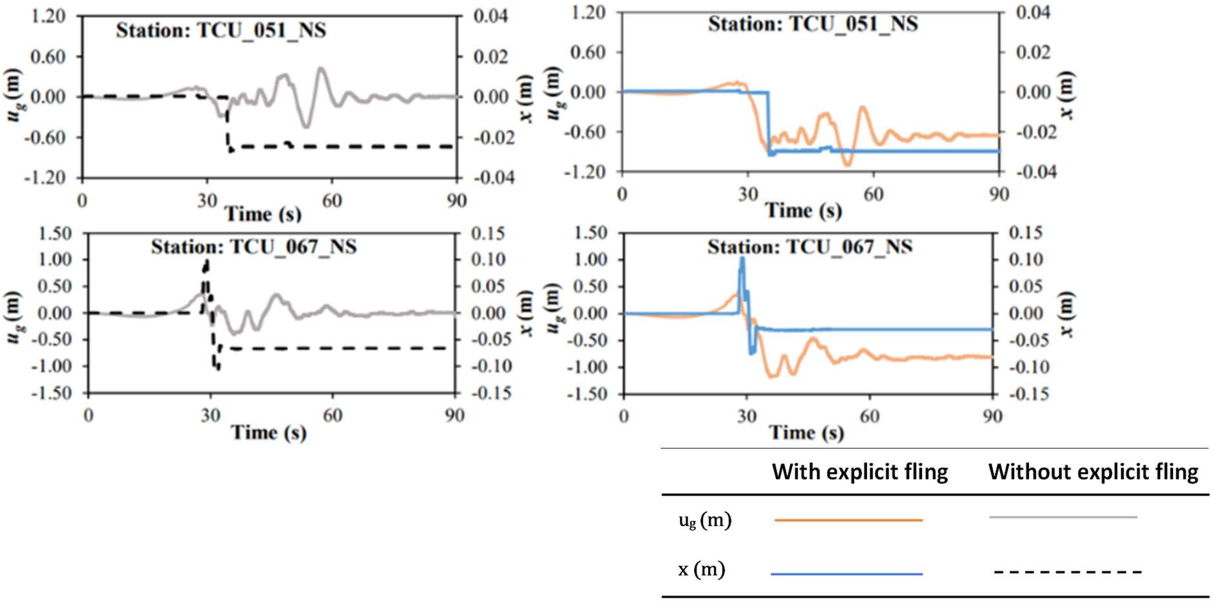


Fig. 3 Variations of ground displacement and the displacement of the rigid sliding block.

superimposed with the corresponding quantities of the ground motion itself. It is apparent that the block does not slide initially, as expected. As yield capacity exceeds, the block begins to slide and a drastic increase in slip is consistent with the pulse-like characteristics of the records. As the energy is primarily concentrated within a short portion of the entire record, the sliding of the block stops and remains constant shortly afterwards. A careful scrutiny suggests that a proper consideration of the explicit fling-step is essential to estimate the effects of fling-step appropriately.

4.2 Response of rocking blocks

In the present study, a rigid block of 2b = 0.5 m and 2h = 2.5 m is taken as reference. This results in the characteristic parameters for block size, R = 1.2748 m,

