An Experimental and Analytical Investigation of the Sliding Behavior of Unanchored Structures

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ABSTRACT

Unanchored objects resting on a horizontal surface may slide, rock, or slide and rock simultaneously when subjected to base excitation. This paper describes an experimental and analytical investigation of the one-dimensional sliding behavior of a rigid object subjected to horizontal harmonic and seismic base motions. The conduct of the experiment is described in some detail, including input signals, instrumentation, data acquisition and sample and support preparation. Two different analytical models were used in the study – one with only the kinetic coefficient of friction (a one-parameter model) and the other with both static and kinetic coefficients (a two-parameter model). The study illustrates the importance of specifying the input signal with a high degree of resolution and setting the cutoff frequencies in the filters at appropriate levels. The results show that the sliding behavior of the object is highly sensitive to variations in the flatness of the sliding surface but that, under ideal conditions, it is possible to obtain results that are quite repeatable and to simulate the sliding behavior of a rigid object quite accurately. Not surprisingly, the model with both static and kinetic coefficients of friction was superior to the model with only one coefficient. We suggest that, to improve the model even further, a velocity-dependent kinetic coefficient of friction be used.

INTRODUCTION

Newmark[1] conducted one of the earliest studies on the sliding behavior of unanchored objects in 1965. He was interested in predicting how large rocks located on an earth-dam would react during an earthquake. His work was followed by experimental work conducted by Aslam, et al[2] in 1975. They developed a computer program to calculate the sliding response of an unanchored object and compared the analytical results from this program with experimental responses obtained during shake table tests. Although the calculated results were quite accurate, many of their tests were short in duration (less than 3 seconds). This short time of excitation does not allow for some of the factors associated with the sliding behavior to be observed. In 1994, Shultz and Jones[3] conducted experiments to determine the mode of response, and the factors that led to this mode. They did not determine the time histories of the rocking or sliding responses. In 1998 Shao[4] conducted analytical work to determine the mode of response. She also calculated time histories and maximum response values. A major product of her work was the computer program SLIDE, which determines both of the desired responses. The objective of our work was to develop an experimental procedure that would ensure repeatable experimental results and then to reconcile these results with the analytical results produced by the SLIDE program.

TEST FACILITY, SPECIMEN AND PROCEDURE

The test facility in the Center for Nuclear Power Plant Structures, Equipment and Piping at North Carolina State University consists of an ANCO Model R-001 Horizontal Shake Table (24-inch by 36-inch table surface, 20 kip hydraulic actuator with +/- 3 inch stroke and 15 inch/second peak velocity, and a Gardener Systems controller), National Instruments/LabView data acquisition system, and associated filters and transducers. For these tests, an 18 by 24 by 1 inch machined and sandblasted steel plate was rigidly attached to the table to act as the sliding surface. The plate was level to within 0.1 degree. The specimen was a 12-inch length of TS 6 x 4 x 0.250 (structural steel tubing) that had a 4.5 x 8 x 1 inch sandblasted steel plate affixed to the base. To prevent out-of-plane behavior, a ball bearing – guideway system was developed and installed. See Warren[5] for details. The excitation signals – harmonic and various recorded and artificial earthquake records – were fed to the controller from LabView. The earthquake acceleration records were integrated twice to obtain displacement time histories, and then subjected to a baseline correction procedure.

The research program consisted of the following phases: (a) verify the ability of the shake table to duplicate the input motion, (b) determine the coefficients of friction, (c) investigate the repeatability of the specimen behavior using harmonic and seismic table motions, (d) reconcile the analytical simulation with the experimental results, and (e) improve the model as needed.

SHAKE TABLE FIDELITY

As reported by Warren[5], the most important point in ensuring that the table motion represented the target motion within engineering accuracy was to use at least 200 points per second (pps) to define the input motion. Because recorded accelerograms are traditionally recorded at 50 pps, it was necessary to use linear interpolation to obtain the more refined description of the motion.

COEFFICIENTS OF FRICTION

Four traditional techniques and one curve-fitting technique were used to determine the coefficients of friction. They are as follows: (1) Manually applied horizontal loading to just initiate motion using a cable and load cell. (2) Statically applied loading using a weight/cable/pulley system – see Figure 1. To determine the kinetic coefficient of friction, the load was increased until, when tapped, the initially quiescent structure would move at approximately a constant velocity. (3) Gravity loading of the specimen placed on a manually adjusted inclined surface. (4) Steady state harmonic shake table motion with increasing amplitude until there is relative motion. (5) Earthquake excitation with curve fitting – details will be given later in the paper.

