MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
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Sliding Fragility of Unrestrained Equipment in Critical Facilities

by

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Preface

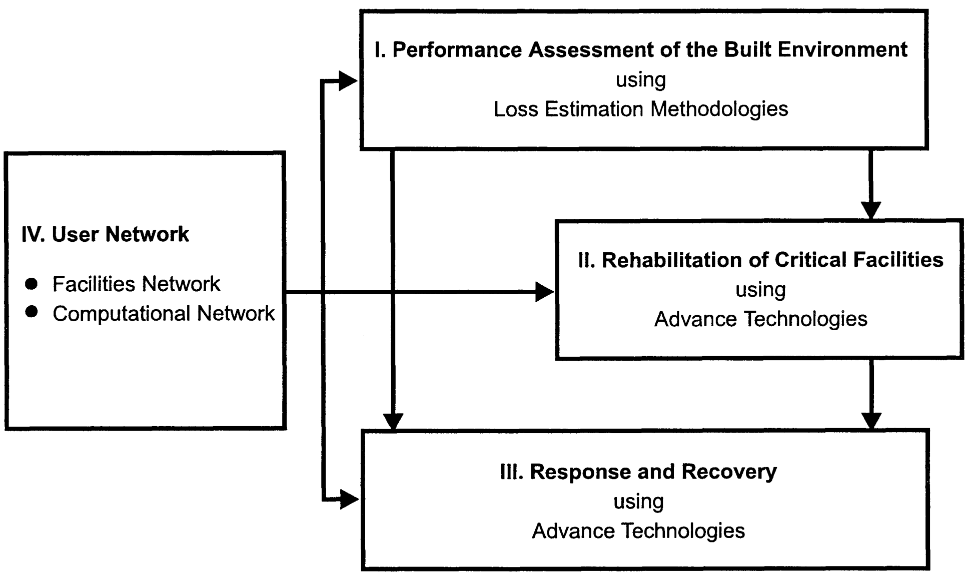
The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

The Center's NSF-sponsored research is focused around four major thrusts, as shown in the figure below:

- quantifying building and lifeline performance in future earthquake through the estimation of expected losses;
- developing cost-effective, performance based, rehabilitation technologies for critical facilities;
- improving response and recovery through strategic planning and crisis management;
- establishing two user networks, one in experimental facilities and computing environments and the other in computational and analytical resources.



The objective of this research is to develop fragility information and rehabilitation strategies for nonstructural components in critical facilities. The research concentrates on experimental and analytical studies of the sliding response of freestanding rigid objects subjected to base excitation. Analytical and experimental techniques are combined to allow determination of fragility curves for freestanding rigid equipment under seismic excitations for further improvement of seismic mitigation measures.

A discrete system model, an analytical model for two-dimensional sliding under two-dimensional excitation, is developed and analyzed for specific base motions. Shaking table testing with a range of excitations and system parameters is used to define stability bounds for pure sliding motion. A comparison of the analytical and experimental results is then performed to further verify the validity of the analytical model. Future improvements and discrepancies in the model assumptions are also discussed in this report.

ABSTRACT

Through the years, seismic design of buildings has been well developed and is continually updated and improved. Yet, nonstructural components housed in buildings are rarely designed with the same degree of consideration as buildings. As a result, buildings that remain structurally sound after a strong earthquake often lose their operational capabilities due to damage to their nonstructural components, such as piping systems, communication equipment and other types of components. The recent 1994 Northridge, 1995 Kobe, and 1999 Turkey and Taiwan earthquakes further demonstrate the importance of controlling damage to nonstructural components, particularly in critical facilities, such as hospitals, in order to ensure their functionality during and after a major earthquake.

Earthquake vulnerability of nonstructural components is usually reduced by fastening or bracing individual objects. However, there are some nonstructural components in buildings which often cannot be restrained for protection from earthquake shaking. The response of these objects will consist of sliding, rocking, or jumping. Understanding these response types will allow estimation of vulnerability to earthquake damage and will assist in the design of appropriate mitigation measures.

This research concentrates on experimental and analytical studies of the sliding response of freestanding rigid objects subjected to base excitation. Analytical and experimental techniques are combined to allow determination of fragility curves for free-standing rigid equipment under seismic excitations for further improvement of seismic mitigation measures.

A discrete system model, an analytical model for two-dimensional sliding under two-dimensional excitation, is developed and analyzed for specific base motions. Shaking table testing with a range of excitations and system parameters is used to define stability bounds for pure sliding motion. A comparison of the analytical and experimental results is then performed to further verify the validity of the analytical model. Discrepancies in the model assumptions and future improvements of the nonstructural model are also discussed in this report.

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INTRODUCTION

1.1 Background

Nonstructural components are, basically, all components of a building other than those considered to perform primary structural functions. They include mechanical and electrical equipment, architectural elements, and building contents. Technically, they are sufficiently strong and rigid to remain in place, but are wholly unintegrated with the primary structure as the structural load-bearing system. In other words, they can affect structural behavior only through inertial forces; they add no stiffness to the primary structure; and are infrequently designed to resist seismic forces. On the other hand, secondary components, which are sometimes confused with nonstructural components, can affect the seismic behavior of a primary structure.

Through the years, earthquakes have earned a growing reputation for their consistent propensity to find the 'weak link' in a complex system and lead that system into a progressive failure mode. As a result of this ability to locate and strike the weakest point of an assembly, nonstructural components have always been the 'victims' of earthquakes.

The bottom line in evaluating a well-constructed building is found in its success in providing safety and comfort for its occupants. In most structural designs, engineers tend to emphasize structural damage in earthquakes. However, in certain situations, damage to nonstructural components can pose a more dangerous threat to life safety than structural damage. This can be revealed from an evaluation of various veterans hospitals following the San Fernando earthquake in 1971. Many facilities, which still structurally intact, were no longer functional because of loss of essential equipment and supplies. More importantly, it has also been recognized that survival after the occurrence of a strong earthquake of nonstructural components may be vital in terms of providing emergency services, as in the case of equipment in power stations, hospitals, or communication facilities.

In addition to safety threat resulted from the failure of nonstructural components, economic loss from nonstructural component damage has also received special attention by engineers. In fact, in some cases, damage to nonstructural components will greatly exceed the cost of structural damage. For example, of $143,000 in total damage of a building caused by the San Fernando earthquake, in 1972-value dollars, only $2,000 was structural damage while the remaining 98.56% was nonstructural. Moreover, costly damage to nonstructural components could occur in earthquakes of moderate intensities, which would cause little or no structural damage.

In accordance with such a concern for human safety as well as economic considerations, effort should be made to reduce the potential for damage to nonstructural components of structures as part of the effort to reduce the overall seismic hazard to structures. Thus, it is very important for structural engineers to not underestimate the performance of nonstructural components during earthquakes. In view of this, understanding the vulnerability of nonstructural components to earthquake excitation is critical to protection from future damage.

1.2 Types of Rigid Block Motion During Earthquake

Nonstructural components are subject to damage during an earthquake either directly due to ground shaking or indirectly due to movement of buildings. Earthquake ground shaking has three primary effects on nonstructural components in buildings. These are inertial or shaking effects on the nonstructural components themselves, distortions imposed on nonstructural components when the building structure vibrates, and separation or pounding at the interface between adjacent structures. These three effects are shown in Figure 1.1 (FEMA, 1994).

Evaluating the seismic performance of nonstructural components which are subjected to damage caused by inertial or shaking effects (first case in Figure 1.1) is of concern in this research. Figure 1.2 shows a free-standing rigid block resting on a supporting base subjected to base excitation due to an earthquake. There are basically four types of response which could occur. The block could either be at rest, or sliding, or rocking, or jumping or having a kind of motion which is a combination of these motion types.

In accordance with the four types of response mentioned above, there are basically three kinds of motion equilibrium equations that dictate the motion of the free-standing rigid block under a seismic excitation :

1. Vertical Equilibrium : Gravity force equals the vertical component of the input excitation:

$$mg + m\ddot{y}_g = 0 \tag{1.1}$$

2. Horizontal Equilibrium : Horizontal component of the input excitation equals the friction force:

$$\left| m\ddot{x}_g \right| = \mu_s m(g + \ddot{y}_g) \quad ; \quad g + \ddot{y}_g \geq 0 \tag{1.2}$$

3. Moment Equilibrium : Moment induced by the input excitation equals the restoring moment:

$$h\left| m\ddot{x}_g \right| = bm(g + \ddot{y}_g) \quad ; \quad g + \ddot{y}_g \geq 0 \tag{1.3}$$

in which,

- m is the mass of the free-standing rigid block
- g is the gravitational acceleration, which is 9.81 m/sec^2 (32.2 ft/sec^2)
- $\ddot{x}_g$ is the horizontal acceleration within an acceleration time history (positive to left)
- $\ddot{y}_g$ is the vertical acceleration within an acceleration time history (positive downward)
- μ_s is the coefficient of static friction between sliding surfaces
- h is one-half of the block height
- b is one-half of the block width

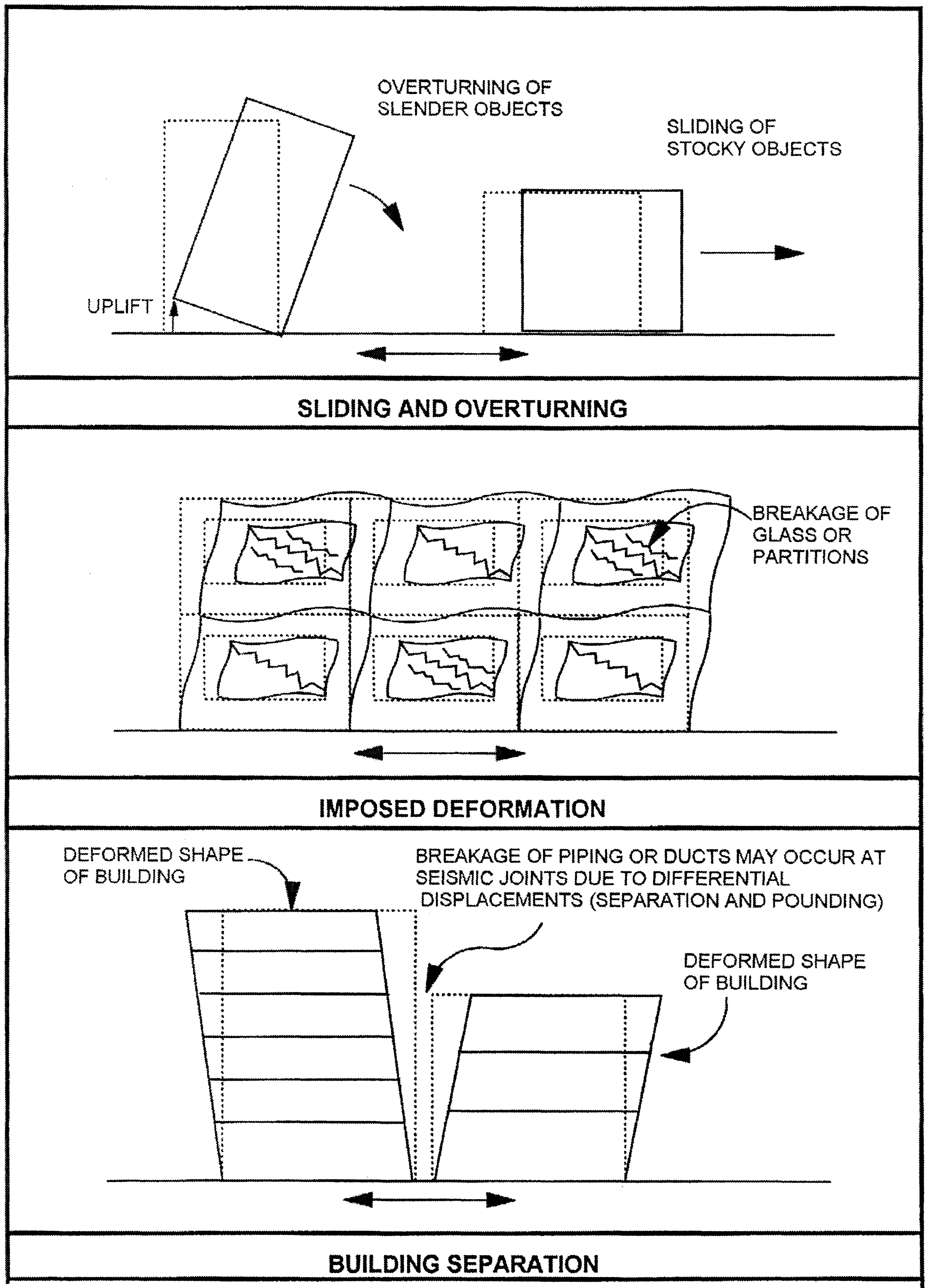


Figure 1.1 Effects of Earthquake on Nonstructural Components (FEMA 74, 1994)

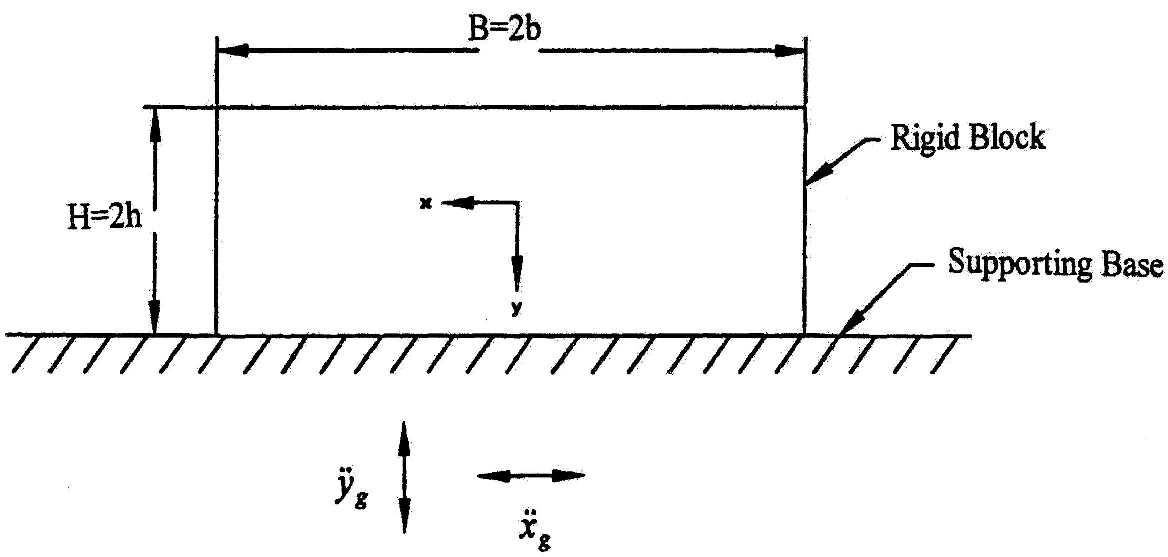


Figure 1.2 Free-Standing Rigid Block Under Base Excitation

If one of the forces exceeds the other in each of the equilibrium equation mentioned above, different types of motions could be initiated. The conditions for initiating these four types of motion are illustrated below in Table 1.1 :

Table 1.1 Conditions for Different Types of Initiated Response during Earthquake

Motion Types	Vertical Inequality	Horizontal Inequality	Moment Inequality
At Rest	$(g+\ddot{y}_g)\geq 0$	$\lvert\ddot{x}_g\rvert \leq \mu_s(g+\ddot{y}_g)$	$\lvert\ddot{x}_g\rvert \leq \frac{b}{h}(g+\ddot{y}_g)$
Jumping	$(g+\ddot{y}_g)\leq 0$	–	–
Rocking	$(g+\ddot{y}_g)\geq 0$	$\lvert\ddot{x}_g\rvert \leq \mu_s(g+\ddot{y}_g)$	$\lvert\ddot{x}_g\rvert \geq \frac{b}{h}(g+\ddot{y}_g)$
Sliding	$(g+\ddot{y}_g)\geq 0$	$\lvert\ddot{x}_g\rvert \geq \mu_s(g+\ddot{y}_g)$	$\lvert\ddot{x}_g\rvert \leq \frac{b}{h}(g+\ddot{y}_g)$

As noticed from Table 1.1, $(g+\ddot{y}_g)\geq 0$ is the pre-requisite for the at rest, sliding and rocking motion. In addition, the prerequisite for the initiation of a sliding motion is $\frac{b}{h} > \mu_s$. On the other hand, $\frac{b}{h} < \mu_s$ is the prerequisite to initiate rocking motion.

1.3 Objectives of Study

Clearly, sliding is an important failure mode for free-standing block-type equipment subjected to strong earthquakes. If an unrestrained rigid object does not rock during earthquake shaking, then it may slide across its mounting surface. Sliding itself is not objectionable. In fact, sliding can be effectively used as a means of horizontal base isolation. However, excessive sliding clearly can damage the object or cause damage to other objects if the sliding displacement is large enough to allow impact with other objects. Failure criteria will therefore depend on the allowable relative displacement as well as the combination of the allowable relative displacement and the absolute acceleration at which allowable relative displacement occurs.

The major objective of this research is to construct fragility curves for different peak ground accelerations (PGA), both horizontal and vertical, as well as different coefficients of friction based on certain sliding failure thresholds as mentioned above. Since base accelerations are random in nature, a statistical method is necessary for both analytical modeling and experimental measurements of sliding response.

With these failure curves constructed, their sensitivity to some important response parameters, which are the coefficient of friction for the sliding surfaces, the peak ground accelerations of excitation, both horizontal and vertical, for pure sliding response could be determined for evaluation of the seismic performance as well as for the design of free-standing block-type equipment.

1.4 Approach of Research

In order to construct the fragility curves for sliding failure mode, the conditions for sliding to be initiated are important in this research. With the determined conditions for pure sliding motion, (excluding rocking and jumping), the equation of sliding motion of a free-standing rigid block could be formed base on the assumptions made for pure sliding motion. This equation of motion can then be solved using a numerical method.

In order to obtain the probability of failure, many varieties of excitation should be included as the inputs in solving the differential equation of motion. In this work, SIMQKE will be used in randomly generating the excitation inputs and fragility results will be obtained through Monte Carlo simulation.

With the solutions solved numerically with given input excitation at discrete points, different failure thresholds could be set to obtain the probability of failure based on three distinct parameters in this research, namely, the coefficient of dynamic friction of the sliding surfaces as well as the horizontal and vertical peak ground accelerations. The probabilities of failure obtained from different sets of combinations of the three parameters can then be plotted in graphs based on different failure thresholds.

