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DYNAMIC RESPONSE OF SLICED RIGID BODIES SUBJECTED TO HARMONIC BASE EXCITATIONS

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ABSTRACT

The dynamic response of sliced rigid-block type bodies is investigated by subjecting a number of specimens to a variety of horizontal sinusoidal base motions as they are reproduced by the Earthquake Simulator of Aristotle University. The sliced specimens are either square prisms, cylinders or truncate cones and are assumed to represent models of prototype structures 20 times larger.

1. INTRODUCTION

The seismic response mechanisms that develop on solid-block structural systems during strong ground motions can include sliding and rocking thus dissipating the seismic energy in a different way from that of conventional contemporary buildings. We can assume that the behaviour of this type of structure or their elements can be investigated by studying the behaviour of solid or sliced rigid bodies during strong simulated ground motions. Therefore, this investigation deals with the dynamic response of three sliced rigid bodies, which are assumed to represent models of prototype structures 20 times larger. The sliced bodies are either square prisms, cylinders or truncate cones and formed with ten slices that lie on top of each other without any connection [fig.1]. The present work is experimental and includes series of tests performed at the Earthquake Simulator Facility of Aristotle University.

2. PRELIMINARY SLIDING TEST

Let us consider a rigid body having a horizontal plane base which is simply lying on a similar horizontal plane belonging to a medium underlying the rigid body, which is considered to be similarly undeformable. Only simple contact exists between the two bodies without any other form of connection or further attachment. Thus at this plane surface, which is a boundary between the two bodies, horizontal friction forces can develop resisting the horizontal sliding of the bodies and vertical forces normal to the contact surface transmitting gravity forces.

When the rigid body at the top is subjected to horizontal forces, either by applying external loads or by the inertia forces developing from horizontal motions, then two types of responses may develop. The first type is sliding and it occurs when the additional applied forces at the top rigid body exceed the resisting friction at the contact surface. The second is rocking and it occurs when the additional forces generated at the contact area exceed the corresponding gravitational forces leading to partial lift of the top rigid body from the horizontal contact plane.

Let us consider a regular shaped top rigid body with a height equal to H (e.g. a prism) having a base width equal to B and let us assume a coefficient of friction at the contact surface of the two bodies equal to μ_s (static coefficient of friction); then the following two contitions specify if one of the two response modes (sliding or rocking) will occur when the bottom rigid body is subjected to motions with horizontal and vertical accelerations equal to $\ddot{u}$ and $\ddot{v}$ respectively,

$$\ddot{u} > \mu_S \ g \ (1 + \frac{\ddot{v}}{g}) \qquad (1) \qquad \text{Sliding will occur}$$

(ignoring the possibility of simultaneous rocking response)

$$\ddot{u} > \frac{B}{H} \ g \ (1 + \frac{\ddot{v}}{g}) \qquad (2) \qquad \text{Rocking will occur}$$

(ignoring the possibility of simultaneous sliding response)

where g is the acceleration of gravity.

Combining the above two conditions it becomes apparent that when $\mu_S < B/H$ and $\ddot{u} > \mu_S \ g \ (1 + \frac{\ddot{v}}{g})$ then the top rigid body will first slide, whereas when $\mu_S > B/H$ and $\ddot{u} > \frac{B}{H} \ g \ (1 + \frac{\ddot{v}}{g})$ then the top rigid body will first rock.

Aslam et al. [1], Ishiyama [2] as well as many researchers in the past have established that during sliding the response of a rigid body is governed by the dynamic friction coefficient (μ_d), which is quite different from the static friction coefficient used above (μ_s). For determining the values of these coefficients, prior to any dynamic testing involving rigid bodies, the following sequence of tests was conducted using the same slices of the rigid bodies that form the whole of the rigid bodies investigated in this study, namely a sliced orthogonal prism (indicated as CUBE), a sliced cylinder (indicated as CYL), and a sliced truncate cone (indicated as CONE) that were finally used in the complex harmonic excitations tests to be described in section 3 below.