Typical results from the various methods are summarized in Table 1. It is difficult to draw firm conclusions from these data, except to observe that scatter does occur, as is typical of tests such as these, and that there does seem to be some directionality associated with the use of machined plates. In general, the sandblasted plates seemed to give more consistent results than did other surfaces we used.

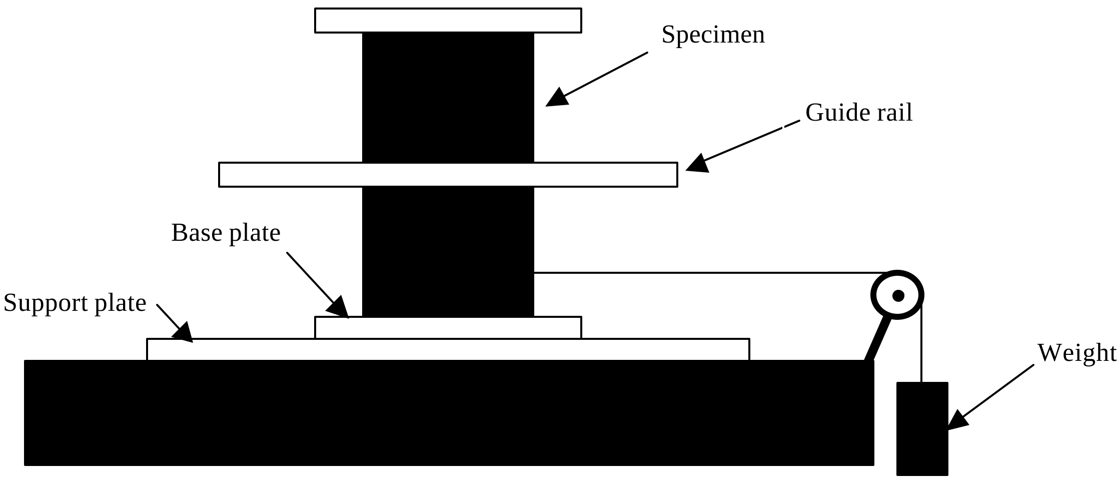

Figure 1. Sketch of the quasi-static pulley test to determine the coefficients of friction

Table 1. Summary of Experimentally Determined Coefficients of Friction

Surface	Test Type	Description	Static Coefficient					Kinetic Coefficient				
			A	B	C	D	E	A	B	C	D	E
Mach.	(1)	Left to Right	0.210	0.207	0.204	0.211	0.204					
Mach.	(2)	Right to Left	0.201	0.199	0.196	0.210	0.206					
Mach.	(4)	Initial Pos. 1	0.233	0.224	0.239	0.217						
Mach.	(4)	Initial Pos. 2	0.314	0.262	0.276							
Mach.	(4)	Initial Pos. 3	0.202	0.227								
Sand	(1)	Left to Right	0.333	0.356	0.355	0.351	0.294					
Sand	(2)	Left to Right	0.376					0.316				
Sand	(3)	Left to Right	0.360	0.364	0.360							
Sand	(5)	W. Wash.	0.348	0.371	0.357	0.370	0.362	0.307	0.312	0.299	0.294	0.305
Sand	(5)	Parkfield	0.356	0.347	0.350	0.354	0.365	0.246	0.248	0.255	0.250	0.233
Sand	(5)	Neg. S. Fernando	0.351	0.342	0.357	0.316	0.370	0.300	0.299	0.317	0.315	0.301

Table Notation: Mach. Machined steel for both surfaces
Sand Sandblasted steel for both surfaces

(1)	Horizontal static load applied manually with a load cell
(2)	Horizontal static load applied with a pulley-cable-weight system
(3)	Inclined surface tilted until motion initiated
(4)	Shake Table – Harmonic excitation
(5)	Shake Table – Earthquake excitation with Curve Fitting
Left to Right	Direction of loading
Right to Left	Direction of loading
Initial Pos. 1 etc.	Three different starting positions for the specimen on the shake table
W. Wash.	N-86°-E component of the April 13, 1949 Western Washington earthquake
Parkfield	N-65°-E component of the June 27, 1966 Parkfield, CA earthquake
Neg. S. Fernando	S-74°-W component of the Feb. 9, 1971 San Fernando, CA earthquake with reversed polarity
A, B, etc	Trial number (for some entries the results are averages of several tests)