Experiments were performed to verify the validity of the analytical solutions described above. The experiments involved putting a free-standing rigid block on a shaking table to simulate the sliding motion during an earthquake and measuring the relative displacement and absolute acceleration time histories of the sliding block, as the results obtained analytically. Fragility curves constructed from these experimental results were compared with the analytical fragility curves. With this comparison performed, discussion and conclusion could be made in accordance with the objectives set previously.

1.5 Organization

In this research, investigations are carried out, analytically and experimentally, to determine the vulnerability of a free-standing rigid block, under the sliding failure mode, and subjected to earthquake excitations. Emphasis is given to constructing the fragility curves based on different failure thresholds, specifically on both sliding and impact thresholds.

In Section 1, background on the nonstructural components and their damageability during and after an earthquake are addressed. Different types of possible response of nonstructural components under base excitations are presented, followed by the objectives and approach of this research.

In Section 2, conditions for sliding are addressed, and reemphasized by a graphical representation. Equation of sliding motion is then developed based upon these sliding conditions. Due to the fact that the performance of nonstructural components under base excitations is stochastic and nonlinear, a Monte Carlo procedure, which will be illustrated throughout Sections

2.4 and 2.5, is used in constructing the analytical sliding fragility curves. Discussion of these analytical results concludes this section.

In Section 3, concentration is placed on seismic simulation testing procedure. In addition, determination of coefficient of static friction of the tested sliding surfaces is presented in order to relate experimental results with the analytical results. A comparison of these two results concludes this section.

In Section 4, conclusions obtained from this research are presented. Moreover, in Section 4.2, the validity of assumptions used in this research such as classical impact model and perfectly horizontal supporting base will be addressed. The idea of determining the dynamic friction coefficient by experimental means concludes this section.

SECTION 2
SLIDING PROBLEM FORMULATION

2.1 Conditions for Sliding

Sliding of a free-standing rigid body occurs when the horizontal seismic load acting on the rigid body exceeds the friction force between the rigid body and its supporting base. Moreover, sliding of a equipment which is bolted to the floor could also occur when bolts fail due to the excessive seismic load. In this research, only free-standing equipment with low centers of gravity is considered, so that the possibility of overturning and rocking of the equipment is ignored.

Theoretically, a free-standing rigid block, under a seismic excitation, as shown in Figure 1.2, will start to slide, but not rock nor jump, when the following conditions are valid :

$(g + \ddot{y}_g) \geq 0$ Vertical Force Inequality (2.1)

$|\ddot{x}_g| \geq \mu_s (g + \ddot{y}_g)$ Horizontal Force Inequality (2.2)

$|\ddot{x}_g| \leq \frac{b}{h}(g + \ddot{y}_g)$ Moment Inequality (2.3)

Equation (2.1) is the vertical force inequality. It ensures that resultant of the vertical gravity force and the vertical input excitation is always in the direction of the gravity force. In other words, the block does not lose its weight so that the jumping condition will not be initiated.

Equation (2.2) is the horizontal force inequality. The maximum horizontal inertia force, within the excitation period, must be larger than the maximum friction force that exists to initiate a sliding motion.

Equation (2.3) is the moment inequality about the free-standing rigid block corner point O, shown in Figure 1.2. The maximum toppling moment caused by base excitation must be smaller than the restoring moment in order to ensure that no overturning motion of the rigid block could occur.

The three equations described above are based on the following assumptions:

1. Only in-plane motions are considered.
2. The block and the supporting base are assumed rigid.
3. The surface of the supporting base is horizontal.

2.2 Graphical Representation of Motion Types

Due to many uncertainties in estimating the vertical excitation level during an earthquake, the vertical acceleration is assumed to be proportional to the horizontal acceleration. Thus, $\ddot{y}_g$ will be represented as $k\ddot{x}_g$ in this study, in which k is the proportional constant, which varies from 0 to 1.

Let us do some mathematical manipulations of $|\ddot{x}_g|$ and $(g+\ddot{y}_g)$ as the following:

1. Divide $|\ddot{x}_g|$ by $(g+\ddot{y}_g)$ => $$\frac{|\ddot{x}_g|}{g+\ddot{y}_g} = \frac{|\ddot{x}_g|}{g+k\ddot{x}_g} \tag{2.4}$$

   or $$\frac{1}{\frac{g}{|\ddot{x}_g|} + k\frac{\ddot{x}_g}{|\ddot{x}_g|}} \tag{2.5}$$

   which can be expressed as :

$$\frac{1}{\frac{g}{|\ddot{x}_g|} + k\,\mathrm{sgn}(\ddot{y}_g)} \tag{2.6}$$

in which $\ddot{y}_g$ is the vertical ground acceleration and $\mathrm{sgn}(\ddot{y}_g)$ is the Signum function defined by :

$\mathrm{sgn}(\ddot{y}_g) = +1$ for $\ddot{y}_g > 0$; $\mathrm{sgn}(\ddot{y}_g) = -1$ for $\ddot{y}_g < 0$

2. Equation (2.6) can be broken down into two values which are expressed as two constants, *a* and *c*, as follows :

$$a = \frac{1}{\frac{g}{|\ddot{x}_g|} + k} \quad \text{, when } \ddot{y}_g > 0 \tag{2.7}$$

$$c = \frac{1}{\frac{g}{|\ddot{x}_g|} - k} \quad \text{, when } \ddot{y}_g < 0 \tag{2.8}$$

With the constants *a* and *c* determined from equation (2.7) and (2.8), one can relate these two constants, the coefficient of static friction, and the rigid block aspect ratio, b/h, with the two possible motions of the rigid block, sliding and rocking, by comparing equations (2.7) and (2.8) with the conditions for sliding and rocking in Table 1.1. The final result of this comparison is shown in Figure 2.1, which is based on the following: For a sliding motion,

1. From Table 1.1, the conditions for sliding could be simplified as follows:

$$\mu_s(g+\ddot{y}_g) \le |\ddot{x}_g| \le \frac{b}{h}(g+\ddot{y}_g) \Rightarrow \mu_s \le \frac{|\ddot{x}_g|}{(g+\ddot{y}_g)} \le \frac{b}{h} \tag{2.9}$$

2. From equation (2.9), the prerequisite for a pure sliding motion is therefore

$$\mu_s \le \frac{b}{h} \text{ , (shown in the squared area in Figure 2.1)} \tag{2.10}$$

3. Combining (2.7), (2.8) and (2.9), we have the following:

$$\mu_s \le a \le \frac{b}{h}, \qquad \text{when } \ddot{y}_g > 0 \tag{2.11}$$

$$\mu_s \le c \le \frac{b}{h}, \qquad \text{when } \ddot{y}_g < 0 \tag{2.12}$$

Thus, we obtained the hatched area, shown in Figure 2.1, for a pure sliding motion region. The rocking motion region could be obtained using the same analysis method as for sliding motion region.

As for the region where both μ_s and $\frac{b}{h}$ are smaller than a, the horizontal inertia force exceeds the static friction force while creating a toppling moment to overcome the restoring moment. Thus, a combination of sliding and rocking motion may occur. On the other hand, when both μ_s and $\frac{b}{h}$ are larger than c, the horizontal inertia force is restricted by the static force while the toppling moment is restricted by the restoring moment at the same time and thus the free-standing rigid block will be at rest under the input seismic loading.

As $\ddot{y}_g = 0$, where a and c vanish, we could obtain a graph as shown in Figure 2.2 (Gates and Scawthorn, 1982).

2.3 Equation of Sliding Motion

As shown in Figure 1.2, the free-standing rigid block, which is undergoing a sliding motion caused by both horizontal and vertical excitations of its supporting base, is a simplified analytical model for an unrestrained block type equipment under seismic loading. The excitations of the supporting base may represent a strong earthquake motion.

The equation of sliding motion that will be established in this section is based on the assumption that the restoring moment is large enough to resist the toppling moment, $b/h > c$, so that rocking will not occur, neither does jumping motion. In other words, pure sliding motion occurs while the block is experiencing earthquake excitations.

With the above assumption established, the equation of sliding motion of rigid block can be expressed as the following :

$$m(\ddot{x} + \ddot{x}_g) + \mu_d(mg + m\ddot{y}_g)\,\mathrm{sgn}(\dot{x}) = 0 \tag{2.13}$$

which is valid when sliding conditions shown in Table 1.1 are satisfied. By eliminating m, equation (2.9) can be simplified as :

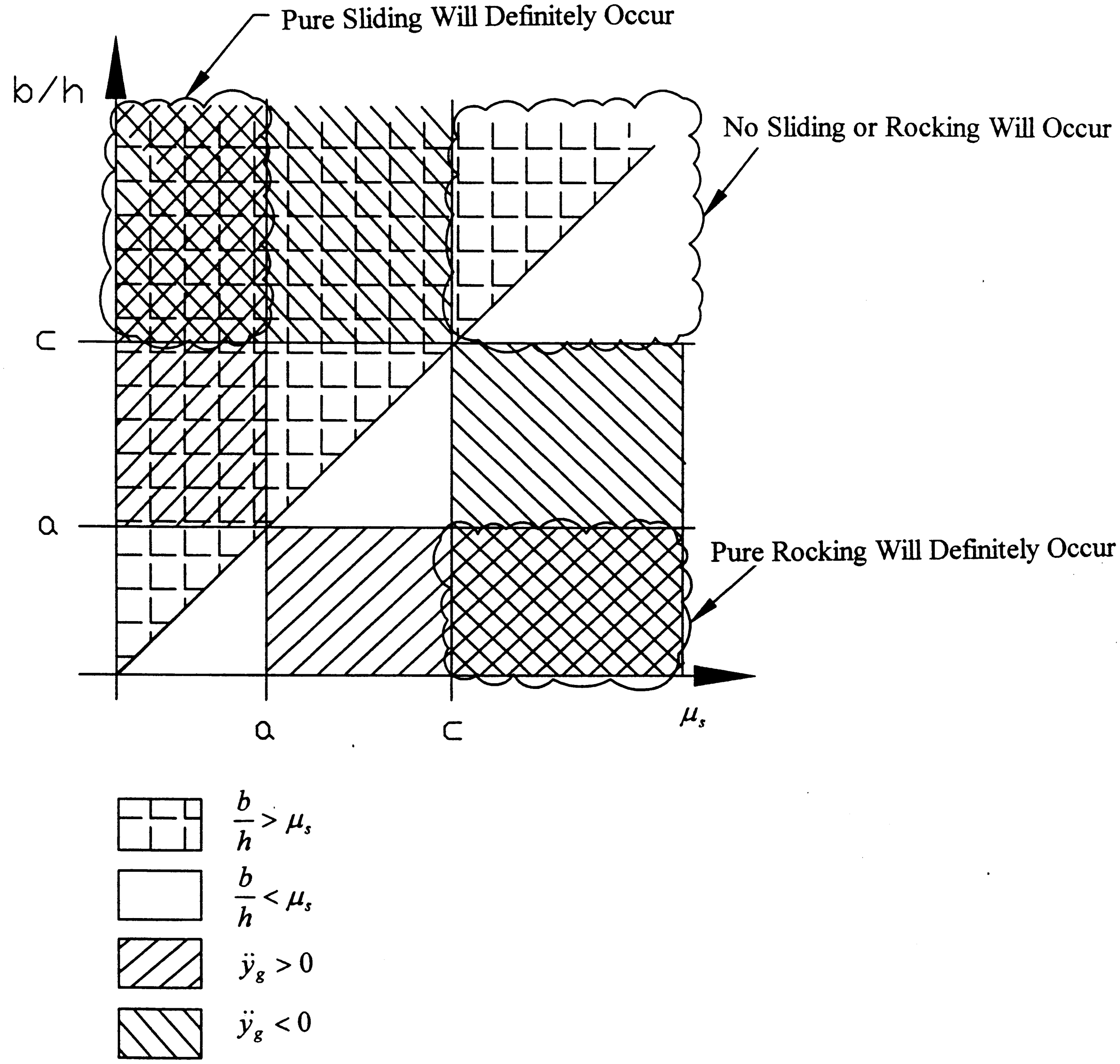


Figure 2.1 Graphical Representation of Motion Types when $\ddot{y}_g > 0$ or $\ddot{y}_g < 0$

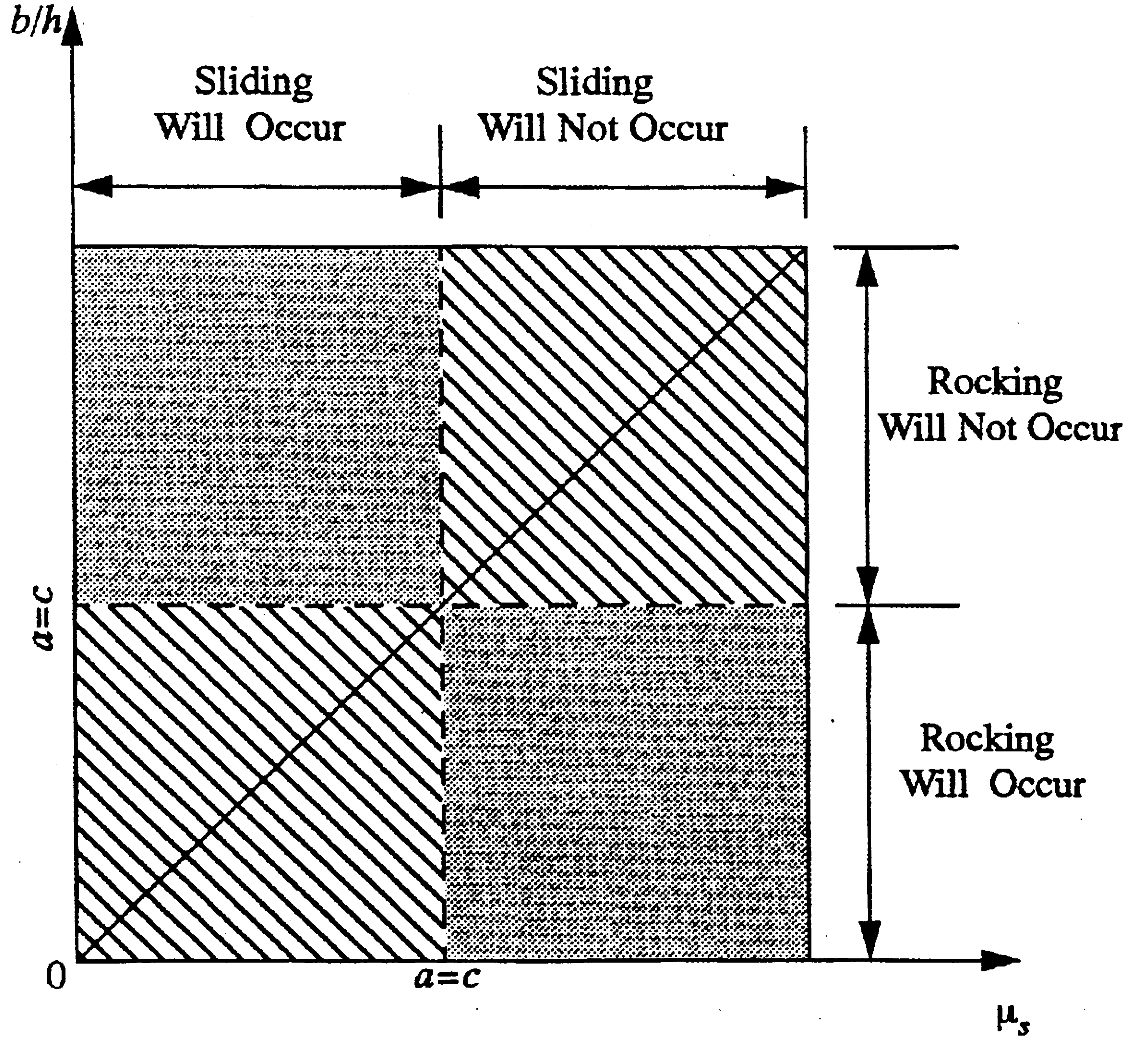


Figure 2.2 Graphical Representation of Motion Types when $\ddot{y}_g = 0$ (Gates and Scawthorn, 1982)

$$(\ddot{x}+\ddot{x}_g)+\mu_d(g+\ddot{y}_g)\,\mathrm{sgn}(\dot{x})=0 \quad (2.14)$$

which is valid when sliding conditions shown in Table 1.1 are satisfied. In the above, $\ddot{x}$ is the block relative acceleration at any instance within a time history and μ_d is the coefficient of dynamic friction.

With equation (2.14) determined to describe the sliding motion of the free-standing rigid block, discrete system solution is performed, as shown in Appendix A, to obtain the analytical solutions shown in Section 2.5. Ninety excitation inputs were generated, as described in Section 2.4. These excitation inputs were scaled down to different horizontal and vertical excitations as the excitation inputs in the discrete system solution. In addition, five dynamic friction coefficients were used as an input parameter in this theoretical solution procedure.

2.4 Generation of Acceleration Time History Inputs

Ninety acceleration time history inputs were generated using SIMQKE, an artificial motion generation program, by inputting a response spectrum, which was generated based on 1997 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures (NEHRP, 1997), into the SIMQKE program. An introduction of the SIMQKE program will be presented in Section 2.4.1, followed by an illustration on generating the response spectrum using the guidelines specified by NEHRP in Section 2.4.2. Finally, some typical acceleration time history inputs, for a horizontal peak ground acceleration (HPGA) of 0.7g, generated by SIMQKE will be presented at the end of this section, as Figures 2.5~2.8.

2.4.1 SIMQKE : An Artificial Motion Generation Program

SIMQKE (Vanmarcke et al., 1976) is a program, written in FORTRAN 77 language, for artificial earthquake motion generation. It has the capabilities of computing a power spectral density function from a specified smooth response spectrum and generating statistically independent artificial acceleration time histories and trying, by iteration, to match the specified response spectrum. The resultant acceleration time history inputs are heavily depend on the response spectrum input to the program. The user's guidelines manual and the SIMQKE program are shown in Appendix B.

2.4.2 Response Spectrum based on 1997 NEHRP Guidelines

The input response spectrum in SIMQKE was generated based on the guidelines in Chapter 4, Ground Motion, of NEHRP Provisions (NEHRP, 1997). According to the 1997 NEHRP, either the general procedure specified in Sec.4.1.2, of 1997 NEHRP, or the site-specific procedure specified in Sec.4.1.3, of 1997 NEHRP, can be used in generating response spectra. In this research, the general procedure was used.

Parameter Determination. In order to generate a response spectrum, two spectra response acceleration parameters need to be determined. They are the Maximum Considered Earthquake (MCE) spectral response acceleration for short periods, S_{MS}, and at one second, S_{M1}, which are adjusted for site class effects to include local site effects. These two parameters are determined according to the following equations to adjust for site class effects :

$$S_{MS} = F_a S_S \tag{2.15}$$

$$S_{M1} = F_v S_1 \tag{2.16}$$

in which F_a, F_v, S_S and S_1 are parameters determined according to Tables 2.1 and 2.2.