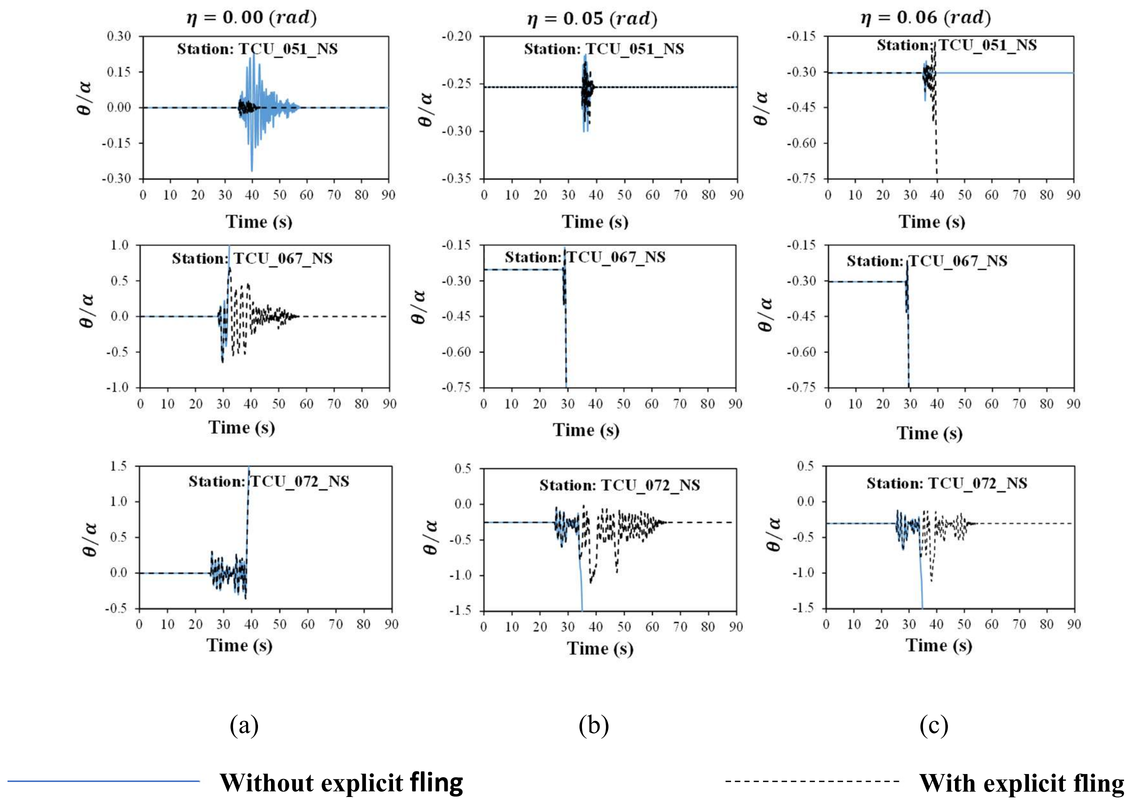
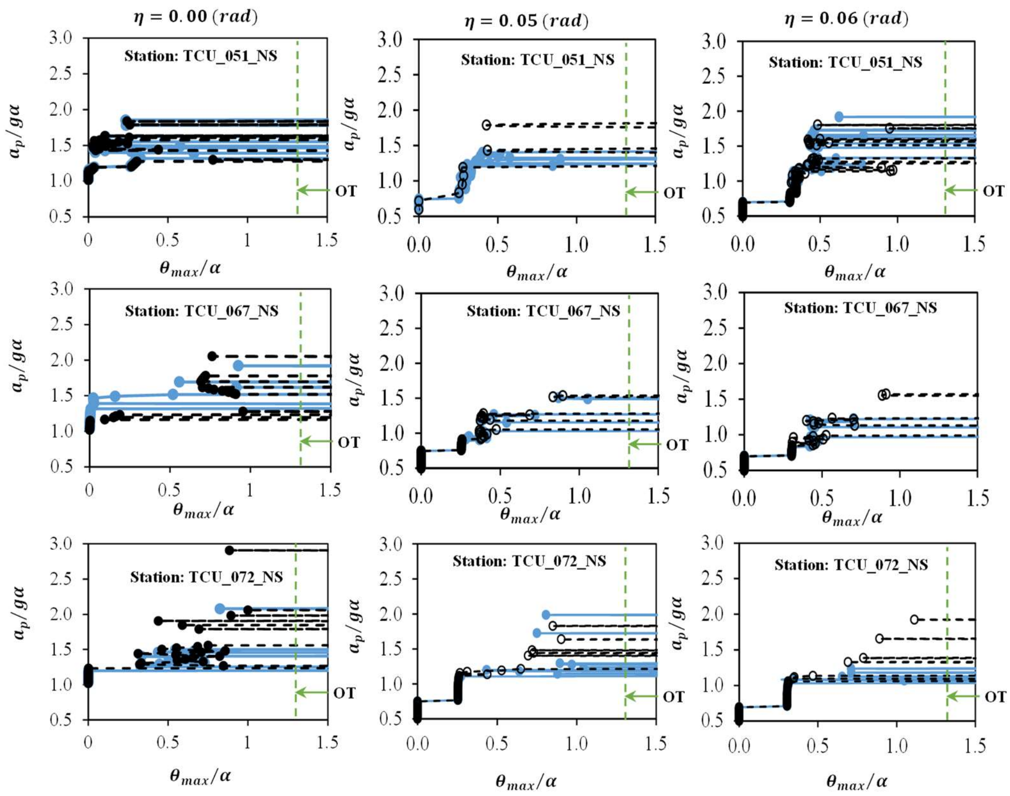