2.1. Static Sliding Test

The static coefficient of friction (μ_s) was determined for each one of the examined specimens (CUBE, CYL and CONE) by placing two of their slices on top of each other on a special apparatus having a horizontal base that could be displaced at a constant speed approximately 0.1mm/sec (see fig. 2). The bottom slice was firmly attached on the moving base thus displacing horizontally simultaneously with the same speed as the moving base. A load cell was placed in contact with the top slice at mid-height having its axis directed horizontally parallel to the contact plane between the slices. The body of the load cell was firmly fixed on an outside stiff steel frame, which was considered to remain undeformed thus representing the motionless reference plane. The base displacement was measured by displacement transducers and the load was measured by the load cell; both recordings were continuously monitored by sampling and storing the measurements at high speed through an Analog to Digital converter and a computer system with permanent storage. The obtained response is depicted in fig. 2. The value for static coefficient of friction was found from the ratio of the maximum load cell measurement (called the maximum friction force), over the weight of the top slice (W). As can be seen in figure 2, after the maximum friction force is attained for relatively low base displacement values (1mm) the base displacement rapidly increases thus indicating sliding at the contact plane between slices, whereas the load cell measurement remains almost constant as can be seen in the same figure but below the peak value.
This later friction force level is called kinetic friction force. Taking the ratio of the kinetic friction force over the weight of the top slice, the value for kinetic friction coefficient is found, namely μ_k. This test sequense was repeated five times for each

specimen and the average values for the static and the kinetic friction coefficients found from these tests are listed in Table 1.

2.2. Dynamic Sliding Test

The dynamic friction coefficient, μ_d, was established for each one of the cube, cylinder and cone specimens by performing sinusoidal tests with horizontal base motion using the earthquake simulator facility. As was done during the Static Sliding test, in each case two of the slices were used again, assumed to represent a typical contact surface between adjacent slices. For every dynamic friction coefficient test the bottom slice was firmly attached to the shaking table thus made to follow the motion of the moving shaking table platform. The top slice was resting freely on top of it in a manner identical to the formation of the sliced specimen as a whole. Two accelerometers were used to monitor the acceleration response; one for the top slice and one for the bottom slice. Figure 3a shows the top slice acceleration response during sliding while figure 3b depicts the bottom slice acceleration response, which coincides with the sinusoidal horizontal base motion. As can be seen from figure 3a the top slice's sliding response approximates a series of square periodic pulses with dominant frequency coinciding with the excitation frequency. A phase lag is also noticeable between top and bottom slice acceleration response indicating the time required for the top slice acceleration response to reach a level necessary to overcome the friction force at the contact surface in order to initiate sliding. Multiplying by $4/\pi$ (π=3.141528) the Fourier spectrum magnitude of the top slice acceleration response at the excitation frequency (according to the assumption that the top slice acceleration response approximates square periodic pulses) a mid-sliding acceleration value was obtained, assumed to represent the dynamic friction coefficient. A series of this type of sliding tests was performed for each specimen (CUBE, CYL or CONE) with sinusoidal base excitation. The frequency of base motion was varied from 2Hz to 8Hz, kept constant for each test, in steps of 1Hz and it was observed that the value of the dynamic friction coefficient was dependent on the frequency base excitation. By averaging the dynamic friction coefficient values that were obtained through these seven tests for the same specimen (CUBE, CYL, or CONE) an average value was found listed in Table 1 as the dynamic friction coefficient for each specimen.

3. SINUSOIDAL TESTS WITH THE SLICED SPECIMENS

3.1. Stable - Unstable Boundaries

The periodic sine wave tests (sine-sweep) used before in determining the dynamic coefficient of friction were employed again. This time the series of tests include horizontal sinusoidal base motions where the frequency of motion was varied from 1Hz to 7Hz, kept constant for each test, in steps of 1Hz. This resulted in groups of tests in which the frequency of the horizontal sinusoidal motion was kept constant. For the various tests belonging to the same group of constant frequency the amplitude of the excitation was varied progressively from test to test. The duration of motion for each test was kept constant, equal to 12 seconds, unless there was an interruption because the response of the specimen exceeded certain limits thus indicating failure from overturning. The acceleration response was measured by two accelerometers at the top of the specimen as well as one at the level of the moving platform. In order to graphically portray the above stages the plot in figure 4 was prepared. The ordinates in this plot represent the non-dimensional amplitude of the base motion whereas the abscisa the non-dimensional frequency given by the following formulae :