Due to the fact that the soil properties are not known in sufficient detail to determine the Site Class, Site Class D in Sec. 4.1.2.1 of 1997 NEHRP is used. The value of S_S is taken to be three and the value of S_1 is taken to be one for the purpose of making the S_{DS} to be 2.0g by referring to equation (2.17), which will be illustrated later in this section. S_S and S_1 can be chosen randomly to create a S_{DS} of 2.0g because they are independent.

After taken into account the site class effect, S_{MS} and S_{M1} are scaled to design values according to the equations below :

$$S_{DS} = \frac{2}{3} S_{MS} \tag{2.17}$$

$$S_{D1} = \frac{2}{3} S_{M1} \tag{2.18}$$

where S_{DS} is the design spectral response acceleration at short periods, and S_{D1} is the design spectral response acceleration at one second period.

General Procedure Response Spectrum. With all the above parameters determined, a design response spectrum curve can be developed as indicated in Figure 2.3 (NEHRP, 1997), which is explained in details as follows :

1. For periods less than or equal to T_o, the design spectral response acceleration, S_a, is given by the following equation :

$$S_a = 0.6 \frac{S_{DS}}{T_o} T + 0.4 S_{DS} \tag{2.19}$$

2. For periods greater than or equal to $T_o (T_o = 0.2 S_{D1} / S_{DS})$ and less than or equal to $T_S (T_S = S_{D1} / S_{DS})$, the design spectral response acceleration, S_a, is taken as equal to S_{DS}.

3. For periods greater than T_S, the design spectral response acceleration, S_a, is taken as given by the following equation :

Table 2.1 Values of F_a as a Function of Site Class and Mapped Short-Period Maximum Considered Earthquake Spectral Acceleration (NEHRP, 1997)

Site Class	**Mapped Maximum Considered Earthquake Spectral Response Acceleration at Short Periods**				
	$S_S \leq 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	*a*
F	*a*	*a*	*a*	*a*	*a*

NOTE: Use straight line interpolation for intermediate values of S_S.

[a] Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

Table 2.2 Values of F_v as a Function of Site Class and Mapped 1 Second Period Maximum Considered Earthquake Spectral Acceleration (NEHRP, 1997)

Site Class	**Mapped Maximum Considered Earthquake Spectral Response Acceleration at 1 Second Periods**				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	*a*
F	*a*	*a*	*a*	*a*	*a*

NOTE: Use straight line interpolation for intermediate values of S_1.

[a] Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

$$S_a = \frac{S_{D1}}{T} \tag{2.20}$$

The generated response spectrum based on the general procedure method specified above is presented in Figure 2.4.

2.5 Summary of Analytical Results

By determining the equation of sliding motion and solving it numerically, displacement and acceleration time histories for the sliding block are obtained. There are ninety different acceleration time history inputs, each scaled to have eight different values of HPGA, ranging from 0.3g~1.0g, with 0.1g increment.

Each of these eight horizontal time histories is combined with four different vertical acceleration inputs, which are scaled to 0,1/4,1/3,and ½ of the horizontal acceleration inputs, one at each time as the inputs for the analytical solutions. The ninety time histories are generated by SIMQKE as discussed in Section 2.4. Table 2.3 illustrates the time history inputs in a more systematical way.

Five different coefficients of dynamic friction, namely, 0.1,0.2, 0.21,0.3 and 0.4, are used to evaluate the frictional effect on the performance of the free-standing rigid block under seismic loading. The value of 0.21 is added to compare analytical and experimental results after it is determined experimentally, as described in Chapter 3. All of the time history combinations shown in Table 2.3 are repeated five times for the five different coefficients of dynamic friction.

2.5.1 Sliding Performance of Free-Standing Rigid Block

Only three parameters affect the pure sliding response of the free-standing rigid block once sliding has been initiated: the peak horizontal and vertical excitations, and the coefficient of dynamic friction. Figures 2.9~2.13 show relative displacement and absolute acceleration time histories from five typical time history inputs for the coefficient of dynamic friction equal to 0.21. The HPGA considered here is 0.7 g, with a vertical peak ground acceleration (VPGA) of 0.23g, which is 1/3 of the HPGA.

The block average relative peak displacements, which are obtained from the ninety peak displacements obtained from the ninety acceleration time history inputs for each of the combination of HPGA and VPGA for values of μ_d equal to 0.1,0.2,0.3 and 0.4 are shown in Tables 2.4, 2.5, 2.6 and 2.7, respectively. In addition, the corresponding average absolute accelerations at which threshold displacements occur are also shown in these tables.

2.5.2 Analytical Fragility Curves

There are eight different relative displacement failure thresholds considered in the analysis. They are relative displacements of 0.1 inch, 0.2 inch, 0.5 inch, 0.75 inch, 1 inch, 2 inches, 2.5 inches and 3 inches. Consideration of the combination of the relative threshold displacement and the absolute acceleration at which threshold relative displacement occurs as the failure threshold for constructing the fragility curves for a specific coefficient of dynamic friction turns out to be unnecessary due to the analytical results obtained, which will be analyzed in Section 2.5.3.

Table 2.3 Number of Time History Inputs for Each Dynamic Friction Coefficient.

Number of runs for each combination of HPGA and VPGA for different dynamic friction coefficients.

	Horizontal PGA, g							
Proportional Constants for Vertical PGA	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
0	90	90	90	90	90	90	90	90
1/4	90	90	90	90	90	90	90	90
1/3	90	90	90	90	90	90	90	90
1/2	90	90	90	90	90	90	90	90
TOTAL	**360**	**360**	**360**	**360**	**360**	**360**	**360**	**360**

Table 2.4 Summary of Analytical Solution for $\mu_d = 0.1$

Average Peak Displacement, inch

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.871877	1.963674	3.316905	4.84207	6.445563	8.142414	9.858388	11.60008
1/4	0.921384	2.104202	3.569039	5.199697	6.942406	8.789935	10.58951	12.36227
1/3	0.962143	2.228275	3.766617	5.496397	7.344542	9.245172	11.12079	12.92271
1/2	1.101465	2.557681	4.359464	6.321035	8.379994	10.40032	12.41299	14.39003

Average Acceleration at which Peak Displacement Occurs, g

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.100495	0.101066	0.102031	0.103067	0.104109	0.105126	0.106381	0.107264
1/4	0.100765	0.102114	0.103406	0.10445	0.106927	0.108995	0.109897	0.111781
1/3	0.100985	0.102439	0.104555	0.105821	0.108929	0.11122	0.112196	0.11464
1/2	0.101406	0.103789	0.106686	0.109926	0.11409	0.115631	0.117889	0.121681

Table 2.5 Summary of Analytical Solution for $\mu_d = 0.2$

Average Peak Displacement, inch

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.050998	0.320753	0.911822	1.74912	2.768411	3.94449	5.252241	6.632879
1/4	0.059841	0.385287	1.111411	2.206614	3.549732	5.142256	6.866747	8.726916
1/3	0.070863	0.440108	1.280512	2.538945	4.110351	5.944972	7.930333	10.05775
1/2	0.095742	0.586989	1.728973	3.43085	5.560253	8.052521	10.74478	13.52066

Average Acceleration at which Peak Displacement Occurs, g

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.200027	0.200162	0.200425	0.20097	0.201442	0.202171	0.202678	0.203965
1/4	0.198913	0.199432	0.200514	0.203377	0.205114	0.20743	0.210553	0.212546
1/3	0.197997	0.199118	0.200961	0.204043	0.207114	0.208798	0.212754	0.215389
1/2	0.195402	0.199043	0.201428	0.204238	0.208484	0.213552	0.220483	0.224917

Table 2.6 Summary of Analytical Solution for $\mu_d = 0.3$

Average Peak Displacement, inch

k	*Horizontal Peak Ground Acceleration, g* 0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0	0.032062	0.16661	0.484541	1.022189	1.736777	2.622881	3.610839
1/4	0.002776	0.048267	0.238398	0.710567	1.535561	2.702194	4.156455	5.796023
1/3	0.003739	0.0572	0.2947	0.875968	1.898381	3.350913	5.096362	7.153305
1/2	0.006102	0.085666	0.438896	1.288715	2.763771	4.852727	7.406389	10.32595

Average Acceleration at which Peak Displacement Occurs, g

k	*Horizontal Peak Ground Acceleration, g* 0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.300000	0.300013	0.300097	0.300197	0.300461	0.300821	0.30136	0.301971
1/4	0.300016	0.299007	0.298809	0.299678	0.301386	0.303952	0.30624	0.309779
1/3	0.299980	0.294329	0.295592	0.299129	0.301413	0.303394	0.305485	0.312039
1/2	0.299978	0.292087	0.294498	0.299552	0.298781	0.301419	0.308011	0.314566

Table 2.7 Summary of Analytical Solution for $\mu_d = 0.4$

Average Peak Displacement, inch

k	*Horizontal Peak Ground Acceleration, g* 0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0	0	0.027903	0.106349	0.294062	0.656252	1.177117	1.827146
1/4	0	0.006243	0.048001	0.192107	0.535539	1.179736	2.147652	3.48398
1/3	0	0.007759	0.062028	0.24896	0.695578	1.535042	2.761142	4.461842
1/2	0	0.014172	0.096248	0.39307	1.092654	2.33019	4.173504	6.637165

Average Acceleration at which Peak Displacement Occurs, g

k	*Horizontal Peak Ground Acceleration, g* 0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.300000	0.400000	0.400013	0.400051	0.400132	0.400224	0.400508	0.400772
1/4	0.300000	0.396667	0.396252	0.397343	0.396613	0.399183	0.401645	0.40217
1/3	0.300000	0.396688	0.396227	0.39852	0.394437	0.398538	0.402789	0.402723
1/2	0.300000	0.395433	0.395374	0.392508	0.39626	0.396192	0.399953	0.400695

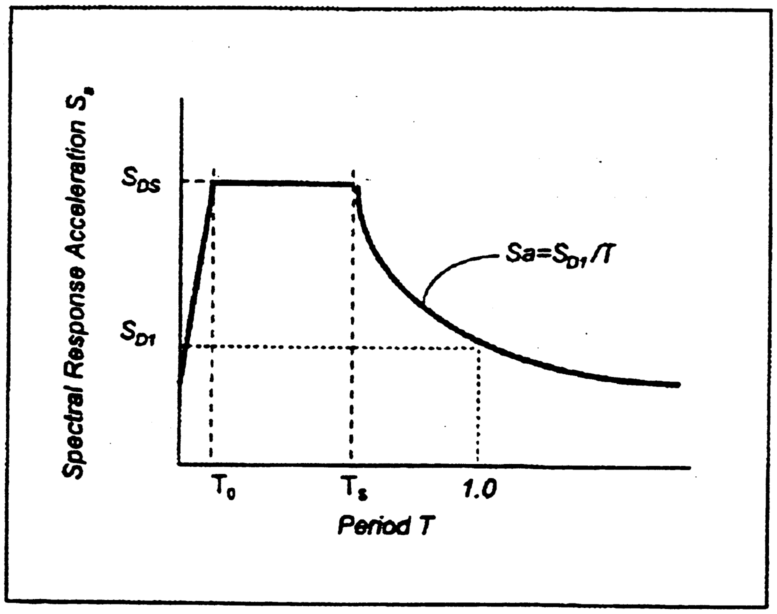


Figure 2.3 General Procedure Response Spectrum (NEHRP, 1997)

