SECTION 5

COMBINED WIRE ROPE AND CASTER SUPPORT SYSTEM FOR EQUIPMENT - COMPARATIVE EXPERIMENTAL STUDY

5.1 Description of Equipment and Support System

An experimental study was performed with IBM 9370 computer equipment installed on top of a raised floor and supported by casters. Figure 5-1 shows a view of the computer equipment installed on the raised floor as it would have been in service. The casters support the weight of the equipment and allow for easy relocation on the raised floor. When in service, the casters are locked and a 90 plus degree plate angle, called the foot, is attached in the front of the body for stability. To prevent excessive displacements and overturning in earthquake excitation, positive connection of the equipment to the floor below the raised floor is normally provided by means of bungee cords or long helical steel springs. These elements run through holes on the tiles of the raised floor.

In general, earthquakes may cause effects to computer equipment which may be catastrophic when overturning occurs, or serious when damage occurs due to excessive acceleration and impact, or minor when execution is interrupted due to large accelerations or pull-out of cables. Installation methods which can reduce accelerations and displacements to acceptable levels while allowing for easy relocation of the equipment are particularly interesting to computer manufacturers. As a part of a NCEER - IBM joint research project, various computer equipment installation methods were tested. One of them consisted of wire rope isolators.

The wire rope installation method followed the standard approach in which the equipment is supported by four locked casters with the foot installed in the front. Four helical wire rope isolators No.5 (see section 2) were connected to metal bars in sets of two isolators each as shown in Figure 5-2. The two sets of isolators were placed under the equipment and bolted to the frame above and to the tiles of the raised floor below. During testing, the isolators deformed only in their shear direction.

The IBM 9370 computer equipment has plan dimensions of 36.2 in. by 25.6 in. (920 mm by 650 mm) and height of 62.1 in. (1578 mm). Its center of mass is located at coordinates X = 12.03 in. (305.6 mm), Y = 25.08 in. (637.1 mm) and Z = 15.4 in. (391.3 mm) according to the coordinate system of Figure 5-2 at point O. Its weight is 828 lbs (3.7 kN). The fundamental frequency of the equipment when fixed at its base was experimentally determined to be 4.1 Hz in the testing (X) direction. Attempts were made to determine the coefficient of friction at the interface of locked casters and angle foot and supporting raised floor. The procedure described by Constantinou 1987 was used, however, it was not possible to exactly determine the coefficient of friction. The coefficient was found to be in the range of 0.20 to 0.30. For such high value of friction, the ability of wire rope isolators to dissipate energy is not important and the isolators act only as restoring force devices. From the data of Table 2-II, each isolator No.5 has horizontal (shear) stiffness of 0.24 Kips/in. (0.042 kN/mm) so that the frequency of the isolated equipment is 3.4 Hz. This frequency is close to that of the equipment on top of the isolators so that the combined system doesn't behave as a rigid body.

5.2 Experimental Results and Comparison to other Installation Methods

The wire rope system was tested on the shake table with the strongest of the input motions described in section 3. Furthermore, tests were conducted with the vertical component being equal to 1/3 of the horizontal component of excitation. The horizontal component was applied in the X - direction as shown in Figure 5-2. The instrumentation diagram is shown in Figure 5-2. The displacement transducers, which are shown mounted on the equipment, measured displacements of the part just above the casters with respect to the raised floor.

The table excitation was filtered through the raised floor and arrived amplified at the supported equipment (see differences between instruments ASEX and AFEX in Table 5-I).

Response spectra of the horizontal components of excitation at the raised floor level for 0.05 damping ratio are presented in Figure 5-3. Comparison of these spectra to those of Figures 3-7 and 3-10 reveal the filtering effect of the raised floor.

The recorded peak response is presented in Table 5-I. It should be noted that the equipment responded with some torsional motion and motion in the transverse (Y) direction. This is due to asymmetry in the distribution of the equipment's weight (center of mass located close to the west side casters). At the level of the support system, this asymmetry was partially counterbalanced by additional frictional force on the east side where the foot plate angle was installed. In general, displacements are small and accelerations are at levels which can not cause any interruption of operation of the computer. This was verified in all tests by monitoring the execution of a computer program during shake table testing.

The wire rope support system performed considerably better than other commonly used installation methods for computer equipment (see section 5.1). Tables 5-II and 5-III compare peak responses of the wire rope system to those of other systems for the Taft 7th floor and El Centro 7th floor motions (both with vertical component equal to 1/3 of horizontal component). The response values included in these tables are the maximum among all of the recorded peak values. Evidently, the wire rope system reduced displacements by an order of magnitude while maintaining accelerations at the same level as the other installation methods. Interestingly, the computer equipment sustained accelerations of more than 3g (see Table 5-III, installation method with springs) without any interruption of its operation.

Concluding, we note that the wire rope isolators used in the described installation method have a displacement capacity of about 0.5 in. prior to initiation of stiffening (see Fig. 2-8). When stiffening occurs, the equipment is prevented from further movement and uplift and impact on return may occur. This is undesirable. Tests were conducted with input motion stronger than the El Centro 7th floor and, as expected, uplift occurred and high accelerations were recorded. To avoid uplift, wire rope isolators with larger displacement capacity must be used. This, of course, requires that analyses are performed to estimate the isolator's expected displacement. Still, uplift may occur in slender equipment.

