The dynamic sliding response of drums composing free-standing rigid bodies

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Abstract

This paper examines the dynamic sliding response between two drums that are basic components in forming free-standing rigid bodies that are practically non-deformable when considering their sliding capabilities. The sliding response of such drums is investigated experimentally and numerically. Both during the experiments as well as in the numerical simulation specimens of such drums are subjected to a variety of horizontal sinusoidal and simulated earthquake base motions; these motions were generated by the Earthquake Simulator at the Laboratory of Strength of Materials of Aristotle University of Thessaloniki, Greece.
Keywords: rigid bodies, sliding response, coefficient of friction, sinusoidal and earthquake excitation, shaking table.

1 Introduction

For contemporary conventional structural systems the sliding response during strong ground motions, either at the foundation level or at the various structural components, is ignored. However, there are important structural systems where sliding, either at the interface between structural elements or at the supports, can be a significant part of their earthquake response and of their overall stability. Moreover, sliding – friction devices have been recently introduced as means of protecting structural systems from developing undesirable performance during expected strong ground motion.

The sliding response, of free standing rigid bodies or of structures that can slide when subjected to dynamic and earthquake ground motions, has been the study of research for quite some-time. Usually, the friction mechanism between sliding surfaces is assumed to be governed by the principles of Coulomb friction, with the coefficients of friction been taken as constant and independent of the amplitude of the forces acting normal to the friction surface or of the size of the contact surface. For static loads these coefficients are distinguished as the static ($\mathbf{\mu_s}$) and the kinetic ($\mathbf{\mu_k}$) coefficient of friction [1]. During dynamic excitations the kinetic coefficient of friction is replaced by the dynamic coefficient ($\mathbf{\mu_d}$) [2].

Aslam et al. [2] studied extensively the sliding of rigid specimens made of concrete, when they were subjected to sinusoidal or simulated earthquake excitations reproduced by the shaking table of the Earthquake Engineering Research Center of the University of California at Berkeley. The employed specimens were either freely supported or constrained in the direction normal to the direction of sliding by a set of springs. The experimental investigation was accompanied by a numerical study.

Westermo and Udwadia [3] and Younis and Tadjbakhsh, [4] studied the sliding response of a rigid body that was subjected to sinusoidal base motions. They derived analytical solutions including the two types of response that develop in the sliding response; that is the sliding – sliding (S-S) response and the sliding – reattachment (S-R) response. As was shown analytically [5] and studied by relevant experiments [6], the sliding of a rigid body may also be accompanied by its rocking response.

A large research has taken place at the Earthquake Simulator of Aristotle University for more than fifteen years, having as main objective to examine the dynamic and earthquake response of model columns or colonnades of ancient temples [7,8,9,10]. The ancient columns are either monolithic or with drums and can develop both sliding or rocking response during base excitations.

The rigid bodies examined in this paper are drums from three steel model columns (truncate cone, cylinder and square prism) with ten drums each; all these columns are assumed to represent models of prototype structures 20 times larger. The sliding response between two drums is studied, as this is considered the basic sub-structure of a column with drums. The static, kinetic and dynamic coefficients of friction were estimated from these specimens using experimental techniques. The observed sliding response during sinusoidal and earthquake excitations is presented and discussed together with the most significant parameters that were found to exert and influence on it. The experimental investigation is followed by a numerical study of the sliding response of a rigid body.

2 Test specimens and experimental configuration

Three different groups of drums were employed in the experimental sequence, all of them made of steel. Employing 10 drums of these groups one can form free-standing rigid bodies of three different geometrical shapes (truncate cone - CONE, cylinder - CYL and square prism - CUBE). The performed study focused on the sliding response between two drums as this is considered the basic sub-structure of the multiple drum rigid bodies (figure 1). The mass and the dimensions of the two examined drums of each group are listed in table 1.

Table 1: Characteristics of test specimens (drums).