$$A = x / (\theta * g) \tag{3}$$

$$\Omega = \omega / P \tag{4}$$

A	=	The non-dimensional base acceleration amplitude.
x	=	The actual horizontal peak acceleration of the sinusoidal motion.
θ	=	The critical angle indicating overturning of the correspondent solid specimen[4]
g	=	The gravitational acceleration
Ω	=	the nondimensional frequency
ω	=	The actual sinusoidal frequency (Hz).
P	=	The natural rocking frequency of the correspondent solid specimen (Hz) [4].

The following points can be made from this figure:

-Because the sliding displacements are coupled with the rocking displacements the overturning or the sliding failure is dependent on the maximum value of the relative sliding displacement that develops at each slice level as compared with the critical value that it can be allowed from the geometry of the specimen at the same level.
-For small values of the non-dimensional frequency the transition from no-rocking to overturning is very close as it occurs with little increase in the non-dimensional amplitude.
-The non-dimensional amplitude of the unstable boundary increases rapidly with the non-dimensional frequency, which indicates greater stability of the sliced bodies for higher frequencies (fig. 5).

3.2. Acceleration Response of the Sliced Specimens

In order to further investigate the response of the sliced specimens during the sinusoidal base motions the following tests were performed where the peak base acceleration was kept constant equal to 0.129g while the frequency was varied from 2Hz to 7Hz, kept constant for each test, in steps of 1Hz. This study involved acceleration response measurements at the mid - height of each slice, which were used to derive the frequency response parameters (magnitude and phase) for the acceleration response of each slice with respect to the acceleration response of the base.
From the observations of the behaviour during the tests with constant peak base acceleration the following points summarize the most important findings (figures 6a,6b and 6c):
- For sinusoidal base motions 2Hz to 4Hz for the sqaure prism and the cone and 2Hz to 3Hz for the cylinder the acceleration response of all the slices is in phace with that of the base motion.
- When all the slices move in phase with the base the magnitude of the peak acceleration response for each slice is almost equal to that of the base motion, except for the truncate cone when subjected to 4 Hz base excitation where the magnitude of the top slice acceleration response is 57% higher than that of the base acceleration.
- For frequency values of the base motion higher than the above mentioned ranges, sliding and rocking develops at many slices along the height of the specimen. The rocking\sliding response between slices can be identified from abrupt changes in the variation of the peak acceleration response along the height of the specimen, which is plotted in figures 6a, 6b and 6c. In this case the acceleration response for each slice is not in phase with that of the base. The distribution of the peak acceleration along the height of the specimen changes significantly from that corresponding to low frequency values, thus reflecting the sliding and rocking response mechanisms that develop at the various contact surfaces.

4. CONCLUSIONS

1. From the performance of the sliced specimens with ten slices, it could be seen that their response involves rocking as well as sliding not only at the base but also at higher contact surface with the coefficient of friction as a dominant parameter.
2. For all solid as well as sliced specimens, despite the one axis of horizontal base motion all specimens developed not only an in phase response but also an out of plane response when there was large excitation amplitude.