An installation method which prevents the occurrence of uplift is illustrated in Figure 5-4. The wire rope isolators are connected by two keeper bars. The top bar is bolted to the frame of the equipment. The bottom keeper bar is connected to the floor below the raised floor by two turnbuckle - toggle wing connectors. This type of connection allows for easy relocation of the equipment. A simple uplift control mechanism is included between the keeper bars. It consists of two intersecting rectangular hooks. Two sets of keeper bars with each set including two wire rope isolators and one uplift control mechanism are placed between the four supporting casters.

5.3 Analytical Prediction of Response

The analytical prediction of the response of the caster - wire rope support system is useful in the selection of wire rope isolators and in the design of the uplift control mechanism. Spectra of peak response of frictional oscillators may be used in estimating the peak response. Such spectra were constructed for a frictional oscillator of coefficient of friction (of Coulomb type) equal to 0.2 and 0.3 and are presented in Figures 5-5 and 5-6. It should be noted that these spectra are valid for a rigid structure and, thus, the acceleration response must be viewed with caution when the equipment above the isolators is flexible and the support system exhibits characteristics of weak restoring force and strong frictional force (Constantinou 1990b and 1991). Such conditions occur when the peak frictional force is larger by at least a factor of two than the peak restoring force.

The spectra of Figures 5-5 and 5-6 were constructed by analysis of a single-degree-of freedom frictional oscillator of mass m, stiffness K, and coefficient of friction μ. The equation of motion is (Constantinou 1990a)

$$m\ddot{U} + KU + \mu mgZ = -m\ddot{u}_g \tag{5-1}$$

where Z is again given by equation 2-2 with Y = 0.01 in. (0.25 mm), $\beta + \gamma = A = 1$ and n an integer. The period is defined as

$$T = 2\pi\left(\frac{m}{K}\right)^{\frac{1}{2}} \tag{5-2}$$

The usefulness of these spectra is demonstrated in a comparison of analytical and experimental (average from instruments on east and west side casters, see Fig. 5-2) time histories of displacement in Figure 5-7. For the analysis, equation 5-1 was used with $\mu = 0.25$ and with the restoring force term, KU, replaced by 4F where F is given by equation 2-1 with the data of Table 2-II for isolator No.5. Almost identical results were obtained in analyses in which the term KU was maintained (linear representation of wire rope isolators) with $K = 4K_x$ (K_x = 0.24 Kip/in, see Table 2-II). The analytical results compare favorably to the experimental ones despite the uncertainties in the nature and value of the coefficient of friction. It should be noted that the large differences in experimental and analytical time histories at small displacements indicate that the coefficient of friction is velocity dependent as that of other interfaces identified in Constantinou 1990a.

Table 5-I - Recorded peak Response of IBM Equipment with Wire Rope Isolators (1 in.= 25.4 mm).

EXCITATION / INSTRUMENT		Taft Ground (H&V)	Taft 7th Floor (H&V)	Taft 7th Floor (H&V*)	El Centro 7th Floor (H&V)	El Centro 7th Floor (H&V*)
ACCELERATION (g)	ASEX	0.155	0.449	0.482	0.724	0.807
	AFEX	0.171	0.557	0.567	0.988	1.002
	ALRRX	0.198	0.888	0.791	0.947	1.060
	ALRFX	0.182	0.797	0.781	0.914	1.014
	ATRRX	0.438	0.988	0.975	1.211	1.109
	ATRFX	0.373	0.883	0.826	1.022	0.991
	ALRRY	0.043	0.129	0.138	0.223	0.266
	ATRFZ	0.155	0.225	0.313	1.063	0.875
	ATRRZ	0.130	0.198	0.258	1.079	0.876
DISPLACEMENT (in)	DSDX	0.306	0.659	0.641	0.833	0.813
	DSDZ	0.142	0.184	0.253	0.657	0.520
	DNEX	0.028	0.208	0.203	0.278	0.344
	DNWX	0.045	0.243	0.211	0.329	0.528
	DNWY	0.013	0.064	0.035	0.058	0.064
	DSWY	0.012	0.046	0.021	0.043	0.087

V* : Vertical component equal to 1/3 of horizontal component.

Table 5-II - Comparison of Peak Response of Equipment with Different Installation Methods for Taft 7th Floor Input (1 in.= 25.4 mm).

Installation System	Horizontal Top Acceleration (g)	Vertical Top Acceleration (g)	Displacement of Casters (in)
Locked Casters	0.434	0.260	6.28
Locked Casters and Bungee Cords	0.705	0.239	3.25
Locked Casters and Springs(2)	0.783	0.374	3.92
Locked Casters and Wire Rope Isolators	0.969	0.285	0.21

Table 5-III - Comparison of Peak Response of Equipment with Different Installation Methods for El Centro 7th Floor Input (1 in.= 25.4 mm).