Specimen	Lower slice				Upper slice			
	d1 (mm)	d2 (mm)	h (mm)	M (kg)	d1 (mm)	d2 (mm)	h (mm)	m (kg)
CONE	97	94.8	48	2.72	94.8	92.7	48	2.58
CYL	97	97	45.5	2.63	97	97	45.5	2.63
CUBE	86x86	86x86	45.6	2.61	86x86	86x86	45.6	2.61

d1 and *d2* the lower and the upper diameter of each drum with circular base.
h the height and *m* the mass of each drum.

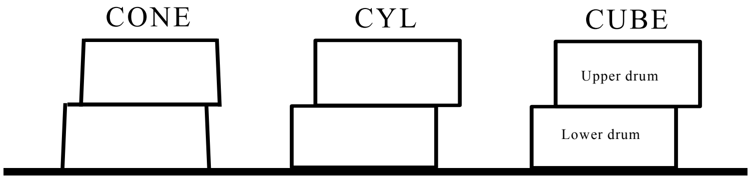

Figure 1: Test specimens.

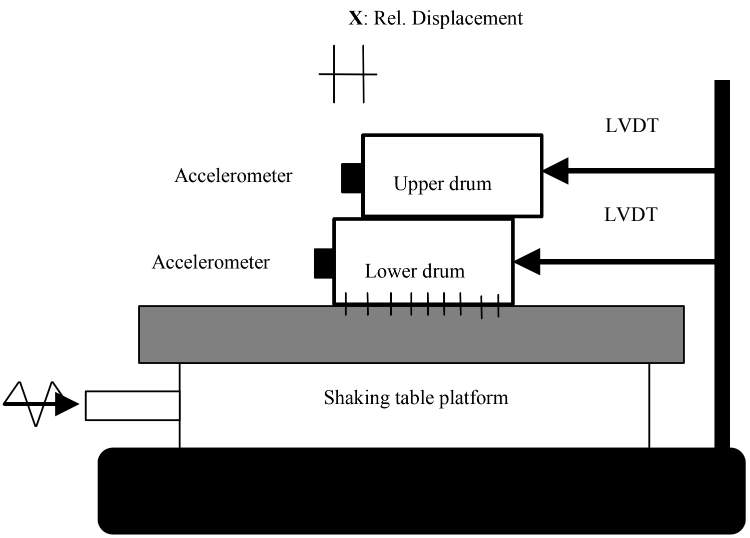

Figure 2: Experimental configuration.

During the experimental sequence, the bottom (lower) drum was firmly attached to the shaking table thus assumed to follow the motion of the moving shaking table platform. The upper drum was left freely resting on top of the bottom drum. During the performed tests the upper drum could slide, rock, overturn or develop a combination of these three types of response depending on the amplitude and type of base excitation, the geometry of the drums and the coefficient of frictions of the contact surface. The maximum amplitude of the base excitation is selected in any case that pure sliding response can be developed. The acceleration and displacement response during sliding of the upper drum is recorded. Also, at the same time the acceleration and the displacement of the lower drum is recorded representing the input excitation from the shaking table as shown in figure 2.

3 Experimental investigation

3.1 Coefficients of friction

For each group of drums (belonging to the truncate cone, cylinder or the square prism) two different conditions of their contact surface were examined:

a) In the first case the contact surface of the two drums was relatively smooth as it resulted from machining the surfaces of all the corresponding drums in order to form in a perfect fit condition the 10-drum free - standing rigid bodies (metal surfaces).
b) In the second case a low - roughness grade sand - paper was interposed at both sides of the sliding contact surface (sandpaper).

A special apparatus was used for determining the values of the static (μ_s) and kinetic (μ_k) coefficients of friction, under static loading. The procedure was repeated five times for the drums of each specimen. With a supplementary series of tests the variation of the previously found values of the coefficients of friction was examined when sliding was introduced to the same specimens as before by rotating them in such a way so sliding occurred in one of four different horizontal directions (0^o, 90^o, 180^o, 270^o). Finally, the influence of the amplitude of the force acting normal to the sliding surface on the value of the coefficients of friction was also investigated, utilizing the same experimental procedure, which was previously described. The increase in the force acting normal to the sliding surface was introduced by adding gradually on top of the "two-drums basic unit" each time an extra drum, however, introducing sliding to the same contact surface. Figure 3 depicts the derived values of the static and the kinetic coefficient of friction of CONE and their variation with the amplitude of the normal force, both for the initial conditions of the sliding surface as well as when the sand paper was added. The current examination resulted in values of static coefficient of friction larger than the corresponding kinetic coefficient ($\boldsymbol{\mu_s > \mu_k}$), in agreement with results from other researchers. The inclusion of the sand paper, in order to investigate intentional or accidental variation of the roughness of the contact surface, increased considerably the values of the coefficients of friction. Moreover, the values of the coefficient of friction found from the various experiments are within a certain range.