REPEATABILITY

Two types of input motions were used in the repeatability study: (a) a harmonic displacement and (b) several earthquake motions. Typical results from early in the research program, before the support plate had been machined, sandblasted, and leveled are shown in Figures 2 and 3. The earthquake in Figure 3 is the S-00°-E component of the May 18, 1940 Imperial Valley. It is apparent that the results are not very repeatable. The harmonic signals, in particular, show a noticeable lack of repeatability. In trials 1-3, the specimen migrated to a point about 5 inches from where it started, and then remained there, oscillating about some fixed mean value. We suspect that there was a slight depression in the plate at that point. Theory would tell us that, under harmonic loading, the specimen would oscillate about a linearly increasing mean relative displacement.

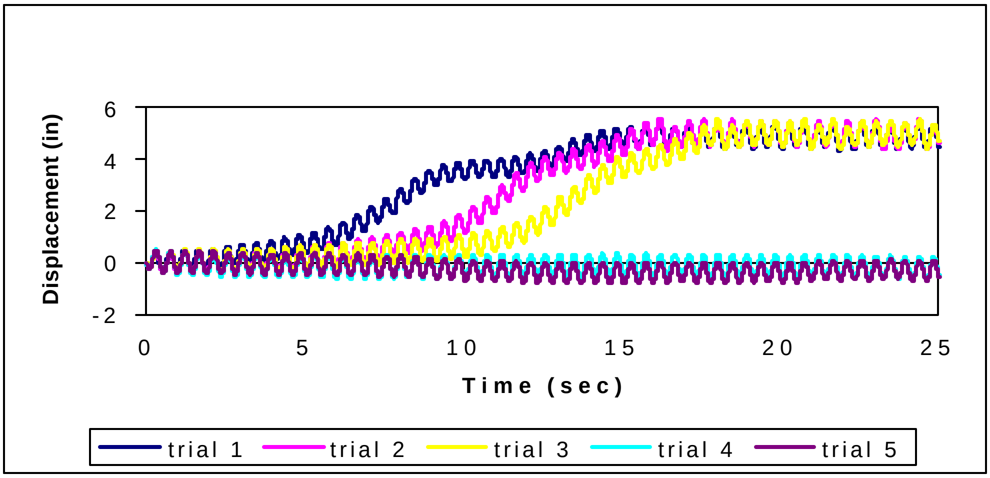

Figure 2 Repeatability results with initial experimental setup: 2 Hz Sinusoidal Excitation

Various steps were taken to improve the repeatability of the tests, but machining and then sandblasting both the base and support plates proved to have the greatest effect. The sandblasting was necessary because the machining left the plates with directional properties – the coefficient of friction was not quite the same in opposite directions. Typical results following modification of the plates are shown in Figure 4 for the N-65°-E component of the June 27, 1966 Parkfield, CA earthquake and Figure 5 for the S-74°-W component of the February 9, 1971 San Fernando earthquake. The horizontal offsets between the various signals are a result of different trigger times, and are left in the graphs intentionally to make it easier to detect the similarities and differences between the results. It is clear that these tests are much more repeatable as a result of the various modifications to the experimental setup.

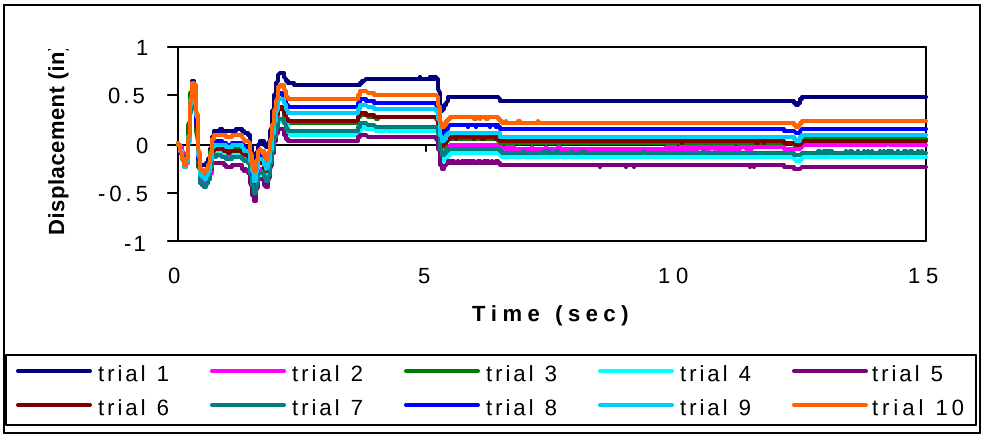

Figure 3 Repeatability results with initial experimental setup: 1940 Imperial Valley Excitation