Installation System	Horizontal Top Acceleration (g)	Vertical Top Acceleration (g)	Displacement of Casters (in)
Locked Casters	0.710	0.408	9.62
Locked Casters and Bungee Cords	1.221	0.559	5.06
Locked Casters and Springs (2)	3.079*	3.482*	8.88
Locked Casters and Wire Rope Isolators	1.056	0.876	0.53

* : Uplift and Impact

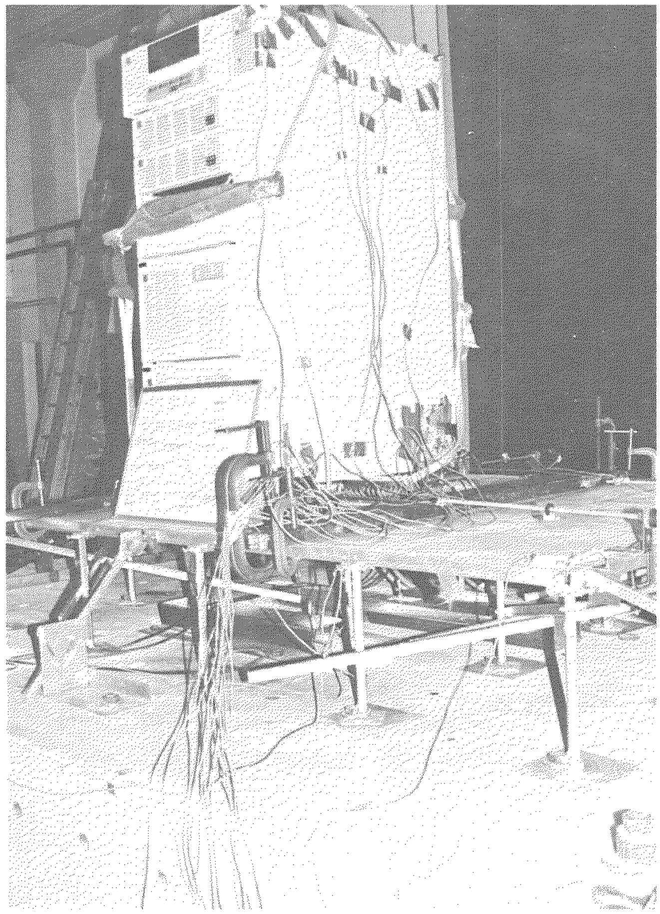


Figure 5-1 View of IBM 9370 Computer Equipment on Raised Floor and Shake Table.

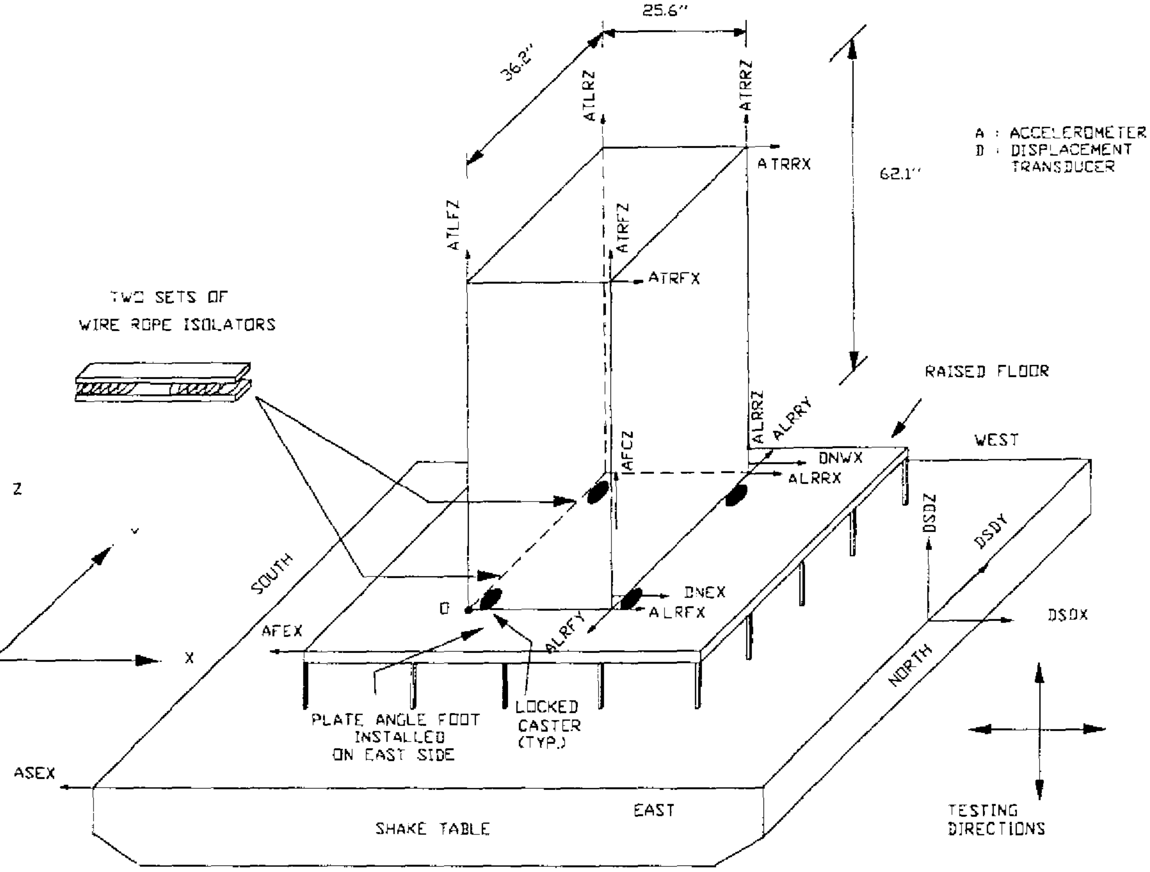


Figure 5-2 Schematic Representation of IBM 9370 Computer Equipment on Shake Table and Instrumentation Diagram.