The dynamic friction coefficient, ($\boldsymbol{\mu_d}$), was established for the drums of each specimen (CONE, CYL, CUBE) from measurements of two series of tests using the experimental configuration as shown in figure 2, under sinusoidal base excitations. In the first series of tests, the frequency of base motion was varied from 3Hz to 10Hz in steps of 1Hz, kept constant for each test and with constant maximum base acceleration. In the second series of tests, the frequency of base motion was kept constant, equal to 8Hz, and a gradual increase of the maximum base acceleration was introduced from test to test. From these two series of tests, it was found that the value of the dynamic friction coefficient ($\boldsymbol{\mu_d}$) for each specimen exhibits only small variations that fluctuate within a certain range from test to test. Figure 4 depicts the variation of the dynamic coefficient of friction with the excitation frequency for the CUBE specimen with or without sand paper.

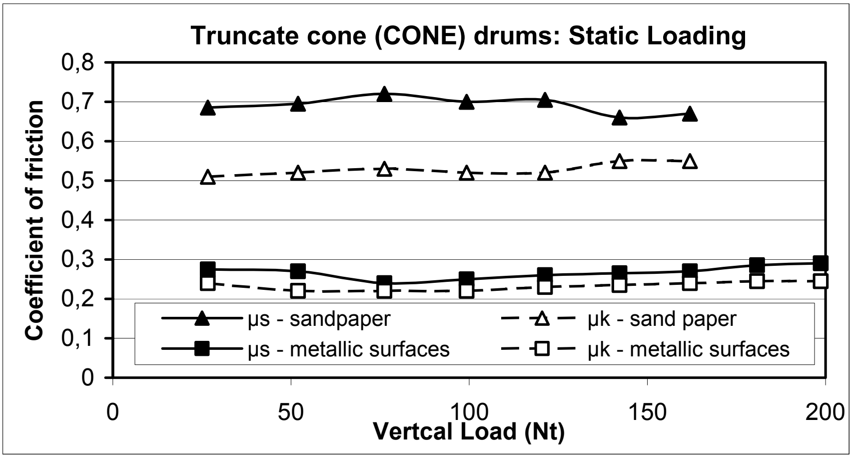

Figure 3: Coefficients of friction of CONE drums under static loading.

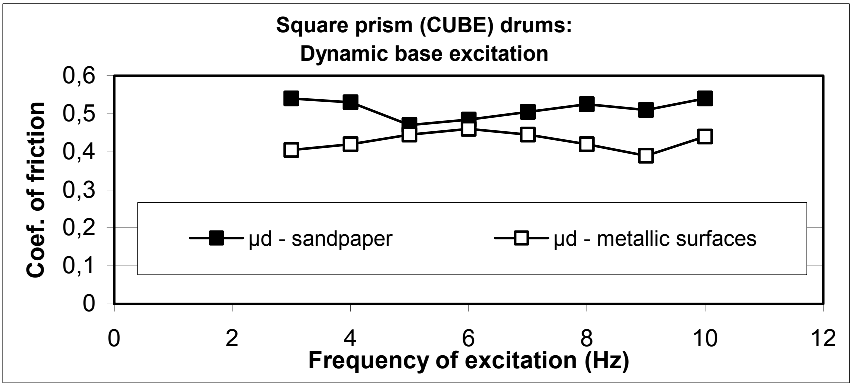

Figure 4: Dynamic coefficient of friction (μ_d) of CUBE drums under sinusoidal base excitations.