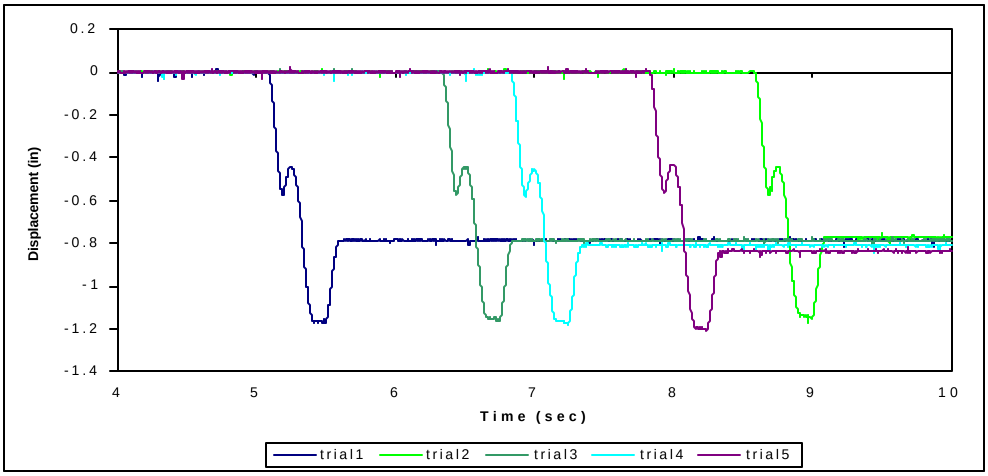

Figure 4. Repeatability results with final experimental setup: 1966 Parkfield Excitation

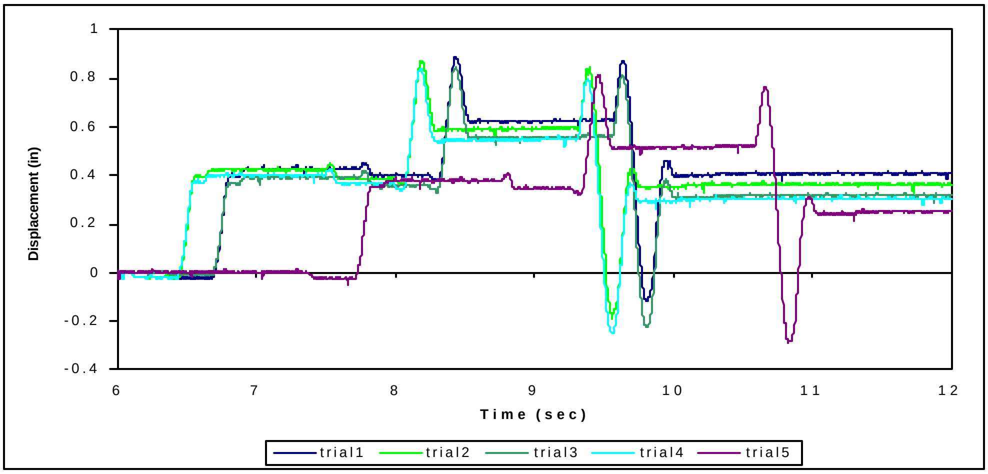

Figure 5. Repeatability results with final experimental setup: 1971 San Fernando Excitation

RECONCILIATION

The SLIDE program developed by Shao[4] was modified by Choi[6] to include both static and kinetic coefficients of friction and renamed SLIDE2. Both programs read a base acceleration and then calculate a relative displacement time history. The correlation results are shown in Figure 6 for the S-74°-W component of the February 9, 1971 San Fernando earthquake and in Figure 7 for the N-86°-E component of the April 13, 1949 Western Washington earthquake. As expected, the SLIDE2 program improved the correlation between the measured and calculated responses in each case.