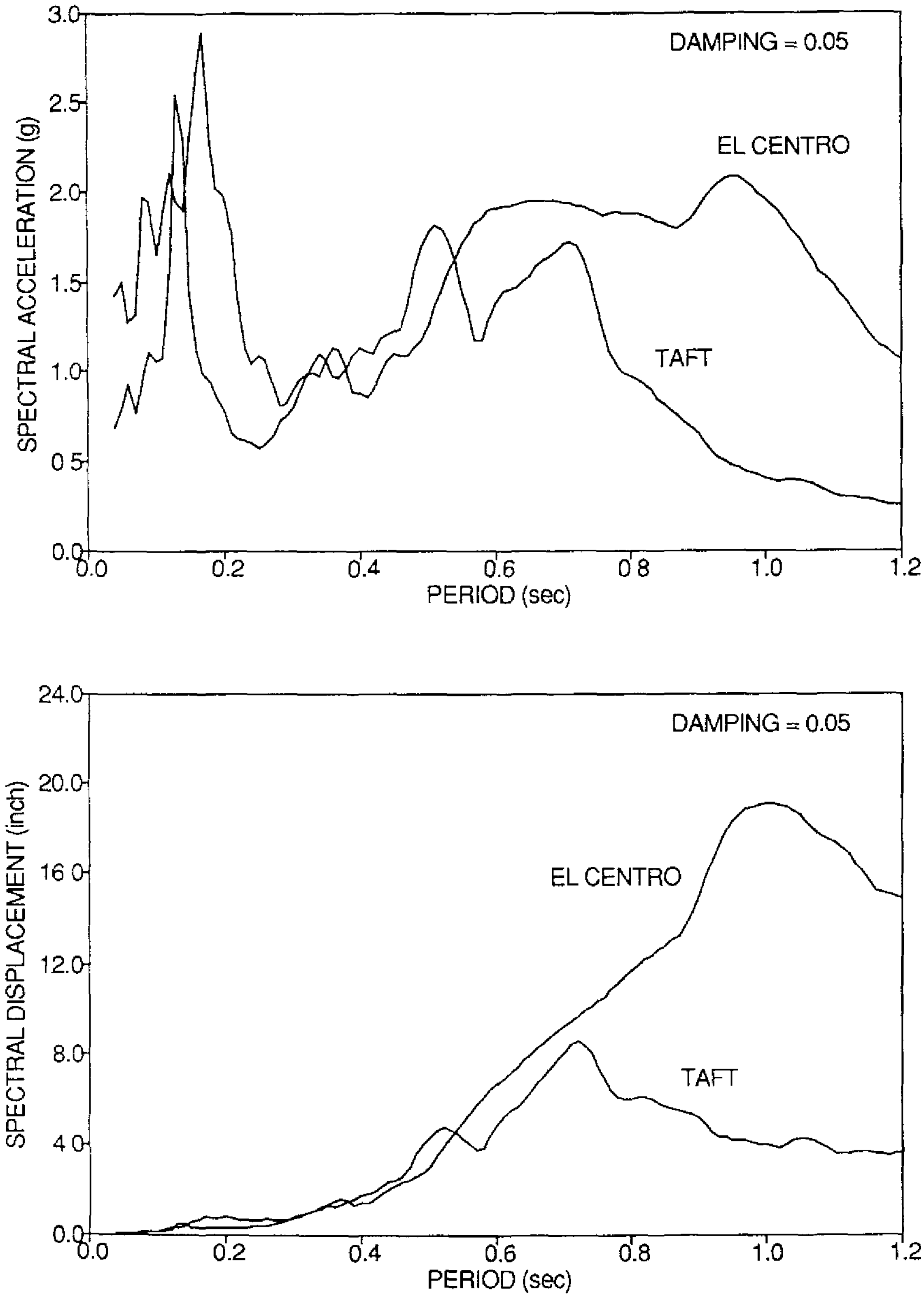


Figure 5-3 Response Spectra at Raised Floor of a 5% Damped System for Taft 7th Floor and El Centro 7th Floor Motion (1 in.= 25.4 mm).