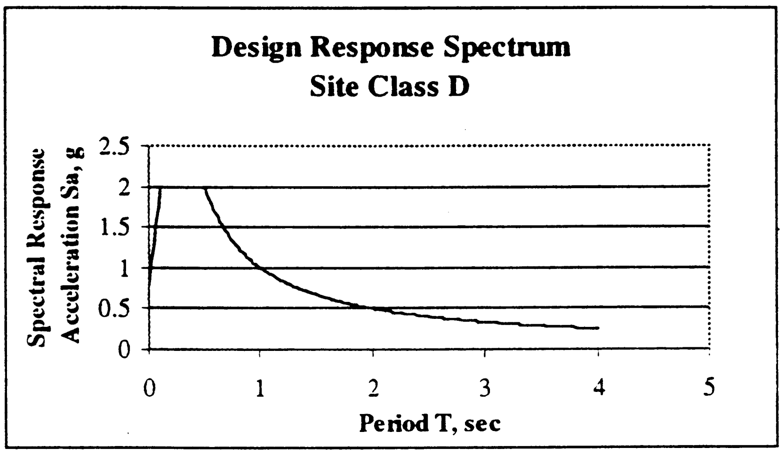


Figure 2.4 Generated Response Spectrum

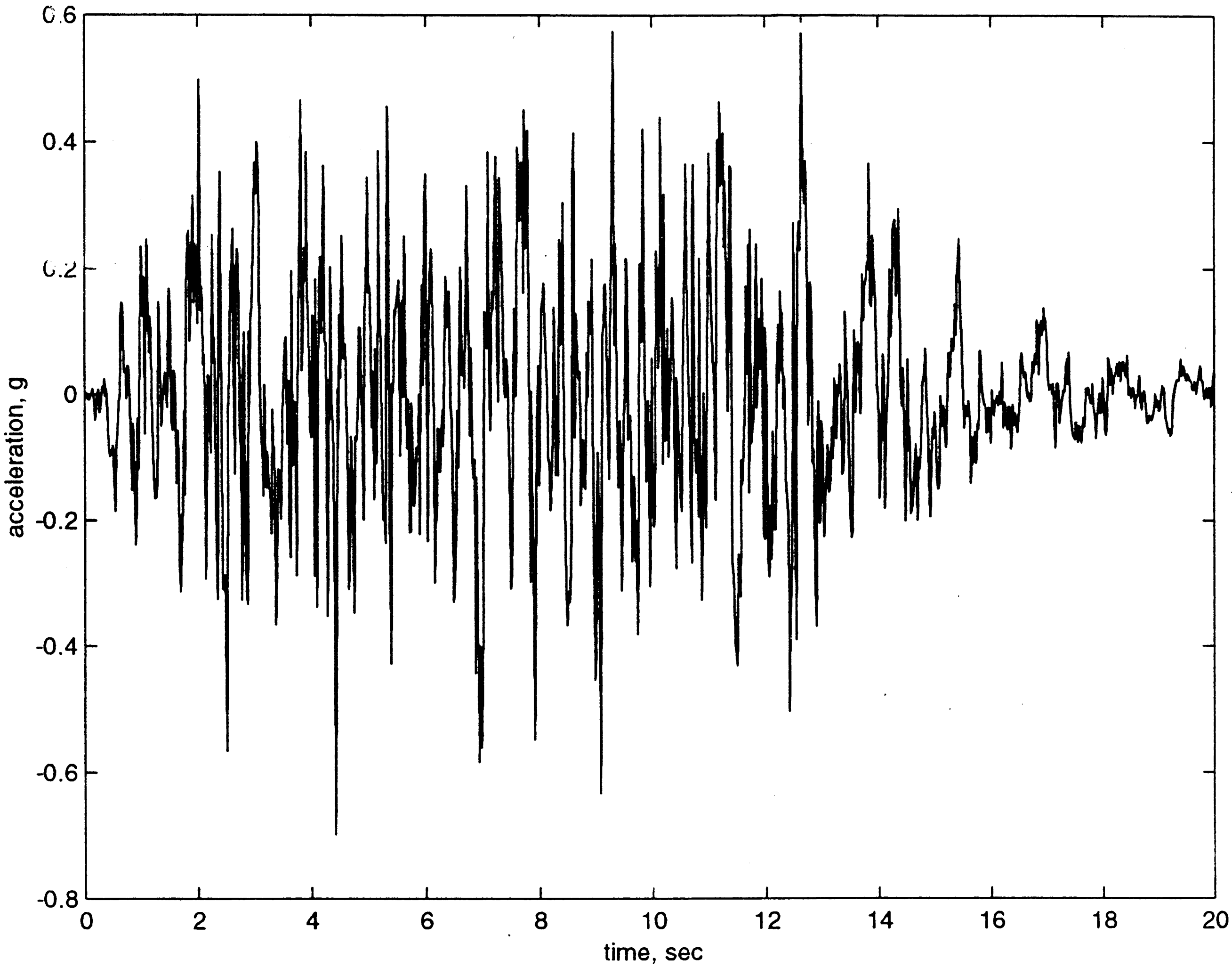


Figure 2.5 Generated Time History Input I : HPGA = 0.7g

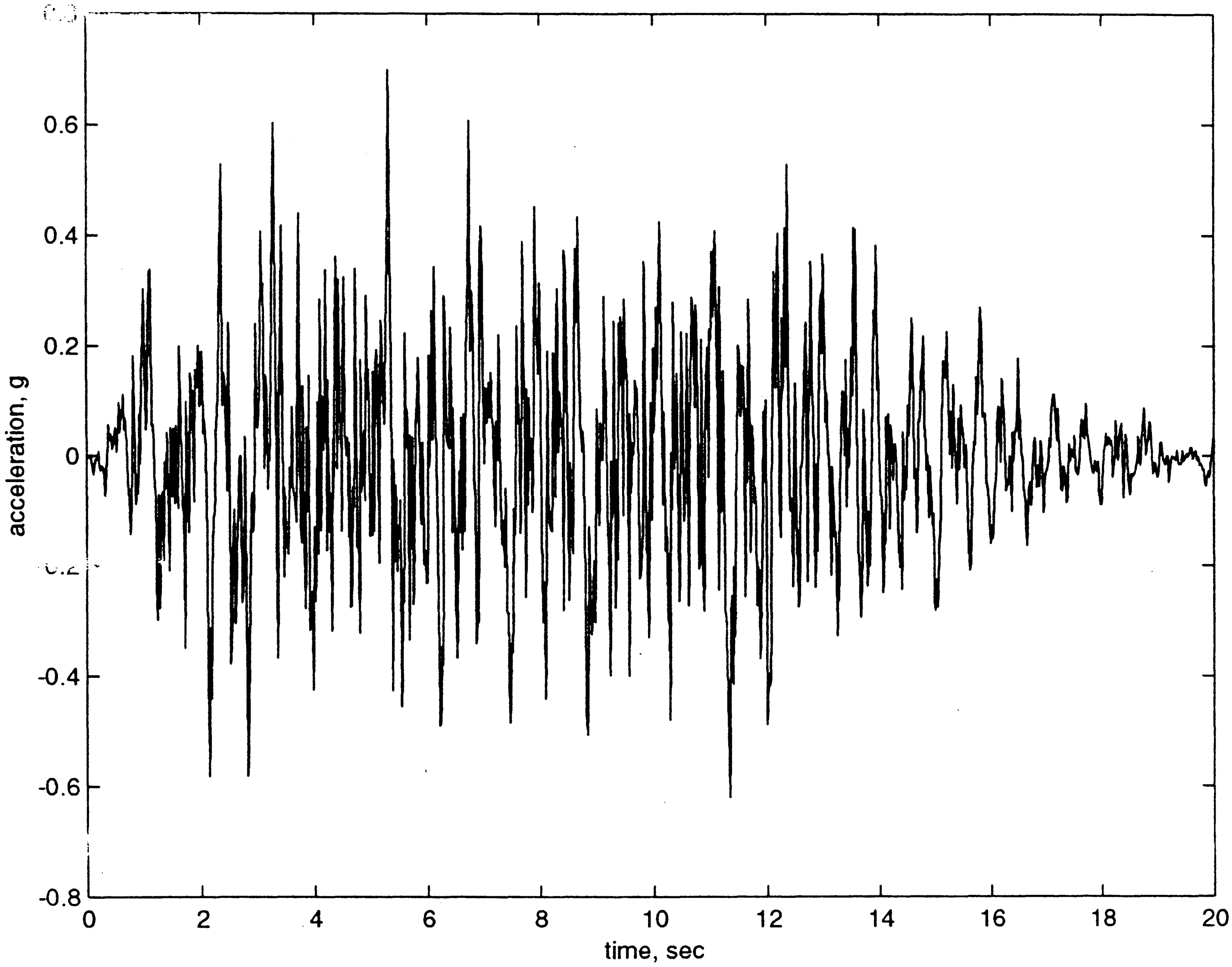


Figure 2.6 Generated Time History Input II : HPGA = 0.7g

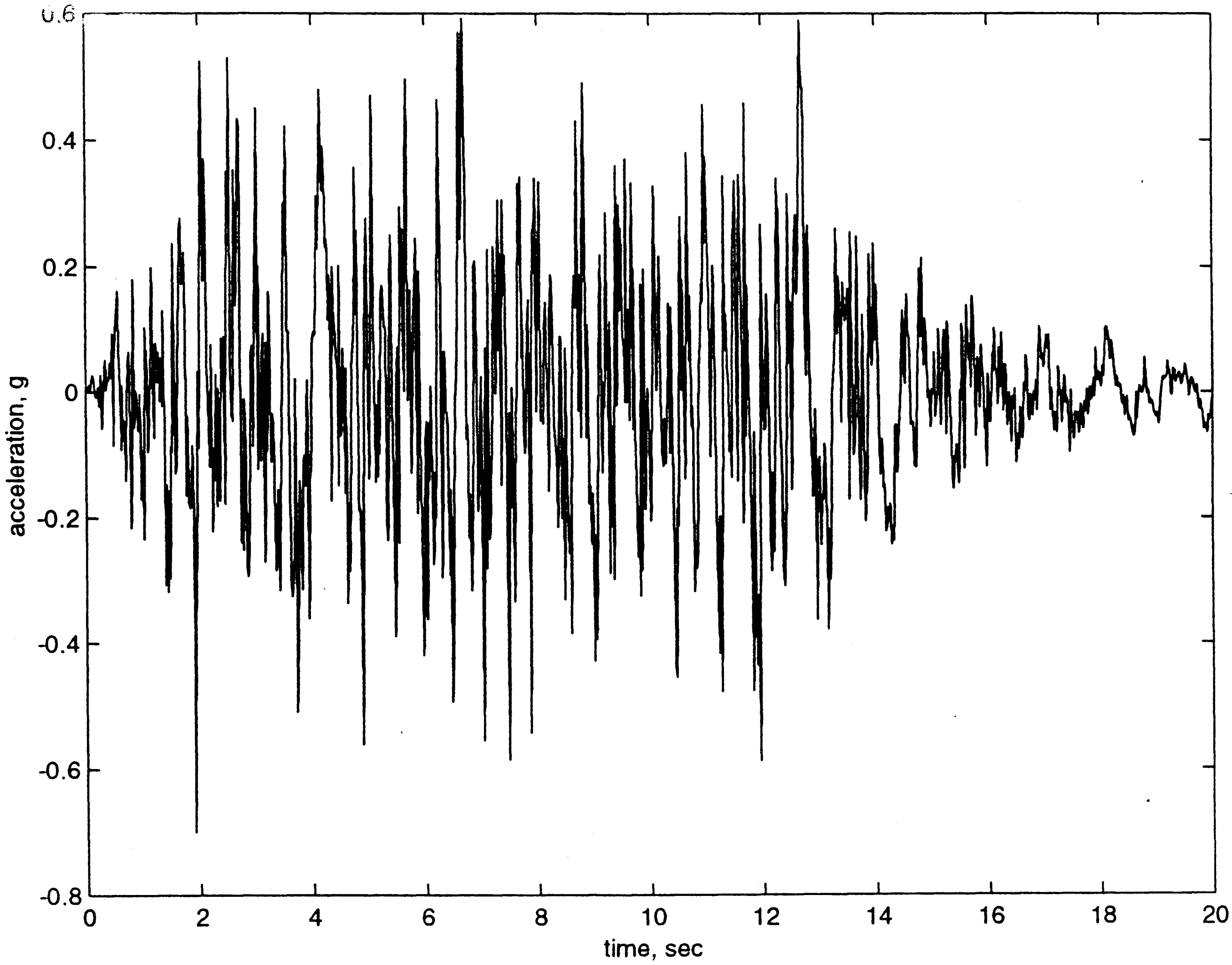


Figure 2.7 Generated Time History Input III : HPGA = 0.7g

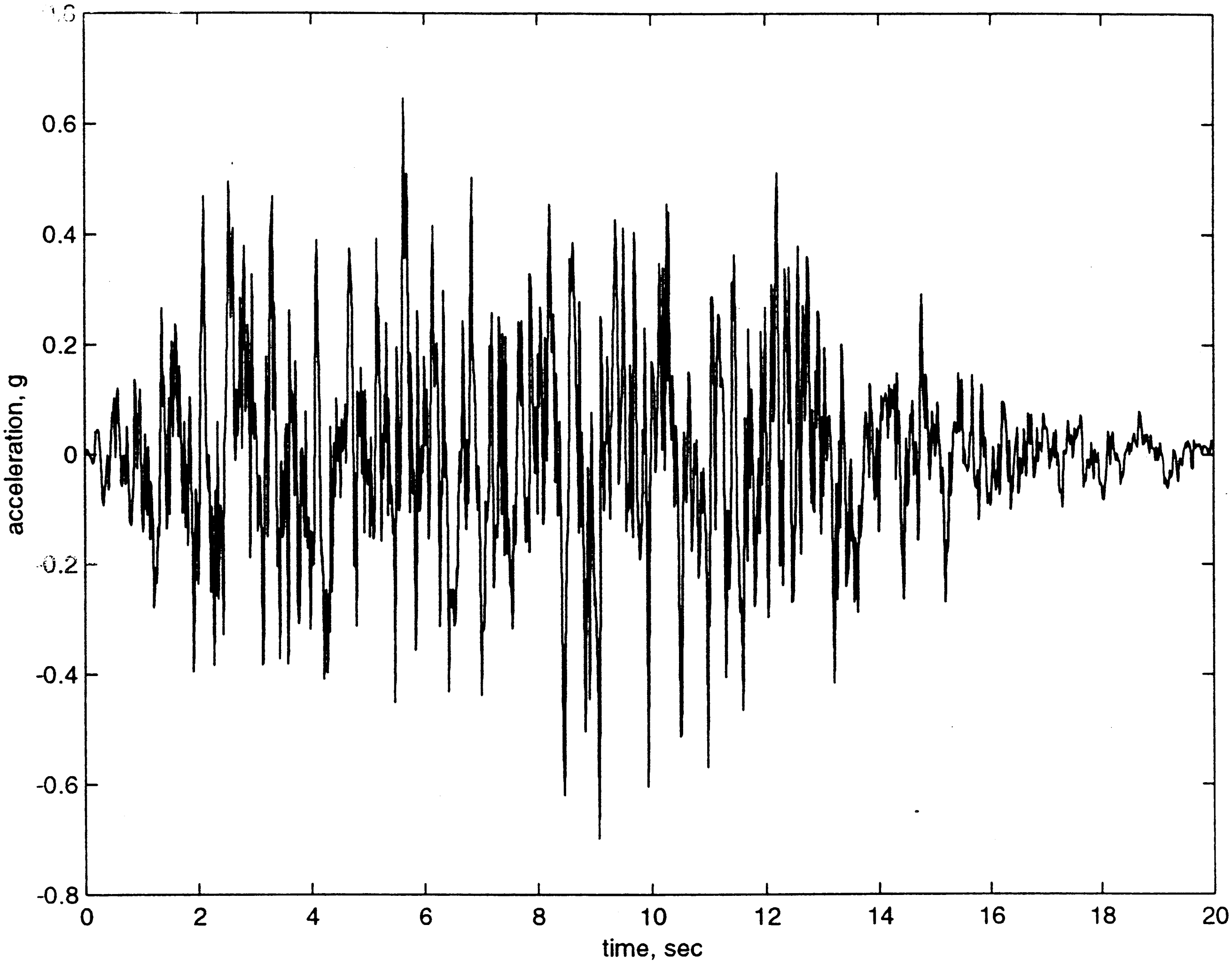


Figure 2.8 Generated Time History Input IV : HPGA = 0.7g

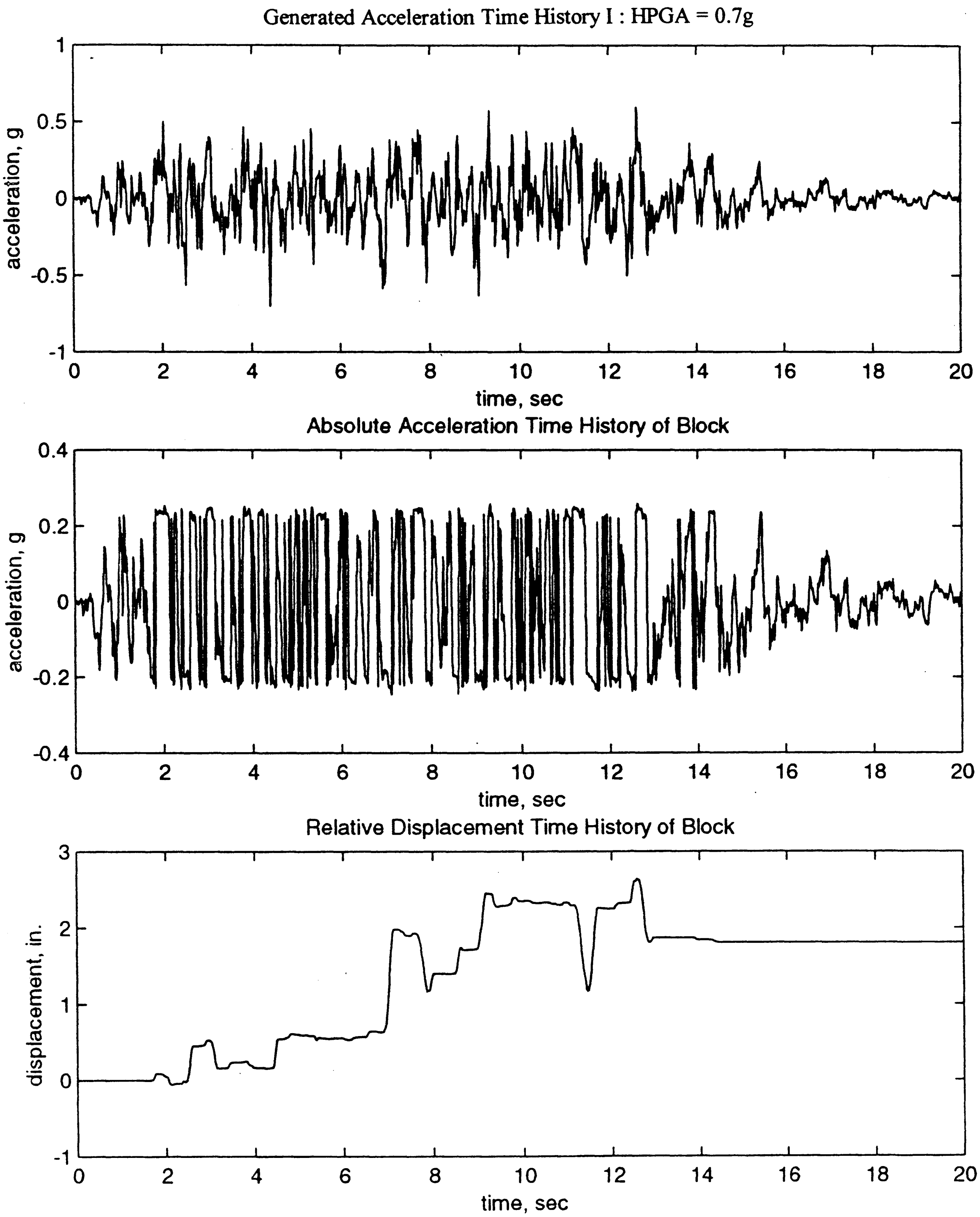


Figure 2.9 Analytical Solution I

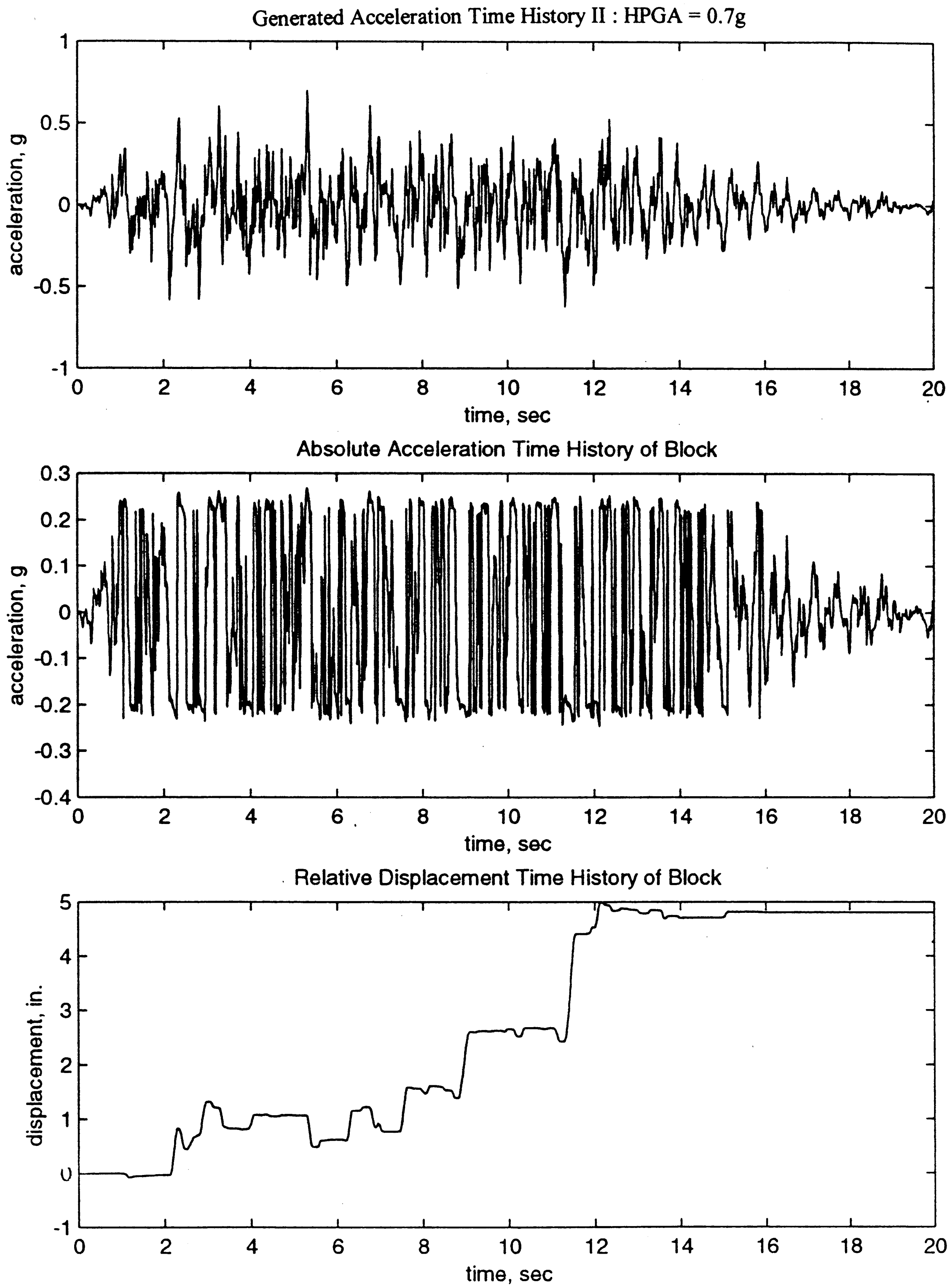


Figure 2.10 Analytical Solution II

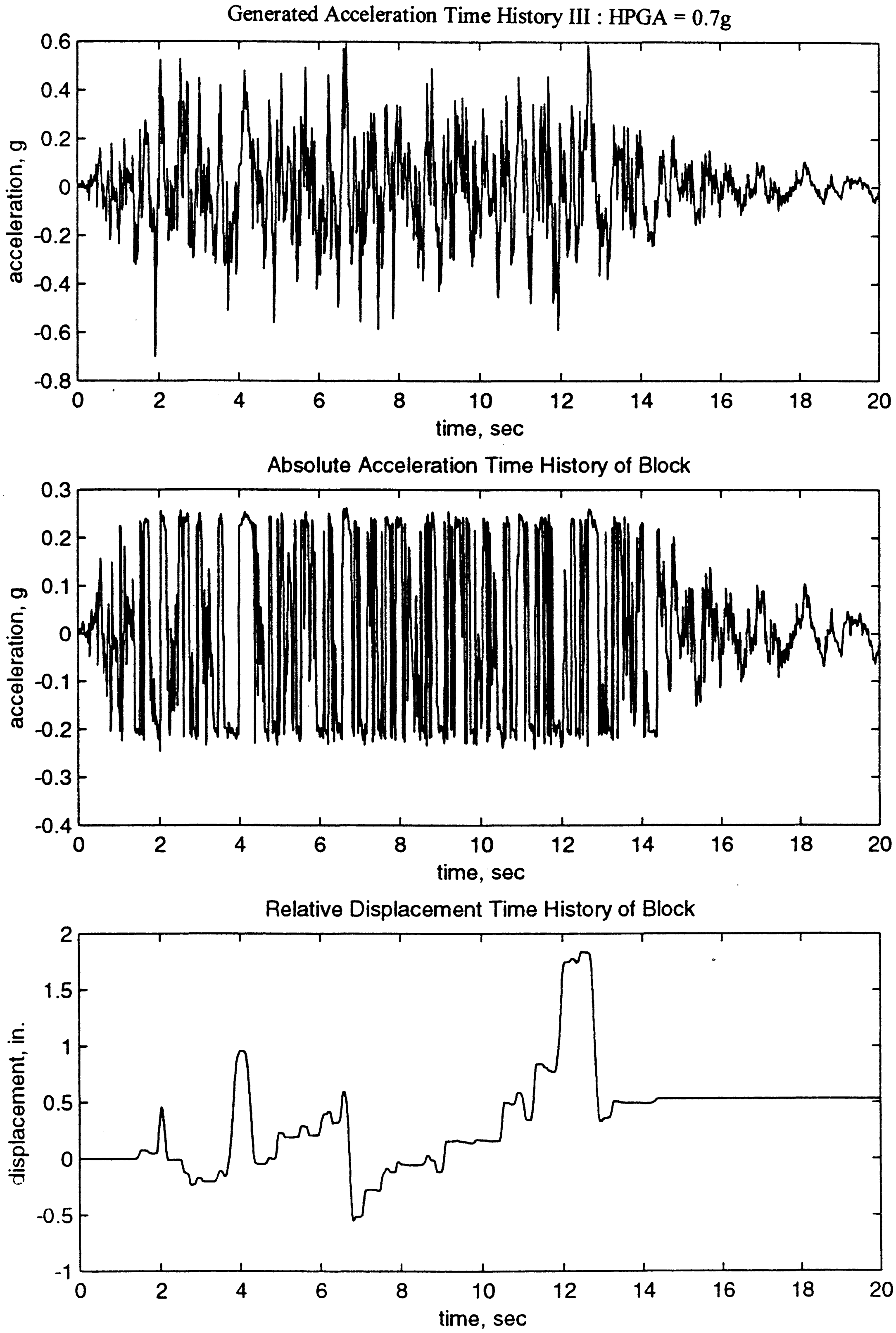


Figure 2.11 Analytical Solution III

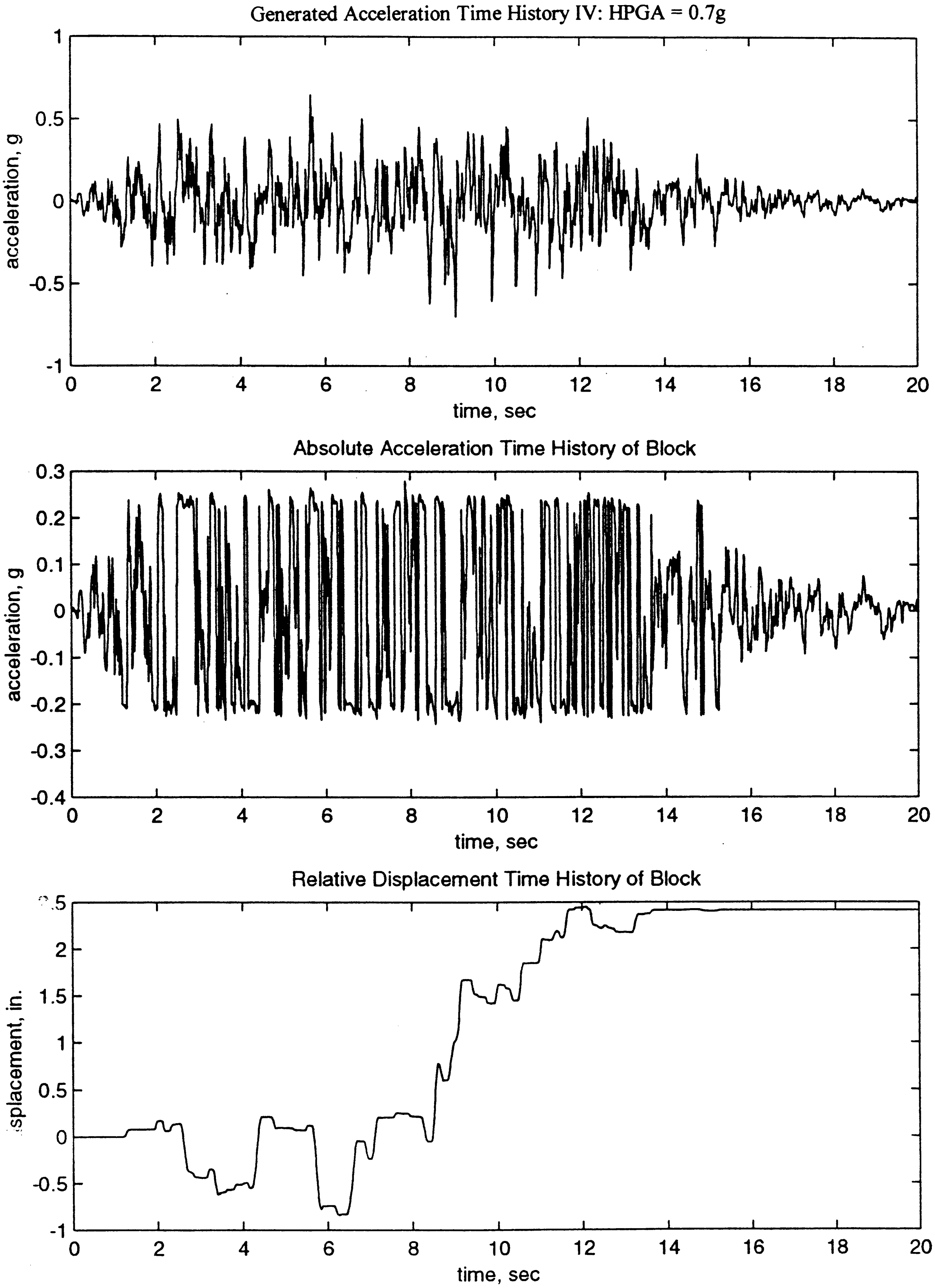


Figure 2.12 Analytical Solution IV

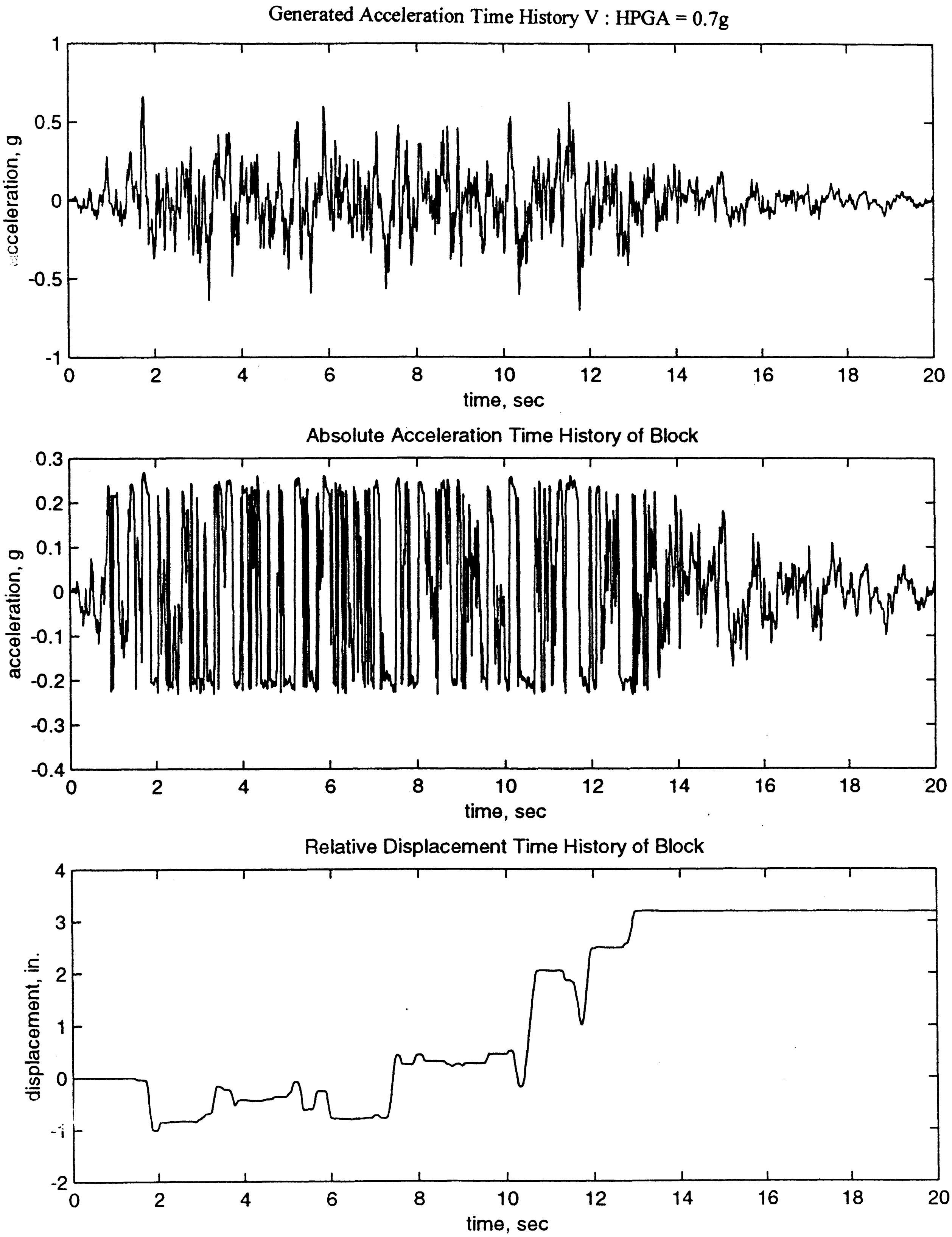


Figure 2.13 Analytical Solution V

The fragility curves for failure thresholds of 1 inch and 2 inches, for the four different coefficients of dynamic friction, (0.1,0.2,0.3,0.4) are shown in Figures 2.15~2.22. A comprehensive presentation of the probabilities of failure for all of the failure thresholds considered are shown in Tables 2.8~2.11.

2.5.3 Discussion of Results

There are three sensitive parameters that determine the sliding performance of a free-standing block-type equipment during an earthquake. They are the peak horizontal acceleration, peak vertical acceleration and coefficient of dynamic friction. As can be seen in Tables 2.4~2.7, every combination of HPGA and VPGA inputs has an almost same effect on the absolute acceleration for a given coefficient of dynamic friction. Thus, it is unnecessary to construct fragility curves for the failure threshold of the combination of relative displacement and the absolute acceleration at which threshold displacement occurs for a specific dynamic friction coefficient, as the fragility will always be either one or zero. On the other hand, as expected, the peak displacement increases as the vertical and horizontal peak accelerations increase.

As can be seen from the results, as k=0, the absolute peak accelerations for each peak ground acceleration are almost exactly the same and they are almost perfectly matched with the coefficient of dynamic friction. As for other k values, the absolute acceleration increases as the $k\ddot{x}_g$ value increases, generally, but not significantly.

Although the magnitudes of HPGA and VPGA have no significant impact on the absolute acceleration at which threshold displacement occurs, but the coefficient of dynamic friction has. As the coefficient of dynamic friction increases, the peak displacement decreases, while the absolute acceleration increases, as shown in Figure 2.14.

As for the fragility curves, as the coefficient of dynamic friction increases, the probability of failure for a free-standing block-type equipment decreases under a specific threshold. As the vertical acceleration increases, under a specific horizontal acceleration, the free-standing block is more prone to failure.

Table 2.8 Analytical Probabilities of Failure for $\mu_d = 0.1$

k = 0

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	1	1	0.833333	0.588889	0.277778	0.022222	0	0
0.4	1	1	1	0.988889	0.933333	0.455556	0.177778	0.088889
0.5	1	1	1	1	1	0.888889	0.677778	0.5
0.6	1	1	1	1	1	0.988889	0.966667	0.855556
0.7	1	1	1	1	1	1	1	0.988889
0.8	1	1	1	1	1	1	1	1
0.9	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1

k = 1/4

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	1	1	0.866667	0.522222	0.322222	0.011111	0.011111	0
0.4	1	1	1	1	0.922222	0.455556	0.3	0.177778
0.5	1	1	1	1	1	0.9	0.722222	0.566667
0.6	1	1	1	1	1	1	0.977778	0.922222
0.7	1	1	1	1	1	1	1	1
0.8	1	1	1	1	1	1	1	1
0.9	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1

k = 1/3

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	1	1	0.877778	0.533333	0.411111	0.022222	0.011111	0
0.4	1	1	1	1	0.966667	0.488889	0.333333	0.222222
0.5	1	1	1	1	1	0.911111	0.777778	0.6
0.6	1	1	1	1	1	1	0.966667	0.933333
0.7	1	1	1	1	1	1	1	1
0.8	1	1	1	1	1	1	1	1
0.9	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1

k = 1/2

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	1	1	0.877778	0.666667	0.488889	0.066667	0.011111	0
0.4	1	1	1	0.977778	0.977778	0.611111	0.477778	0.322222
0.5	1	1	1	1	1	0.944444	0.877778	0.766667