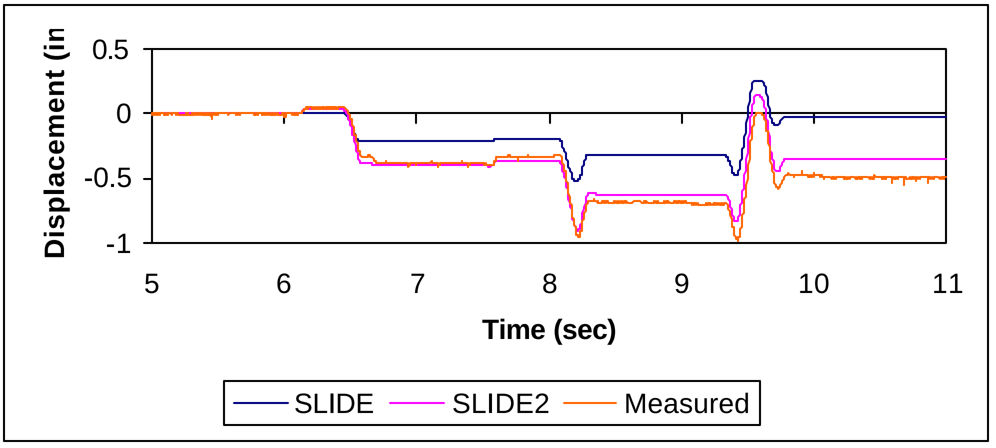

Figure 6. Measured and calculated responses from SLIDE and SLIDE2: 1971 San Fernando Excitation.

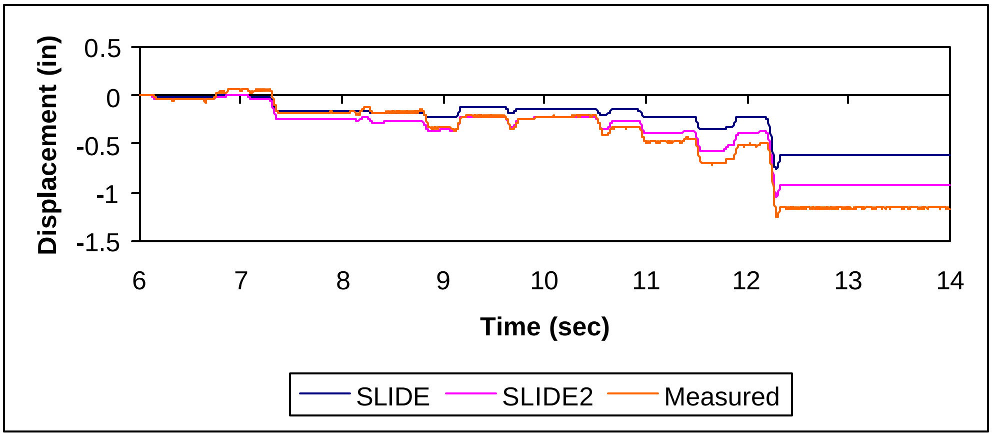

Figure 7. Measured and calculated responses from SLIDE and SLIDE2: 1949 Western Washington Excitation.

MODEL IMPROVEMENT USING PARAMETER IDENTIFICATION

Although the correlation in Figures 6 and 7 is quite good, it appeared that the results might be even better if the coefficients of friction were calculated using an inverse technique, that is by using a particular test record and then determining the coefficients of friction, or parameters, such that the analytical and experimental curves matched each other as well as possible. A FORTRAN subroutine was added to SLIDE2 to accomplish this procedure. The subroutine iterates through a range of practical values of μ_s and μ_k ($\mu_s \geq \mu_k$), calculates a relative displacement time history for each combination of coefficients, then reads in the measured relative displacement time history and calculates a squared error between the two time histories. The output file lists each combination of μ_s and μ_k for which a time history was calculated, along with the corresponding squared error. From these data, the coefficients associated with the minimum squared error can be then obtained. There are, of course, ways to automate this procedure but, for our small two-parameter problem, this manual approach worked well. Typical results for the coefficients of friction using this inverse approach are shown in the last three rows of Table 1 (Test type (5)). Figures 8 and 9 shows the correlation between the measured the computed responses (Parkfield and San Fernando - with the polarity reversed - respectively) using these last results.