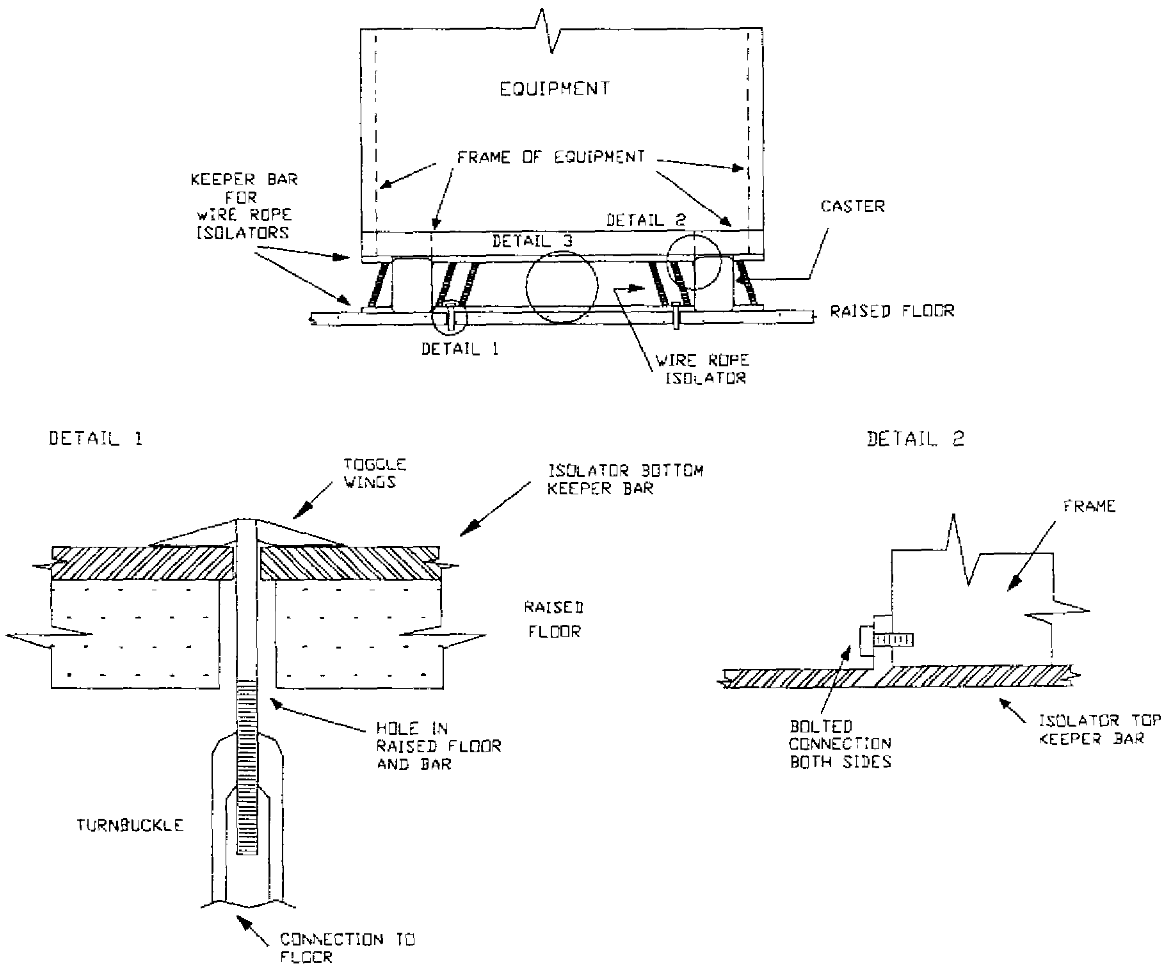
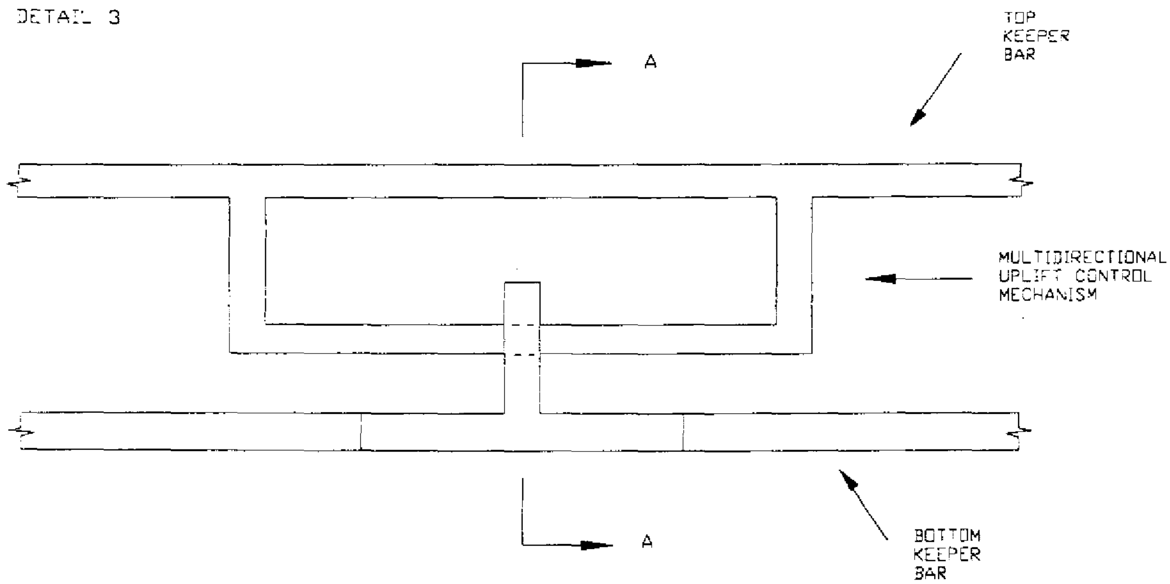


Figure 5-4 Details of Installation of Wire Rope Isolators with Uplift Restrainer.