0.6	1	1	1	1	1	1	0.977778	0.911111
0.7	1	1	1	1	1	1	0.988889	0.988889
0.8	1	1	1	1	1	1	1	1
0.9	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1

Table 2.9 Analytical Probabilities of Failure for $\mu_d = 0.2$

k = 0

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0.1	0	0	0	0	0	0	0
0.4	0.944444	0.744444	0.144444	0	0	0	0	0
0.5	1	1	0.8	0.622222	0.322222	0.033333	0	0
0.6	1	1	1	0.944444	0.833333	0.3	0.122222	0.077778
0.7	1	1	1	1	0.977778	0.711111	0.488889	0.355556
0.8	1	1	1	1	1	0.944444	0.822222	0.655556
0.9	1	1	1	1	1	0.988889	0.955556	0.9
1	1	1	1	1	1	1	0.988889	0.988889

k = 1/4

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0.144444	0.022222	0	0	0	0	0	0
0.4	0.988889	0.822222	0.211111	0.077778	0.011111	0	0	0
0.5	1	1	0.9	0.677778	0.488889	0.1	0.011111	0.011111
0.6	1	1	1	0.966667	0.9	0.5	0.366667	0.222222
0.7	1	1	1	1	0.977778	0.833333	0.622222	0.533333
0.8	1	1	1	1	1	0.977778	0.933333	0.822222
0.9	1	1	1	1	1	1	1	0.966667
1	1	1	1	1	1	1	1	1

k = 1/3

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0.188889	0.033333	0	0	0	0	0	0
0.4	0.988889	0.8	0.355556	0.122222	0.044444	0	0	0
0.5	1	1	0.9	0.733333	0.6	0.144444	0.077778	0.011111
0.6	1	1	1	0.977778	0.877778	0.611111	0.466667	0.311111
0.7	1	1	1	1	1	0.866667	0.811111	0.7
0.8	1	1	1	1	1	0.955556	0.911111	0.888889
0.9	1	1	1	1	1	1	0.977778	0.944444
1	1	1	1	1	1	1	1	1

k = 1/2

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0.377778	0.1	0	0	0	0	0	0
0.4	0.988889	0.955556	0.544444	0.266667	0.122222	0	0	0
0.5	1	1	0.977778	0.933333	0.777778	0.333333	0.155556	0.1
0.6	1	1	1	1	0.977778	0.8	0.7	0.588889
0.7	1	1	1	1	1	0.966667	0.955556	0.855556
0.8	1	1	1	1	1	1	0.977778	0.966667
0.9	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1

Table 2.10 Analytical Probabilities of Failure for $\mu_d = 0.3$

k = 0

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0.011111	0	0	0	0	0	0	0
0.5	0.777778	0.3	0	0	0	0	0	0
0.6	1	0.888889	0.377778	0.144444	0.055556	0	0	0
0.7	1	1	0.888889	0.688889	0.444444	0.044444	0	0
0.8	1	1	0.966667	0.933333	0.833333	0.255556	0.144444	0.077778
0.9	1	1	1	1	0.977778	0.666667	0.466667	0.288889
1	1	1	1	1	1	0.866667	0.755556	0.6

k = 1/4

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0.1	0.011111	0	0	0	0	0	0
0.5	0.822222	0.5	0.077778	0.011111	0	0	0	0
0.6	1	0.933333	0.588889	0.388889	0.222222	0	0	0
0.7	1	1	0.944444	0.844444	0.688889	0.255556	0.133333	0.088889
0.8	1	1	1	0.977778	0.911111	0.644444	0.511111	0.377778
0.9	1	1	1	1	0.988889	0.855556	0.8	0.688889
1	1	1	1	1	1	0.966667	0.877778	0.866667

k = 1/3

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0.133333	0.011111	0	0	0	0	0	0
0.5	0.9	0.633333	0.133333	0.033333	0	0	0	0
0.6	1	0.988889	0.777778	0.522222	0.333333	0.022222	0	0
0.7	1	1	0.988889	0.933333	0.844444	0.411111	0.222222	0.133333
0.8	1	1	1	0.988889	0.977778	0.788889	0.7	0.533333
0.9	1	1	1	1	1	0.966667	0.877778	0.788889
1	1	1	1	1	1	0.988889	0.966667	0.966667

k = 1/2

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0.322222	0.055556	0	0	0	0	0	0
0.5	0.988889	0.888889	0.311111	0.1	0.033333	0	0	0
0.6	1	1	0.988889	0.855556	0.655556	0.122222	0.022222	0
0.7	1	1	1	1	0.988889	0.733333	0.566667	0.4
0.8	1	1	1	1	1	0.988889	0.955556	0.877778
0.9	1	1	1	1	1	0.988889	0.988889	0.988889
1	1	1	1	1	1	1	1	1

Table 2.11 Analytical Probabilities of Failure for $\mu_d = 0.4$

k = 0

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0
0.5	0.011111	0	0	0	0	0	0	0
0.6	0.422222	0.088889	0	0	0	0	0	0
0.7	0.933333	0.666667	0.122222	0	0	0	0	0
0.8	1	0.944444	0.666667	0.333333	0.155556	0	0	0
0.9	1	1	0.922222	0.744444	0.555556	0.1	0.022222	0
1	1	1	1	0.966667	0.822222	0.333333	0.166667	0.122222

k = 1/4

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0
0.5	0.066667	0.011111	0	0	0	0	0	0
0.6	0.711111	0.377778	0.033333	0	0	0	0	0
0.7	0.966667	0.9	0.444444	0.188889	0.1	0	0	0
0.8	1	0.988889	0.888889	0.688889	0.566667	0.122222	0.044444	0
0.9	1	1	0.977778	0.933333	0.911111	0.488889	0.322222	0.188889
1	1	1	1	0.988889	0.988889	0.811111	0.7	0.577778

k = 1/3

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0
0.5	0.188889	0.011111	0	0	0	0	0	0
0.6	0.855556	0.511111	0.1	0.011111	0	0	0	0
0.7	1	0.966667	0.655556	0.4	0.177778	0	0	0
0.8	1	1	0.988889	0.9	0.755556	0.211111	0.111111	0.044444
0.9	1	1	1	0.988889	0.966667	0.733333	0.533333	0.366667
1	1	1	1	1	1	0.944444	0.9	0.788889

k = 1/2

Maximum Sliding Distance, in.

HPGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.3	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0
0.5	0.355556	0.077778	0	0	0	0	0	0
0.6	0.988889	0.788889	0.255556	0.088889	0.011111	0	0	0
0.7	1	1	0.955556	0.733333	0.522222	0.055556	0	0
0.8	1	1	1	1	0.988889	0.588889	0.344444	0.2
0.9	1	1	1	1	1	0.988889	0.922222	0.8
1	1	1	1	1	1	1	1	0.988889

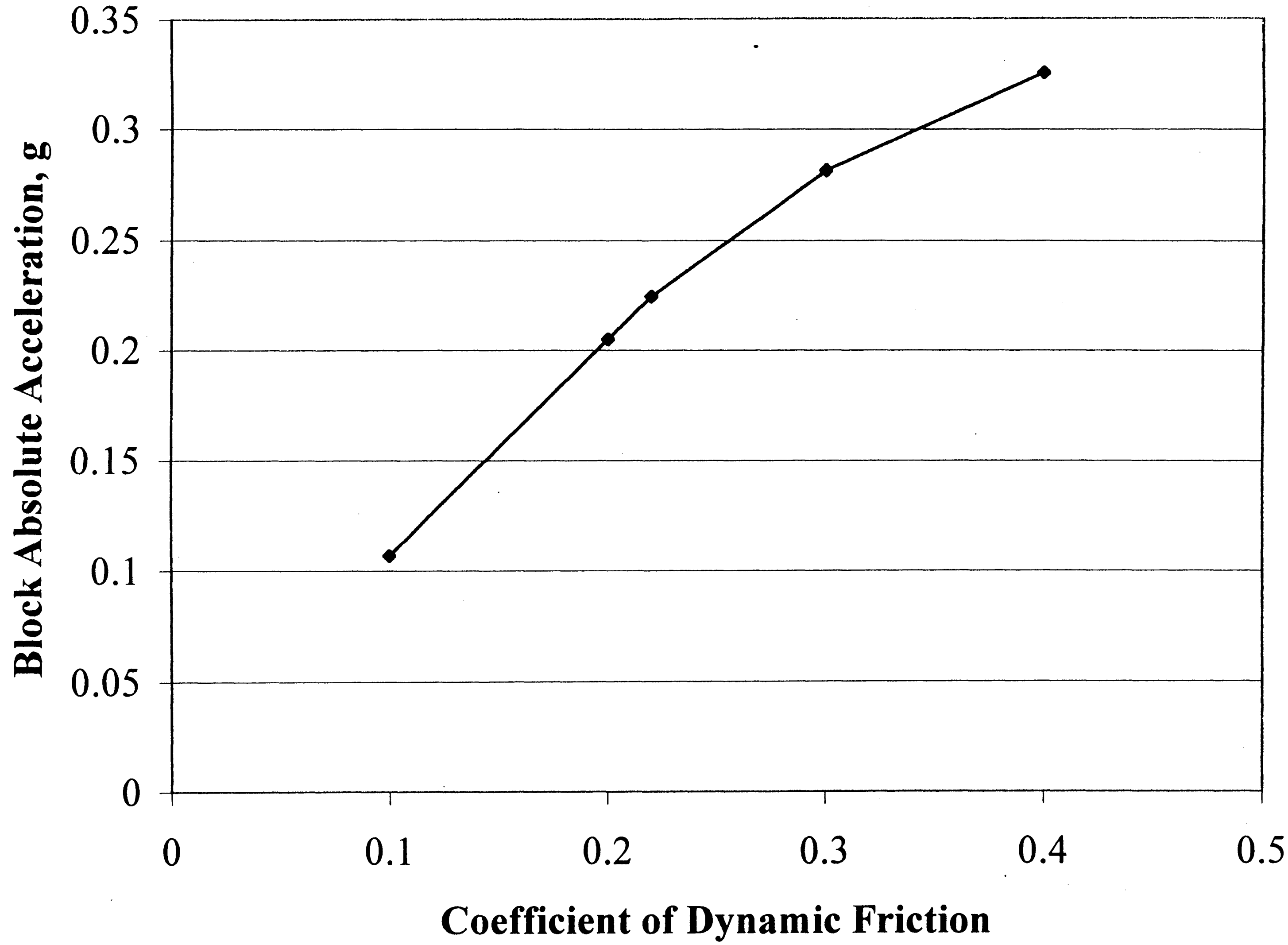


Figure 2.14 Effect of Dynamic Friction Coefficient on the Acceleration-at-which-Threshold-Displacement-Occur