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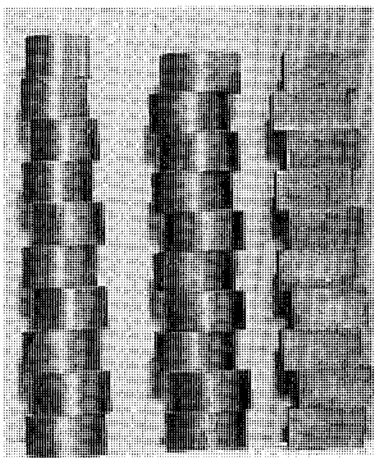

Fig. 1 Slices Specimens

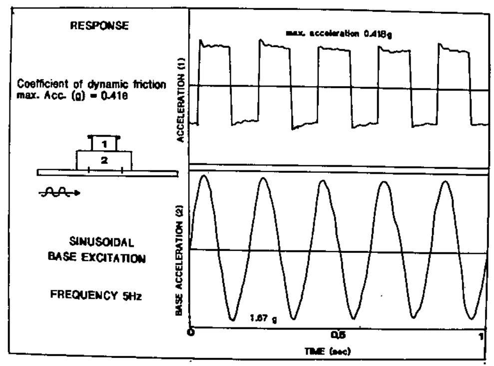

Fig. 3 Dynamic Sliding Test for Cone Slices

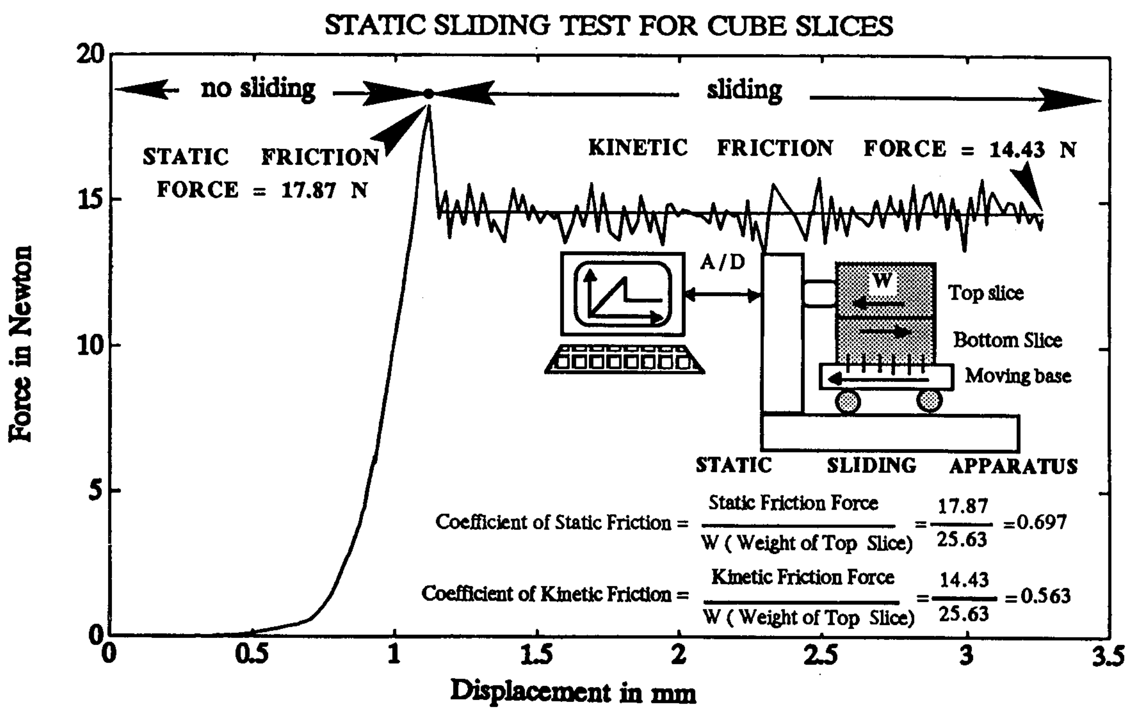

Fig. 2 Static Sliding Test for Cube Slices

Table 1. Static, Kinetic and Dynamic Coefficient of friction

COEFFICIENT OF FRICTION			
SPECIMEN	Static μ_{st}	Kinetic μ_k	Dynamic μ_d
CUBE	0.697	0.563	0.600
CYLINDER	0.697	0.544	0.418
CONE	0.652	0.514	0.418