The mean values of the dynamic coefficient of friction were found to be larger than the corresponding values of the static coefficient of friction ($\mu_d > \mu_s$), for all specimens without sand paper. However, when sand paper was added, the mean values of the dynamic coefficient of friction were found to be smaller than the corresponding values of the static coefficient of friction ($\mu_d < \mu_s$), for all specimens. For the cases where sand paper was added, the coefficient of friction has larger values than for the cases without the sand paper; this is valid for the static, the kinetic and the dynamic coefficients of friction (μ_s, μ_K, μ_d) and for all steel specimens. When $\mu_s > \mu_d$, in the cases with the sand paper, the static coefficient of friction can be derived as the ratio of the maximum acceleration at the initiation of sliding divided by the acceleration of gravity. On the contrary, when $\mu_s < \mu_d$, as it is in the cases of the steel specimens without sand paper, only the dynamic coefficient of friction can be derived. Apart from the small variation in the values of the three coefficients of friction (μ_s, μ_K, μ_d), which was already mentioned, it can be concluded from the values found from all the tests that the value of these coefficients was not found to be influenced by the orientation of the specimens with regard to the direction of sliding, by the amplitude of the force normal to the contact surface, or by the frequency and amplitude of the excitation. However, because of the observed small variation, the response of each test is characterized by the values of the friction coefficients derived from each particular test and not by the mean values.

3.2 Sinusoidal base excitations

The dynamic acceleration sliding response under sinusoidal base excitation was shown to be periodic and symmetric. In many cases however, the observed displacement sliding response was not symmetric. As was expected, the maximum sliding displacement response of the specimens without sand paper is almost twice as much as the corresponding sliding displacement response of the specimens with sand paper interposed at both sides of the sliding contact surface. Moreover, after an experimental parametric investigation with sinusoidal base motion, having constant maximum acceleration and a variety of different frequencies (from 3 – 14Hz), the maximum sliding response attains somewhat larger values when the corresponding excitation frequency has relatively lower values (figure 5).

3.3 Earthquake base excitations

Finally, the sliding response was investigated experimentally utilizing the horizontal component of the ground acceleration recorded during El Centro (N-S, 1940), Taft (1952) and Parkfield (1971) prototype strong earthquakes compressed in the time domain in order to have the same time duration, equal to 12sec. The use of these three simulated earthquake base motions covers a wide frequency range. The excitations based on either the El Centro (4-12Hz) or the Taft (5-15Hz) earthquake record are rich in a much wider frequency range than the one based on the Parkfield record; the later is richer than the other two in content at the relatively low frequency range (3-8Hz).

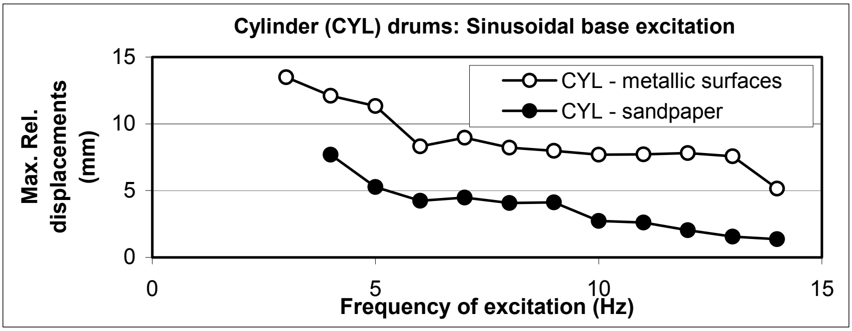

Figure 5: Max. relative displacements of the CYL upper drum during sinusoidal base excitations.

A number of tests were performed with progressively increasing intensity (in terms of peak base acceleration). Summary results of the observed maximum sliding displacement response of the CUBE drums, during simulated earthquake tests utilizing all three simulated earthquake base motions, are depicted in figure 6 (with and without sandpaper between the metallic contact surfaces). When the seismic excitation remains low in terms of base acceleration there is no sliding; this is initiated when the seismic excitation becomes more intense capable to overcome the friction in the contact surface. More intense base motions produce larger sliding displacement amplitudes for all employed simulated earthquake base motions. As was observed before (figure 5), the specimen with relatively lower coefficient of friction values (metallic surfaces) exhibits larger sliding displacement values than the specimen with higher values for the coefficients of friction (sandpaper), for tests of the same intensity.