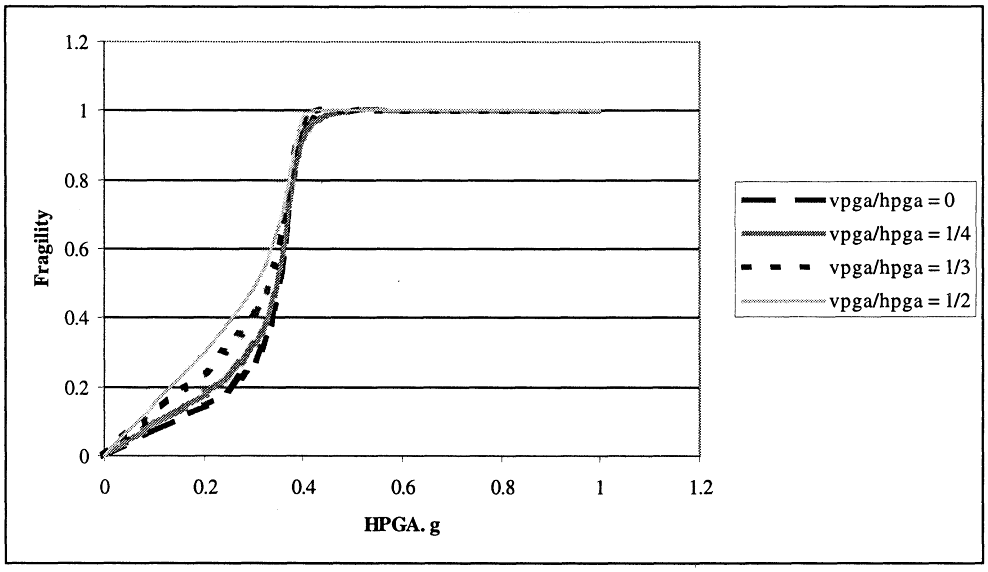


Figure 2.15 Fragility Curves for $\mu_d = 0.1$; Failure Threshold = 1 inch

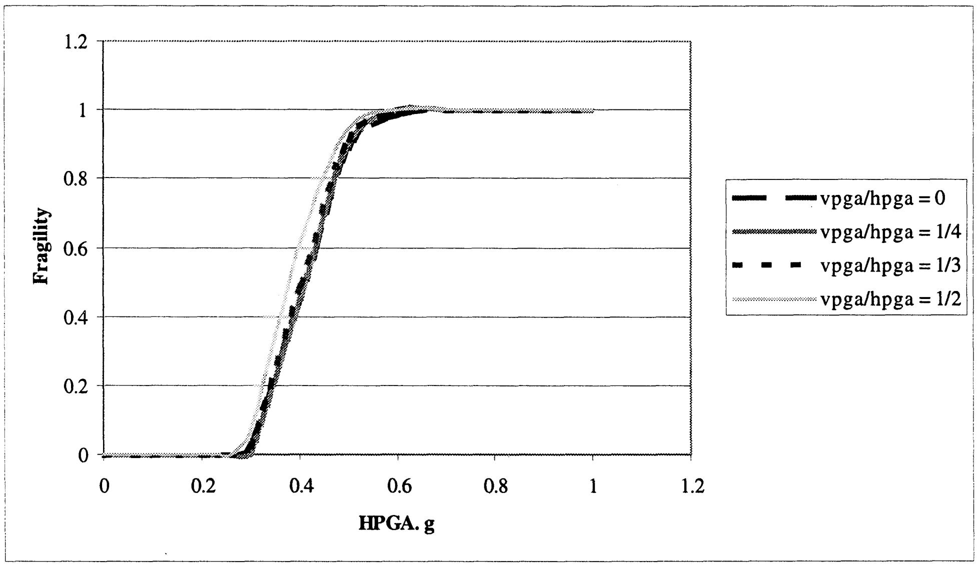


Figure 2.16 Fragility Curves for $\mu_d = 0.1$; Failure Threshold = 2 inches

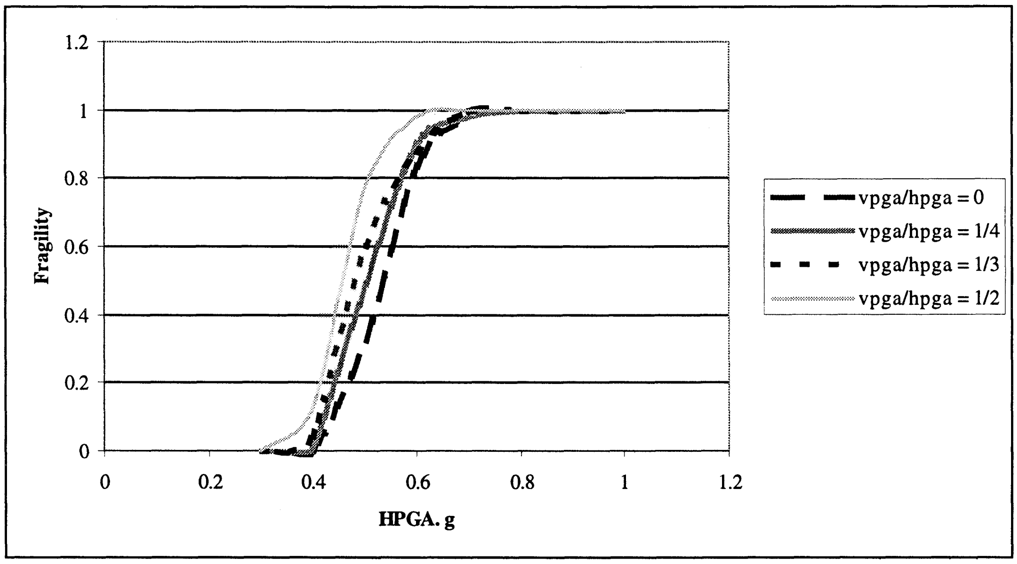


Figure 2.17 Fragility Curves for $\mu_d = 0.2$; Failure Threshold = 1 inch

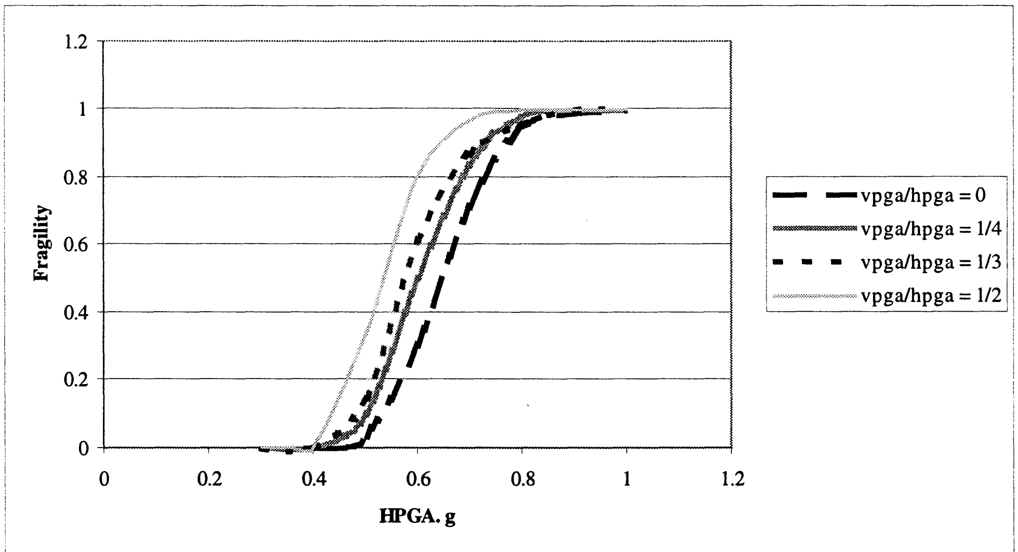


Figure 2.18 Fragility Curves for $\mu_d = 0.2$; Failure Threshold = 2 inches

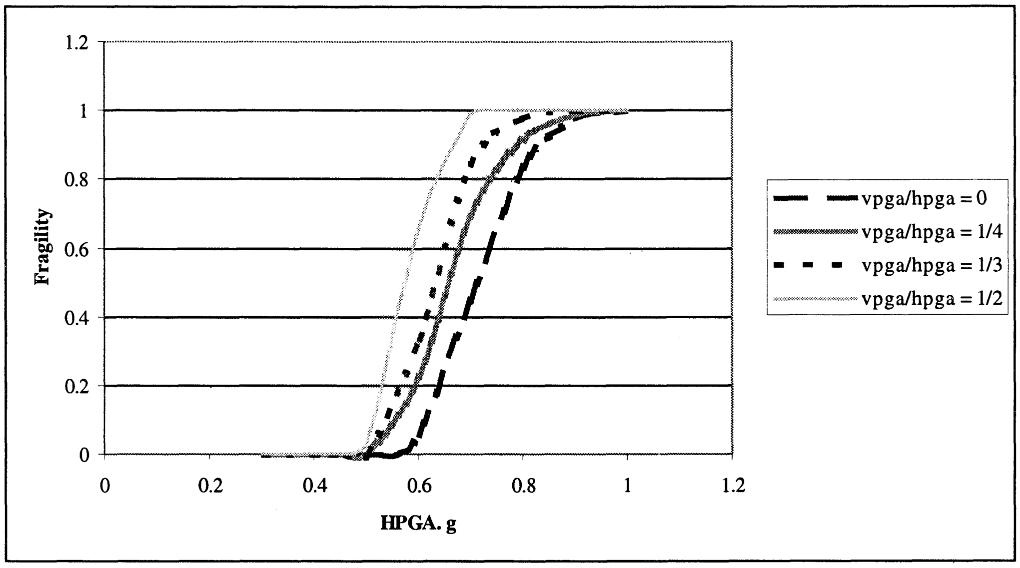


Figure 2.19 Fragility Curves for $\mu_d = 0.3$; Failure Threshold = 1 inch

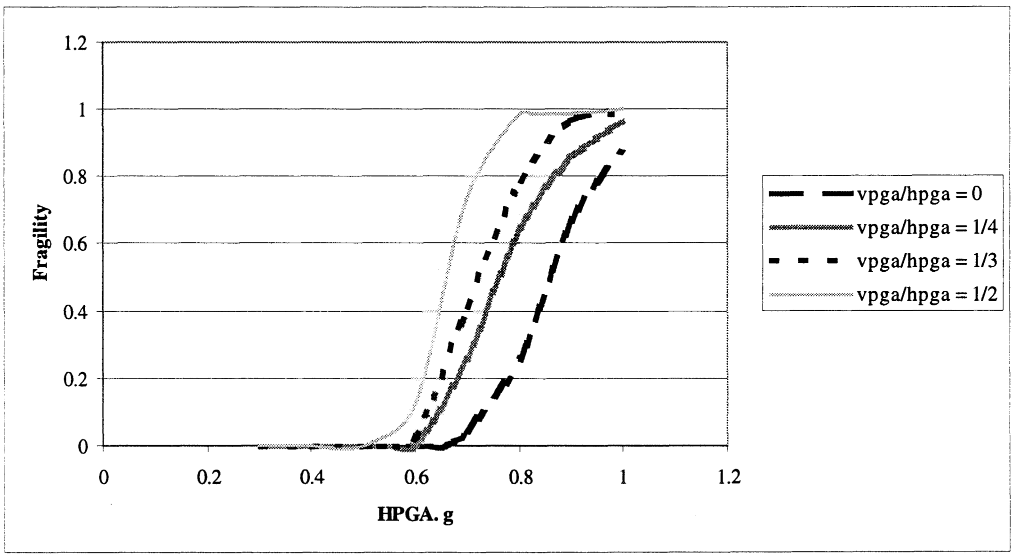


Figure 2.20 Fragility Curves for $\mu_d = 0.3$; Failure Threshold = 2 inches

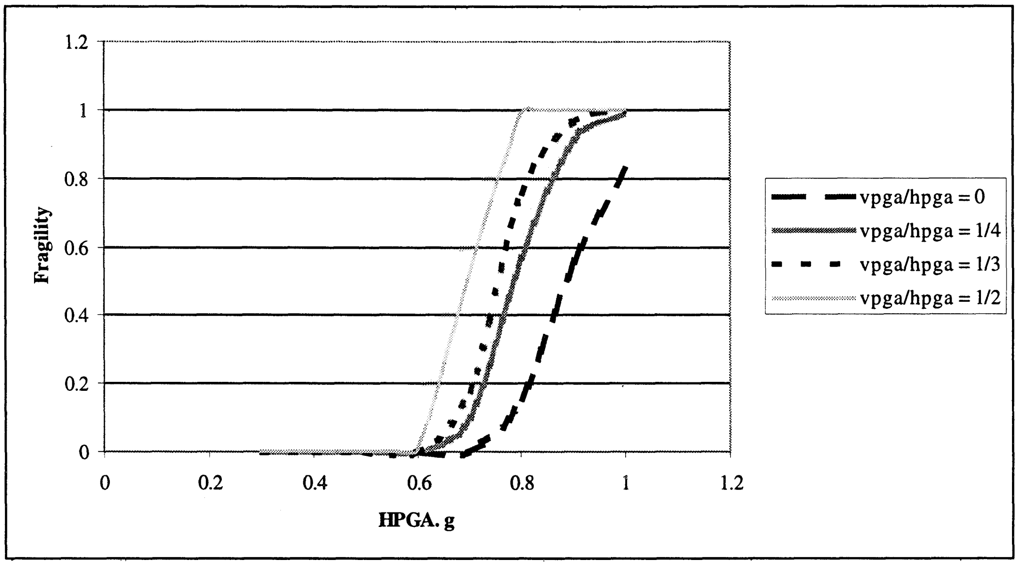


Figure 2.21 Fragility Curves for $\mu_d = 0.4$; Failure Threshold = 1 inch

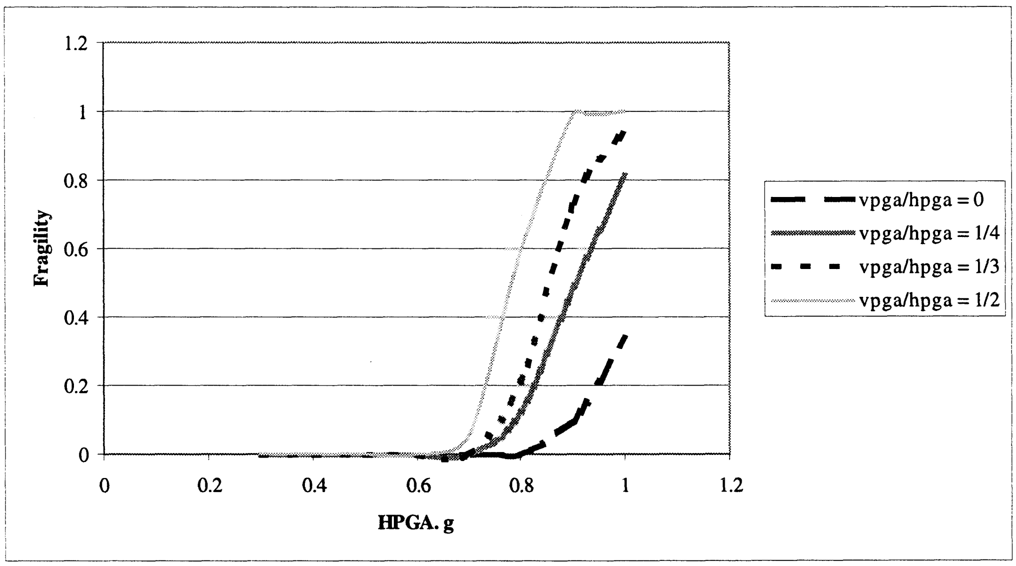


Figure 2.22 Fragility Curves for $\mu_d = 0.4$; Failure Threshold = 2 inches

SECTION 3
EXPERIMENTS FOR SLIDING PROBLEM

The basic objective of the experiments described in this chapter was to investigate the sliding response of a free-standing rigid block under seismic loading in order to verify the validity of the analytical solution described in Section 2. The sliding motion of a rigid block against the surface of a raised floor was tested on a shaking table using five randomly chosen earthquake time histories. In addition, two different friction tests were conducted to determine the static coefficient of friction of the two sliding surfaces for a quantitative comparison of the experimental and analytical results. This comparison will later be described in the end of this section.

3.1 Test Set-Up

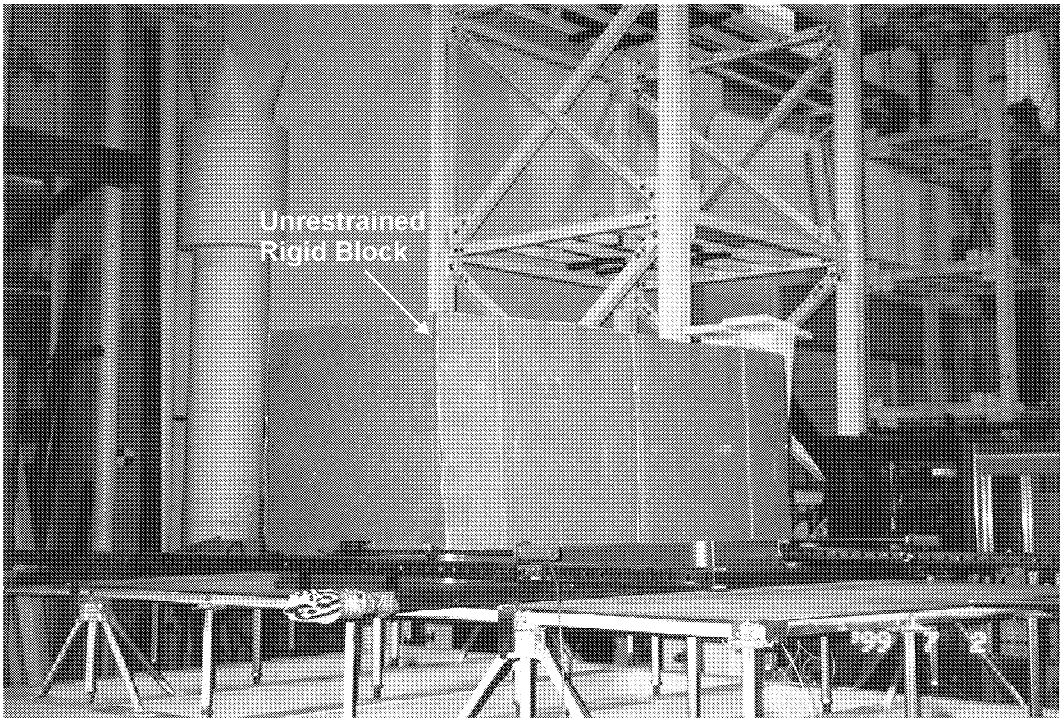
The experiments were set-up on a shaking table, which provides the earthquake motion. The free standing rigid block was tested on a 1.83 m x 1.83 m (6 ft x 6 ft) raised floor surface that was fixed on top of a concrete slab attached to the shaking table, shown in Figure 3.1. Five randomly chosen earthquake time histories were used as the earthquake inputs, with a scale of 0.3g~0.7g of peak ground acceleration (PGA) in the horizontal direction and four proportional scales of the horizontal acceleration, ranging between 0~1, in the vertical direction. Displacement and acceleration measurements were of interest in these experiments.

3.1.1 The Shaking Table

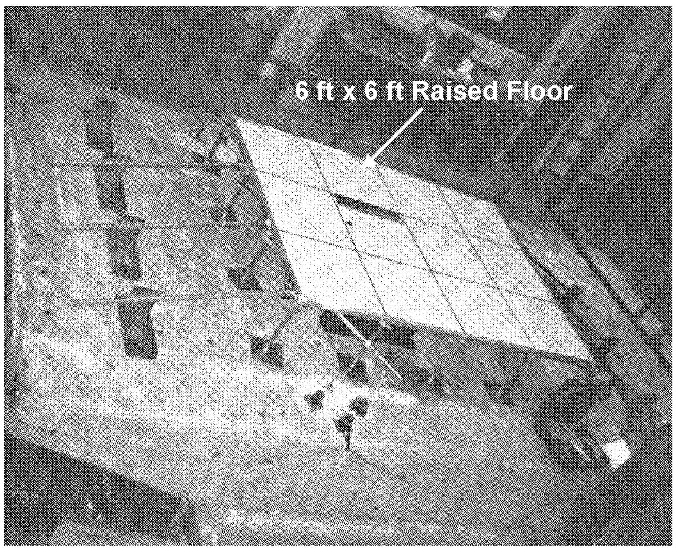
The shaking table has a dimension of 3.66 m x 3.66 m (12 ft x 12 ft) with a capacity of 50 mtons (110 kips). It has a total of five degrees of freedom (DOF) with three programmable DOFs (horizontal, vertical, and roll) and the other two DOFs corrected for cross coupling only. The system has two horizontal actuators with a capacity of 32 mtons (70 kips), which can provide a maximum horizontal acceleration of 0.625 g with maximum payload. Four vertical actuators with a total capacity of 100 mtons (220 kips) can accelerate the system to 1.05 g at maximum payload. With lighter payloads, the system can produce larger accelerations (up to 4.0g horizontally and 8.0g vertically). A schematic sketch of the system is shown in Figure 3.2 (Kosar et al., 1993).

3.1.2 The Sliding Surfaces

The two sliding surfaces used in the experiments were a raised floor surface, shown in Figure 3.1(b), and the surface of a free-standing rigid block. Two steel bars were placed closely to the sides of the rigid block to prevent any rotation to occur while the block was sliding. In addition, two more steel bars were placed perpendicular to the sliding direction of the rigid block to prevent the block from falling off the edge of the raised floor when the relative displacement was too large. The descriptions above are clearly shown in Figure 3.3.



(a)



(b)

Figure 3.1 Shaking Table and Experimental Set-up

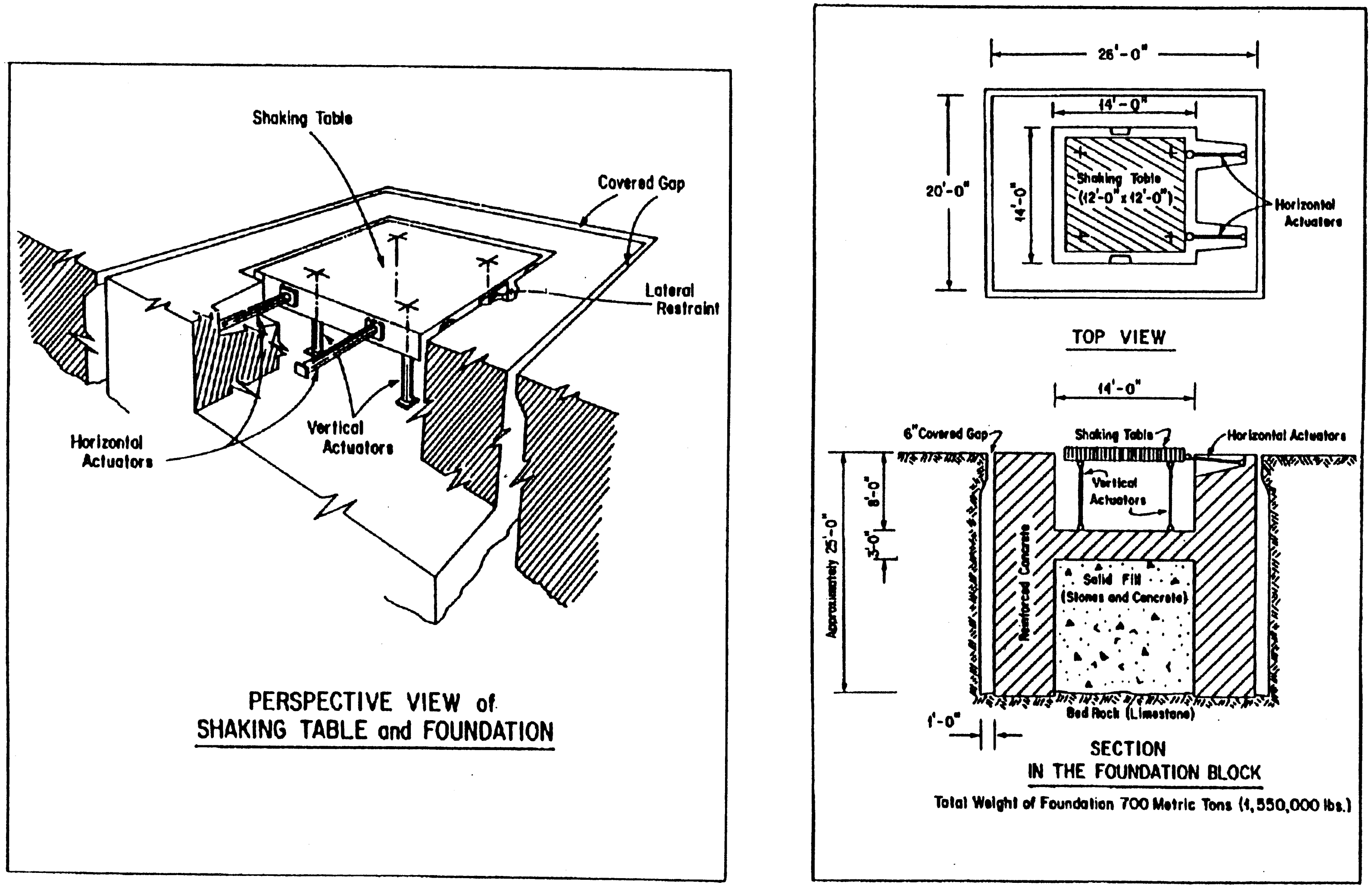
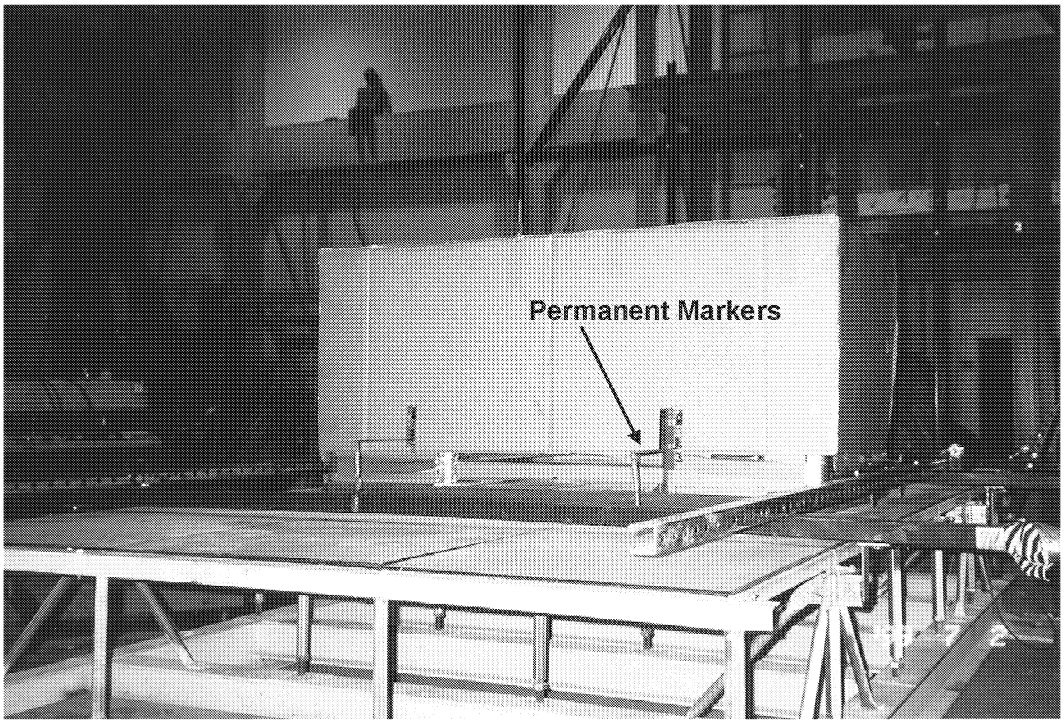
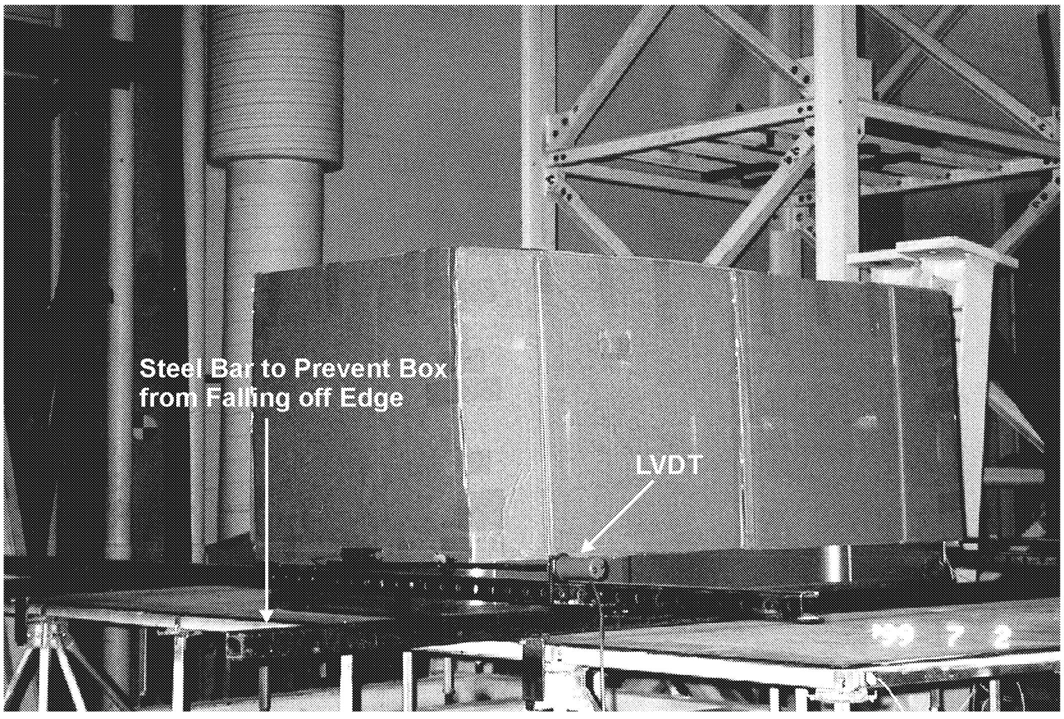


Figure 3.2 Schematic Sketch of Shaking Table System (Kosar, et al., 1993)



(a)



(b)

Figure 3.3 Steel Bars to Constrain Sliding Performance

3.1.3 Instrumentation

Horizontal and vertical acceleration measurements using accelerometers were made at several locations on the shaking table, the raised floor, and the free standing rigid block. The placements and designations for the accelerometers attached to the block are shown in Figure 3.4. For all measurements, the sampling rate was set at 100 samples/second.

The horizontal displacements of the block were measured by Temposonic displacement transducers (LVDT) as well as two permanent markers attached to the left and right side on the surface facing the sliding direction. The locations of the Temposonic transducers attached to the sliding block are shown in Figure 3.5. Figure 3.6 shows the locations of the permanent markers.

3.1.4 Acceleration Time History Inputs

Five acceleration time histories representing some typical past earthquakes were randomly chosen as excitation inputs in these experiments. The particular earthquake inputs selected were El Centro, Taft, Pacoima, Kobe, and Northridge earthquake records. They are shown in Figure 3.7~3.11.

Horizontal and vertical accelerations were considered in these experiments. There were five HPGAs being considered in the experiments. They are, namely, 0.3g, 0.4g, 0.5g, 0.6g, and 0.7g. Due to displacement limitations of the shaking table, the HPGA being tested can only be increased up to a maximum acceleration of 0.7g. As for the VPGA, four different scale factors were used to represent them in terms of HPGA. They were 0, ¼ , 1/3 , ½. For each HPGA, these four different VPGA values were applied, individually, with the horizontal acceleration. Three repeated tests, from the same earthquake input, were conducted for most of the combinations of horizontal and vertical accelerations. Some combinations were only tested for two runs due to the constraints experienced during the experiments. Table 3.1, presented in Section 3.3, shows all the combinations of horizontal and vertical accelerations and the number of tests conducted for each combination.