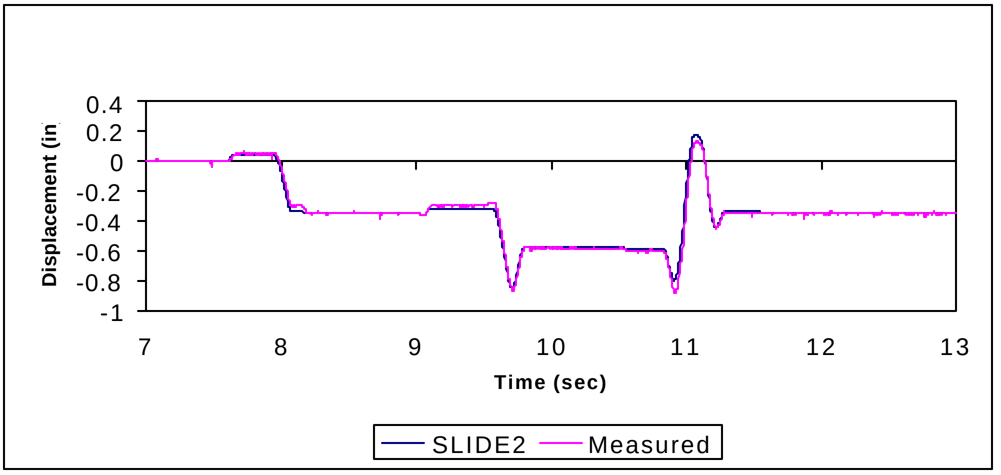

Figure 8. Best simulation from SLIDE2:. 1971 San Fernando earthquake with reversed polarity.

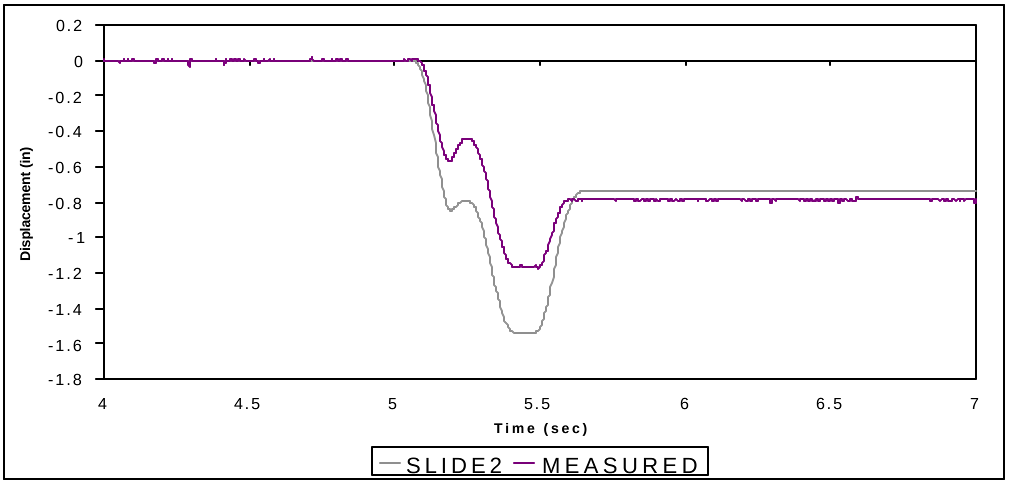

Figure 9. Best simulation from SLIDE2: 1966 Parkfield earthquake

From Figure 9, we see that the best two-parameter model cannot always simulate the sliding behavior of an unanchored object. Also we note from Table 1 that the value of the kinetic coefficient of friction changes from one seismic input to the next, i.e. it is motion dependent. According to the Standard Handbook for Mechanical Engineers[7], this behavior can be expected. As the relative velocity between the two contact surfaces increases, the maximum sliding frictional force, and hence the kinetic coefficient of friction, decreases. To further improve the mathematical model for sliding, a new, more realistic analytical model, which includes a velocity dependent kinetic coefficient of friction, could be developed.

CONCLUSIONS

We have shown that, with sufficient thought given to the experimental procedures, it is possible to obtain sliding behavior that is reasonably repeatable. Also, it is possible to simulate quite accurately the one-dimensional sliding behavior of an unanchored object subjected to horizontal seismic base motion. As expected, using both a static and a kinetic coefficient of friction gives better results than using only a single coefficient. Further improvement in the model would require that the coefficients be velocity or perhaps position dependent. Improvements of this type are left for future research.

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