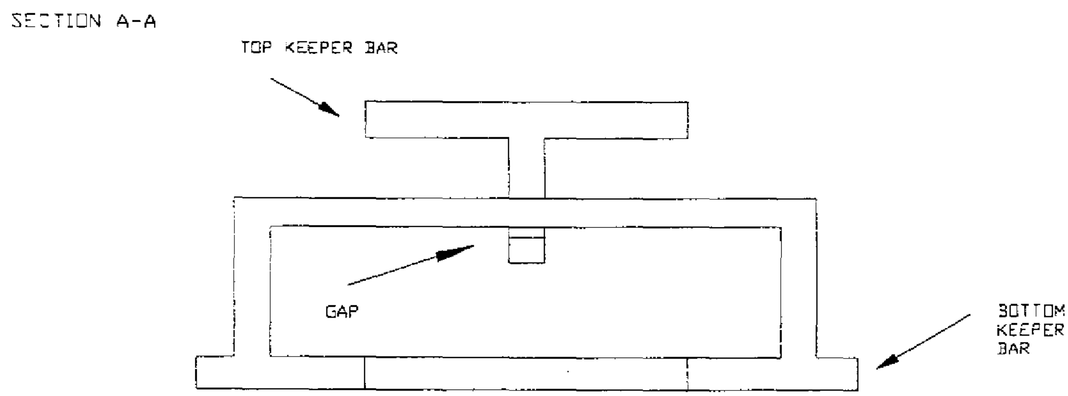


Figure 5-4 Continued.