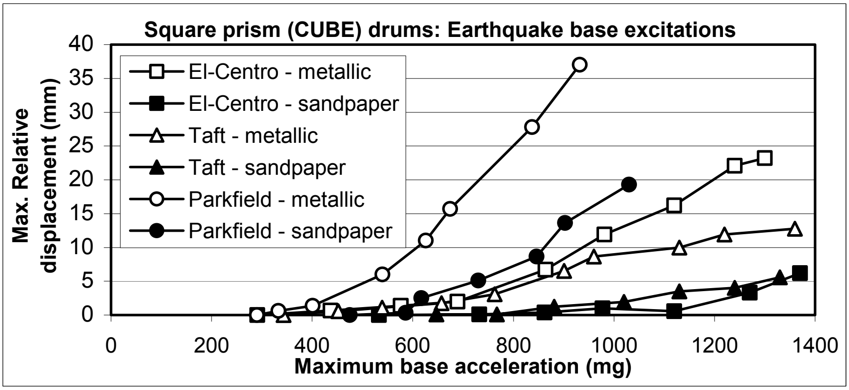

Figure 6: Max. relative displacements of CUBE drums under EQ excitations.

Finally, for both specimens the simulated base motion based on the Parkfield earthquake record results in much larger sliding displacement amplitudes than the other two simulated earthquake base motions (El Centro or Taft); this can be observed for all base motion intensities. This observation must be attributed to the fact that the Parkfield record is richer than the other two in content at the relatively low frequency range (3-8Hz). This is in agreement with a similar observation during the dynamic sliding response under sinusoidal base excitations whereby it was also seen that low excitation frequencies maximized the sliding response.

4 Numerical investigation

4.1 Numerical model and equations of motion

A free-standing rigid body on a horizontal rigid base can develop sliding or/and rocking under horizontal base excitations. The mode of response is depended on the geometrical dimensions of the rigid body and the coefficient of static friction (μ_s) at the contact surface between the rigid body and the base.

If $\ddot{U}(t) > \mu s\, g$ and μs<B/H then sliding will occur.

If $\ddot{U}(t) > \dfrac{B}{H}$ and μs>B/H, then rocking will occur.

If $\ddot{U}(t) > \dfrac{B}{H}$ and μs=B/H, then sliding and rocking will occur at the same time, where, $\ddot{U}(t)$, the acceleration of the base excitation.

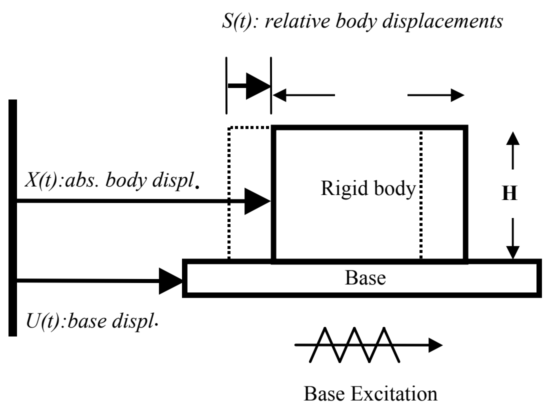

Figure 7: Numerical model of a free-standing rigid body during sliding.

During sliding, the acceleration response of the rigid body is equal to $\ddot{X}(t) = \mu d\, g$, where μ_d the dynamic coefficient of friction. The equations of motion of a rigid body during sliding, under sinusoidal or earthquake excitations are given by other researchers [2, 3, 4], describing the sliding response of the numerical model as shown in figure 7. For the purposes of the present investigation this numerical model was used in order to simulate the sliding responses of the upper drums of the test specimens (CONE, CYL, CUBE) as recorded by the experimental sequence.