Fig. 4 Response of rigid rocking block for different initial conditions.



(a) (b) (c)

Without explicit fling ------------------ With explicit fling

Fig. 5 Response of the rigid rocking block to scaled ground motion for different initial conditions**.**

slenderness, tanα = 0.2000 rad and restitution, r = 0.9423. Value of r, as calculated from equation (3), is taken herein even though any other lesser value could be chosen. Response is computed for motions with and without explicit fling-step for three different initial conditions, i.e., η = 0.00^0 (0.00 rad), η = 2.86^0 (0.05 rad) and 3.44^0 (0.06 rad). Results in Figure 4 suggest that the response may be dramatically altered (a body expected to rock would overturn or vice versa) due to the existence of explicit fling.

Also, the small difference in the initial condition may lead to considerable difference in response of nonlinear system such as the rocking block in reference. This inspires the authors to further investigate the behaviour of the rocking oscillator under the ground motions with increasing amplitudes.

For this purpose, response of the block is calculated by factorizing the motion with and without explicit fling as is commonly done in Incremental Dynamic Analysis (IDA).

Figure 5 presents the values of the normalized intensity $a_p/g\alpha$ for maximum normalized rotation ($\theta_{max.}/\alpha$). The cases of overturning (OT), i.e., $\theta_{max.} \geq \alpha$ are presented in the figure by choosing a large value of $\theta_{max.}/\alpha$ and marked in the figure by OT line. It is evident that the response can be strongly influenced by the explicit existence of fling-step. The variation in results for small changes of η clearly corroborates the sensitivity of rocking oscillators to initial conditions. It is interesting to note that the body can rock at intensities greater than what may induce overturning to the system. This resurrection of the system at a potentially higher intensity is not a surprise and can occur in many other contexts (Kar and Roy, 2018).

5 Summary and conclusions

The current investigation examines the response of two mathematical analogues representative of numerous structural and geotechnical systems under the near-fault motions with fling-step. In the standard processing of near-fault motions, permanent displacement is removed, and the fling-step, in essence, does not exist. However, it is commonly believed that this removal of permanent displacement hardly affects the dynamic action. As such, the ground motions without explicit fling, as available in the standard ground motion libraries such as the NGA-WEST2 database, may be used for structural engineering perspectives. In its bid to resolve this dilemma, the present study confirms that the fling 'do matter, a lot' (Gazetas et al. 2009) and an appropriate seismic analysis and design strategy must

consider ground motions that explicitly contain fling-step. This conclusion, obtained from the analysis of rigid sliding and rigid rocking systems, applies to most real structures. The elastic period of both rigid systems is zero; hence, the study reveals that the effect of fling-step may also be significant for very stiff systems.

Analysis of rocking systems under increasing intensities of motion reveals that the structures may overturn at a lower level of shaking, while such systems may survive at a higher intensity. This indicates that the seismic foreshocks or aftershocks can be more damaging than the corresponding mainshocks for the rocking oscillators. The consequences of the sequence of motions, especially for rocking oscillators, therefore, deserve further attention.

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