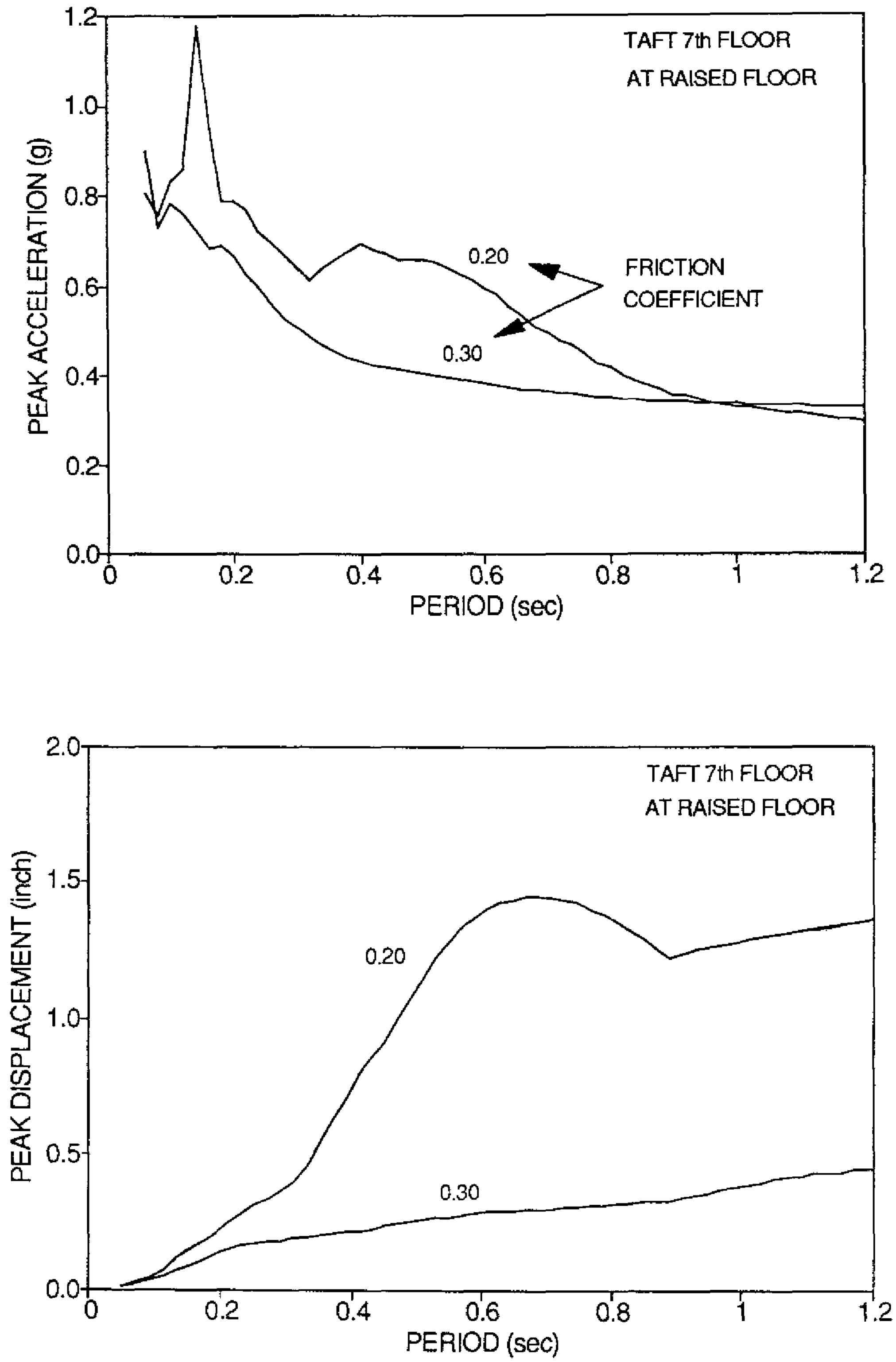


Figure 5-5 Response of Frictional Oscillator of Taft 7th Floor at Raised Floor Level (1 in.= 25.4 mm).

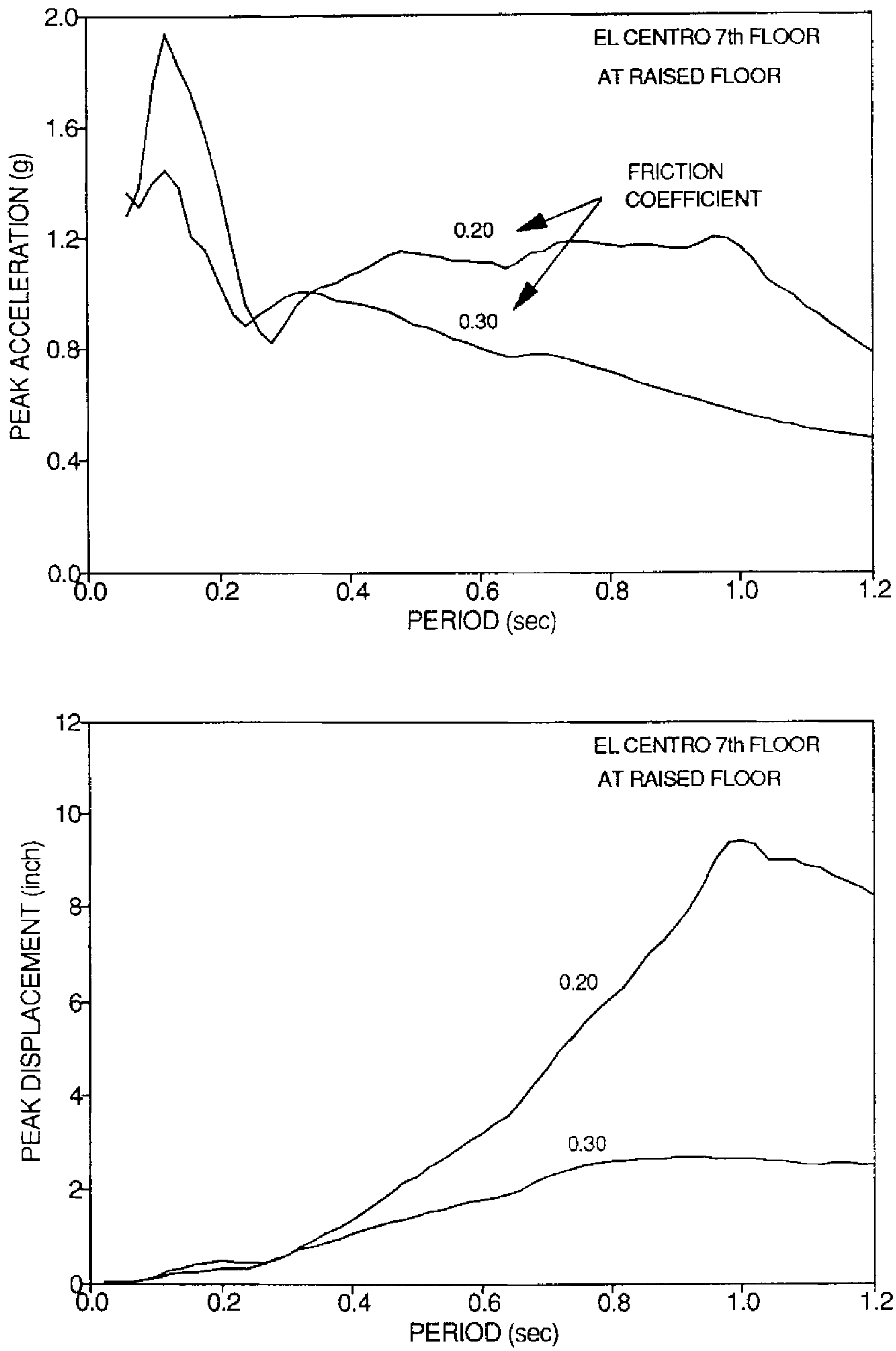
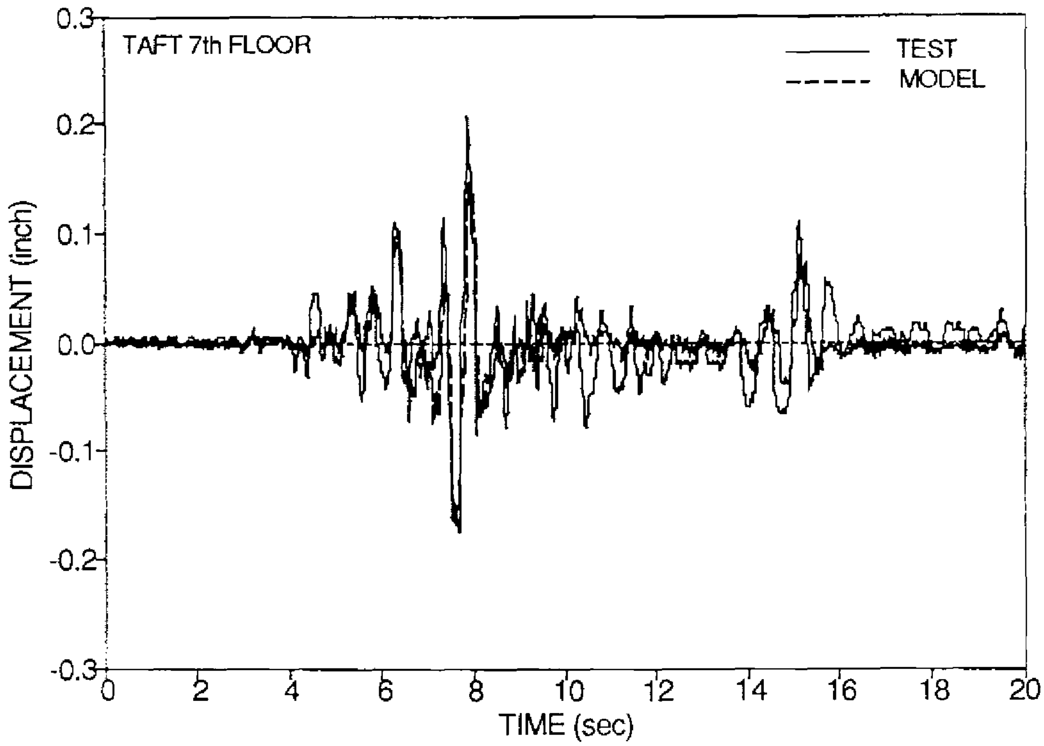