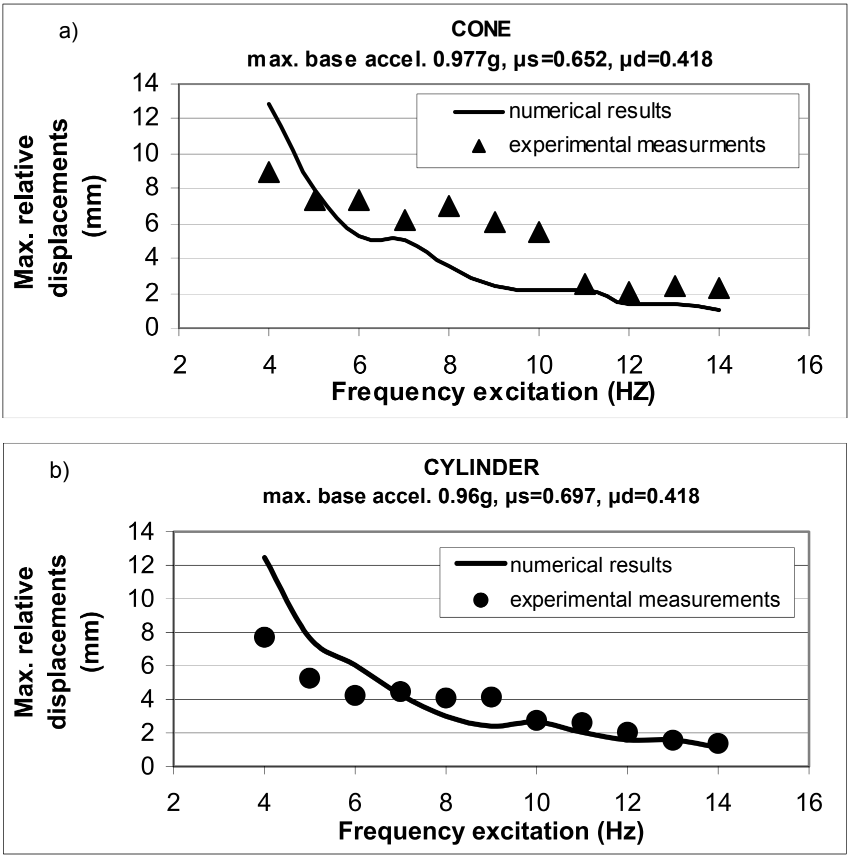

Figure 8: Numerical and experimental results of the sliding response of CONE (a) and CYL (b) upper drums.

4.2 Summary of numerical results

Special software was developed and utilised, in order to numerically simulate the sliding response of the tested drums. This software is based on the numerical integration of the equations of motion of a sliding rigid body when subjected to horizontal sinusoidal or earthquake base excitations. From obtaining a large number of solutions it could be seen that the stability of the numerical simulation depended on the integration time step that had to be relatively very small. Moreover, through a numerical parametric study it was shown that the dynamic rather than the static coefficient of friction dictates the type and amplitude of the dynamic sliding displacement response. Finally, the employed software was successful in simulating the type of sliding response and its relative amplitude, which was measured during the experimental sequence for various groups of drums, as they were briefly described above. A correlation between numerical results and experimental measurements of the maximum relative displacements of the truncate cone (CONE) and cylinder (CYL), during sinusoidal base excitations, are given in figures 8a and 8b.

5 Conclusions

The static, the kinetic and the dynamic coefficients of friction were found between two drums of three different metallic shapes (CONE, CYL, CUBE). The values of these coefficients are not influenced by the level of forces normal to the contact surface, of the orientation of sliding, or of the frequency and amplitude of the excitation and sliding response.

For all the examined specimens it was found that the sliding displacement response is amplified when the excitation is on the relatively low frequency range than when it attains higher frequency values. This conclusion is also valid for the simulated earthquake sliding displacement response.

For the numerical investigation, a software was developed and utilised, in order to simulate the sliding response of the tested drums. The stability of the numerical simulation depended on the integration time step of the equations of motion that have to be relatively very small.

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