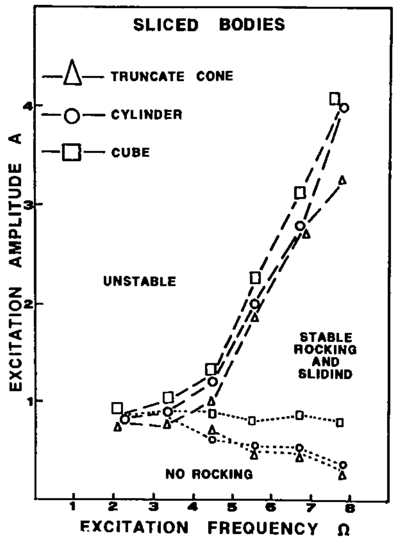

Fig. 4 Summary of Sinusoidal tests for Slices bodies

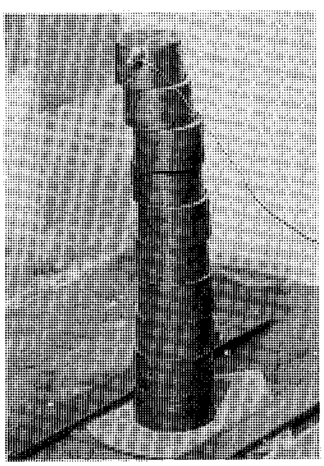

Fig. 5 The Truncate Cone after dynamic base excitat.

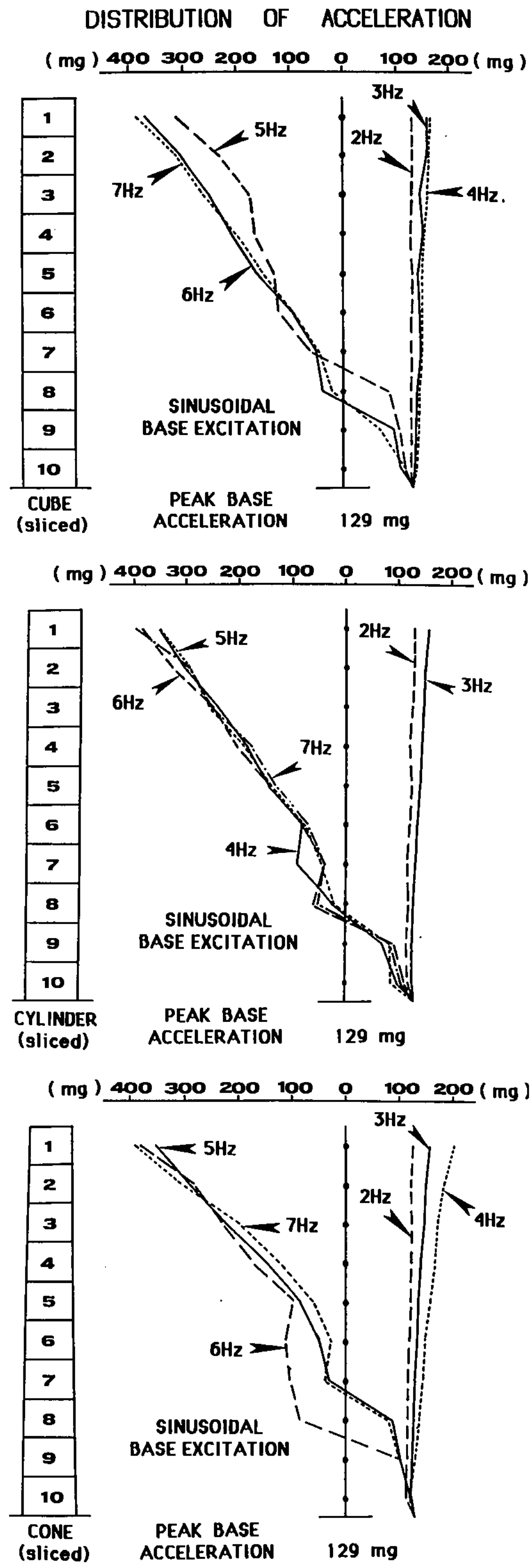

Fig. 6a, b, c, Acceleration response of sliced bodies with constant peak base acceleration