Figure 5-6 Response of Frictional Oscillator of El Centro 7th Floor at Raised Floor Level (1 in.= 25.4 mm).



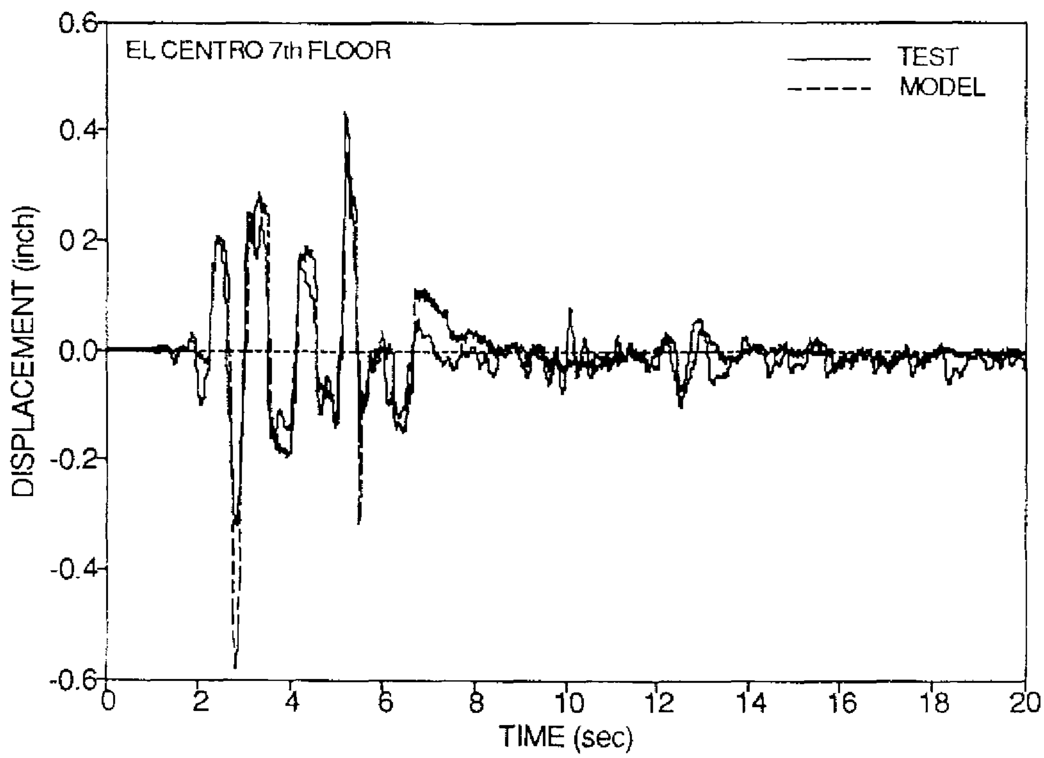


Figure 5-7 Comparison of Experimental and Analytical Time Histories of Displacement of Casters in Tested IBM Equipment (1 in.= 25.4 mm).