Table 3.1 Number of Runs for Each Combination of HPGA and VPGA in Experiment

	Horizontal PGA, g				
Proportional Constants for Vertical PGA	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**
0	10	10	13	13	11
¼	10	10	13	13	11
1/3	10	10	13	13	11
½	10	10	13	13	11
TOTAL	**40**	**40**	**52**	**52**	**44**

* there are five different time history inputs used in each combination of horizontal and vertical PGA.

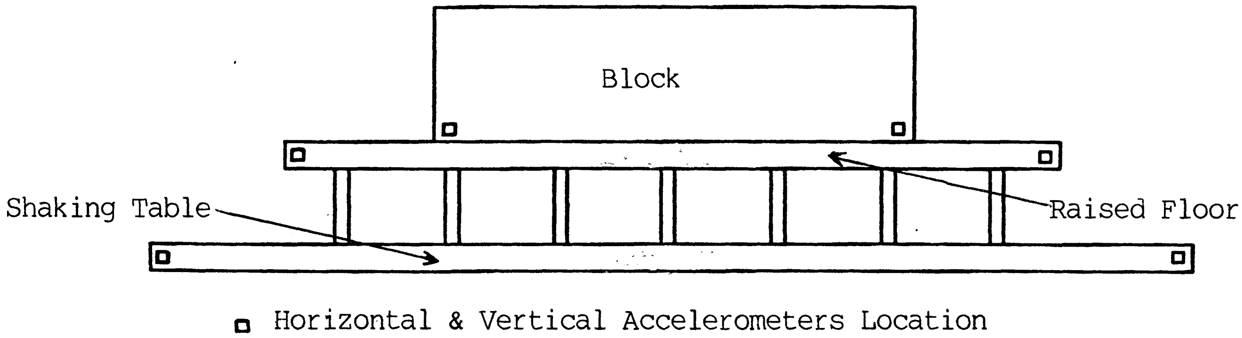


Figure 3.4(a) Locations of Horizontal and Vertical Accelerometers

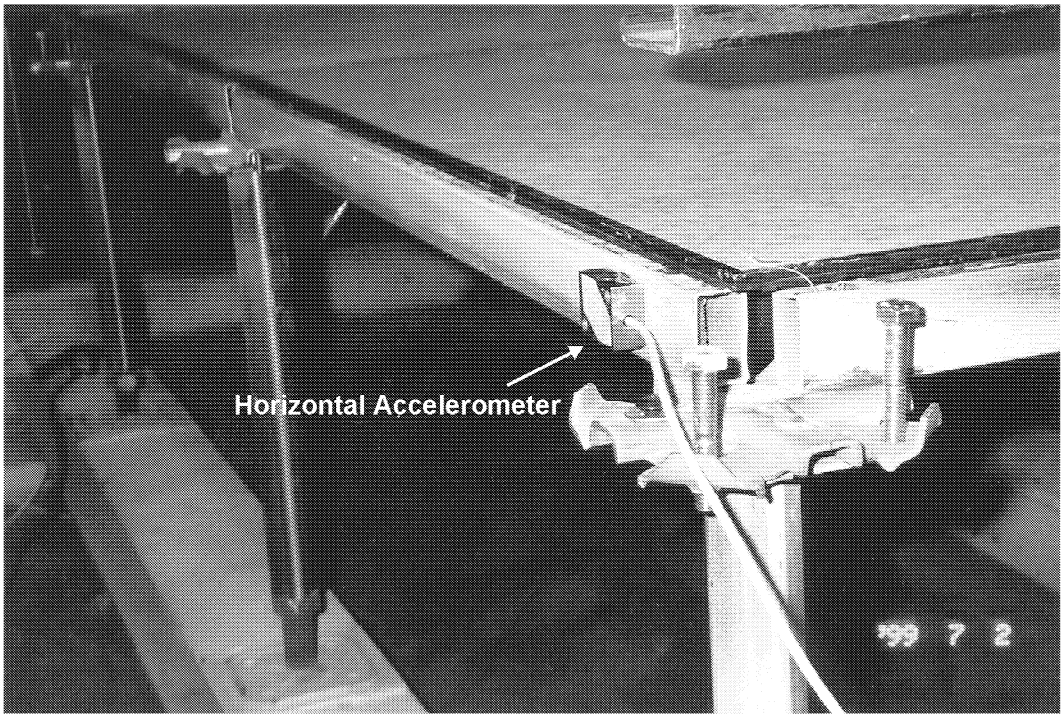


Figure 3.4(b) Location of Horizontal Accelerometer

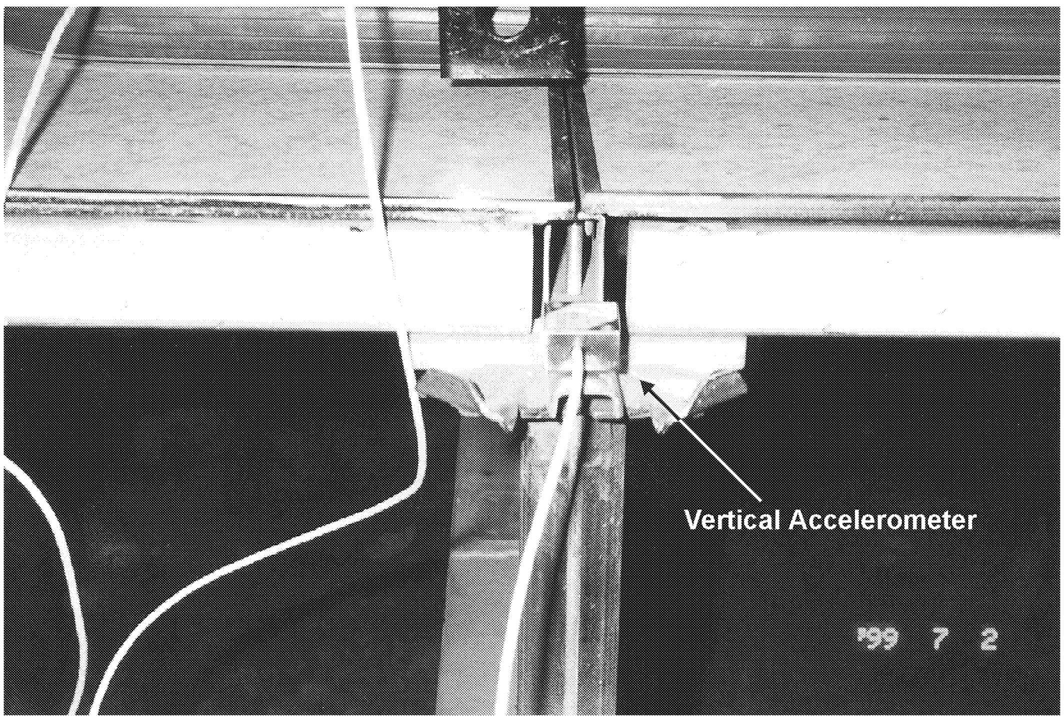


Figure 3.4(c) Location of Vertical Accelerometer

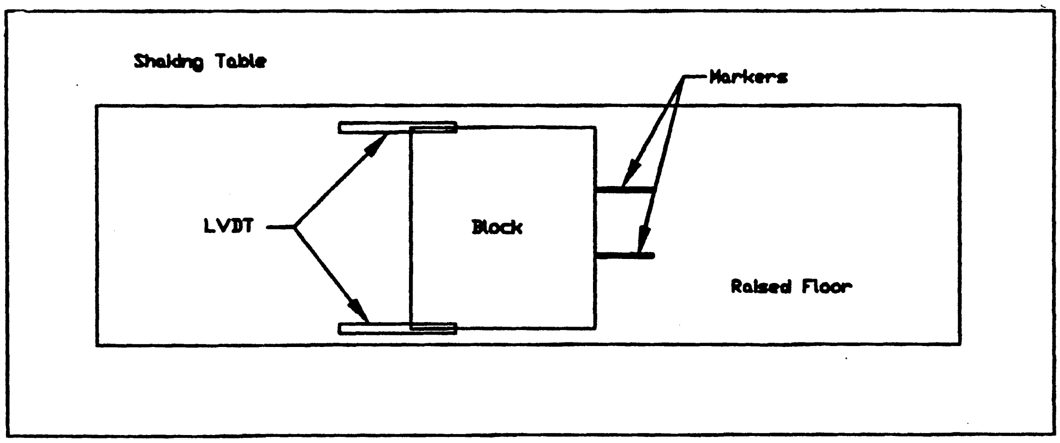


Figure 3.5(a) Locations of Horizontal LVDT and Markers

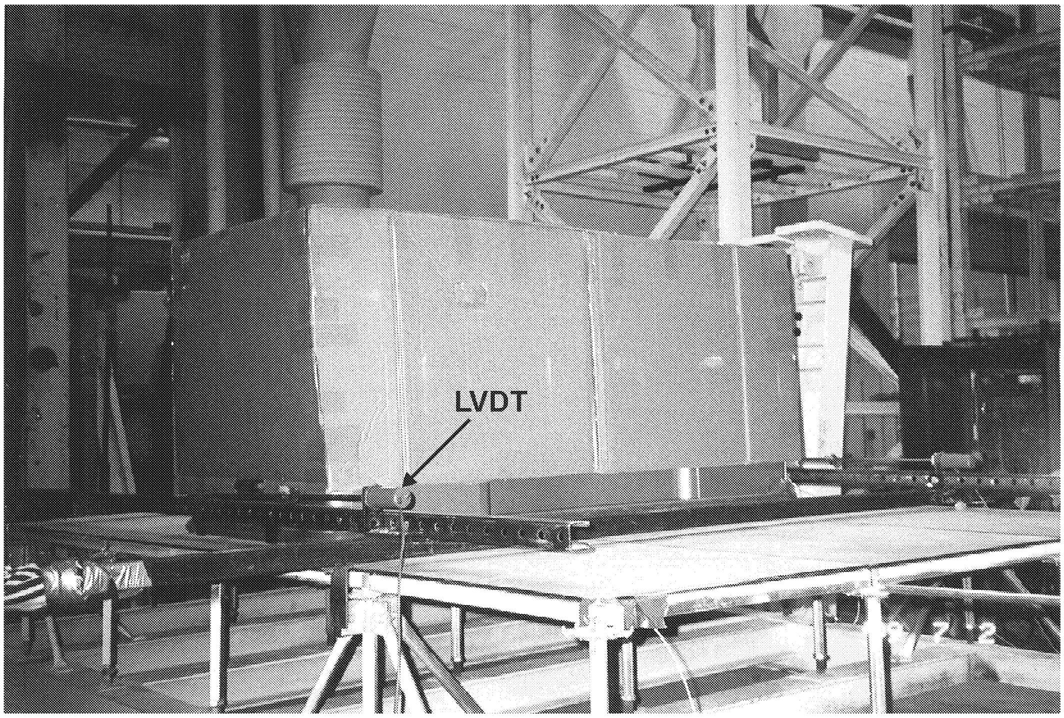


Figure 3.5(b) Front View of Rigid Block with LVDT attached

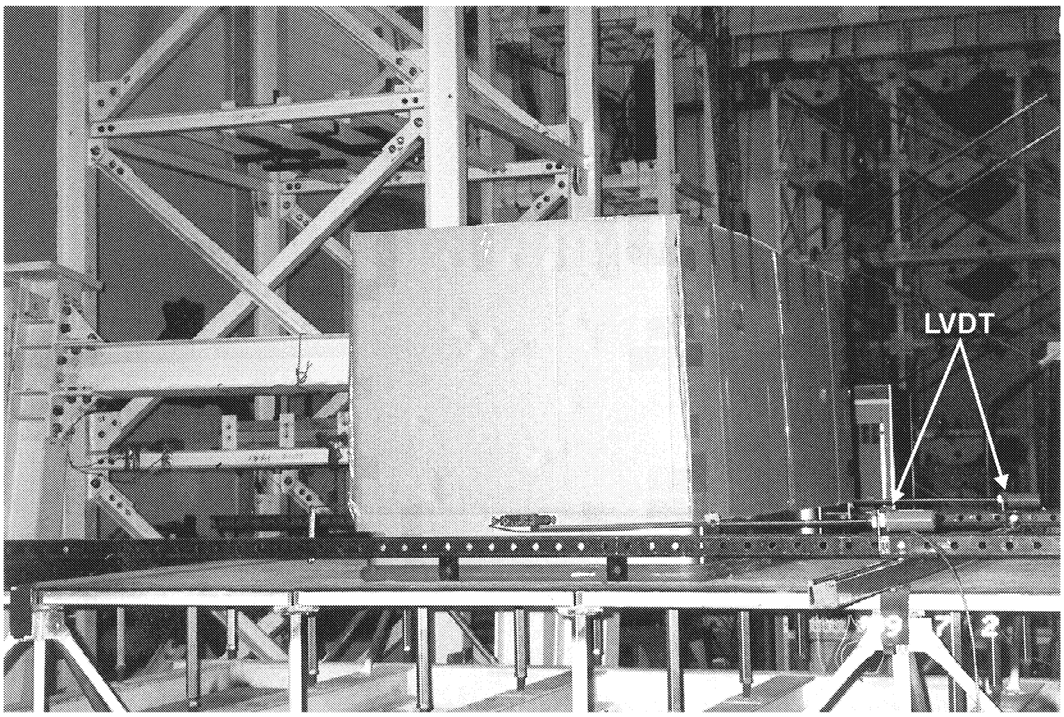


Figure 3.5(c) Side View of Rigid Block with LVDT attached

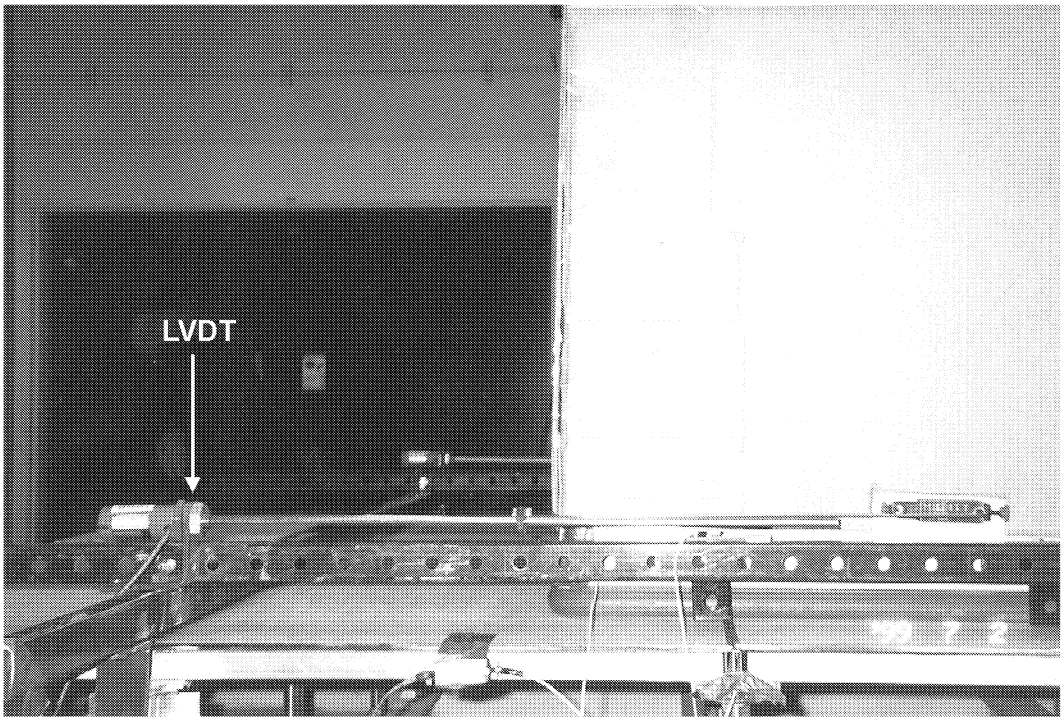


Figure 3.5(d) Side View of LVDT

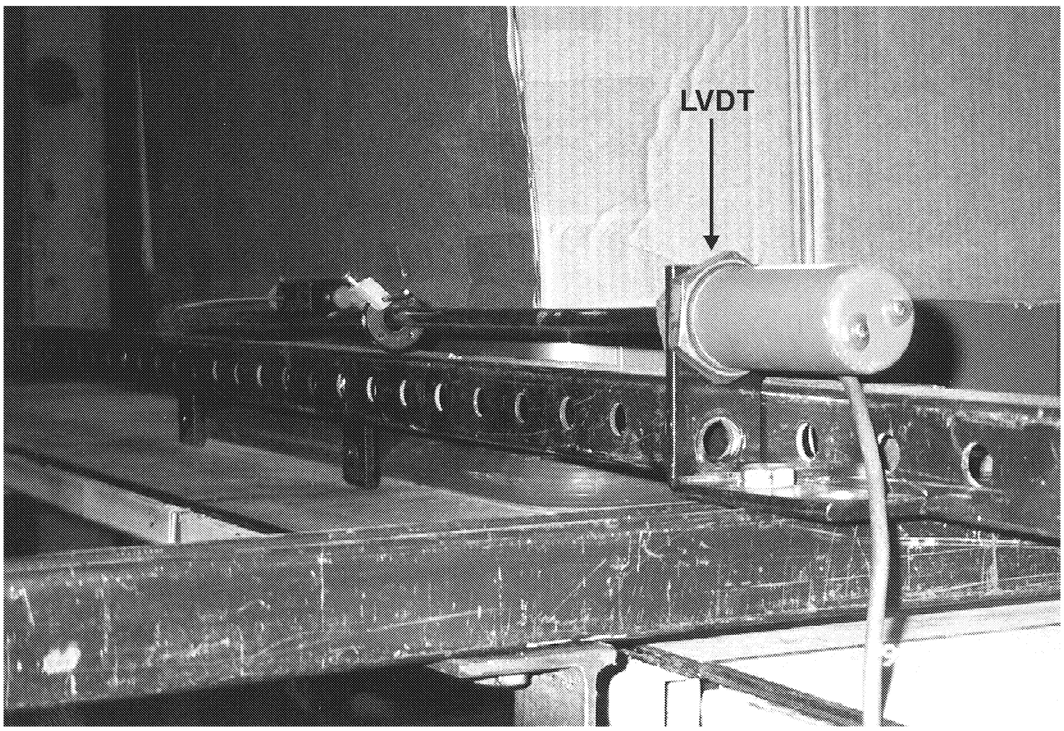
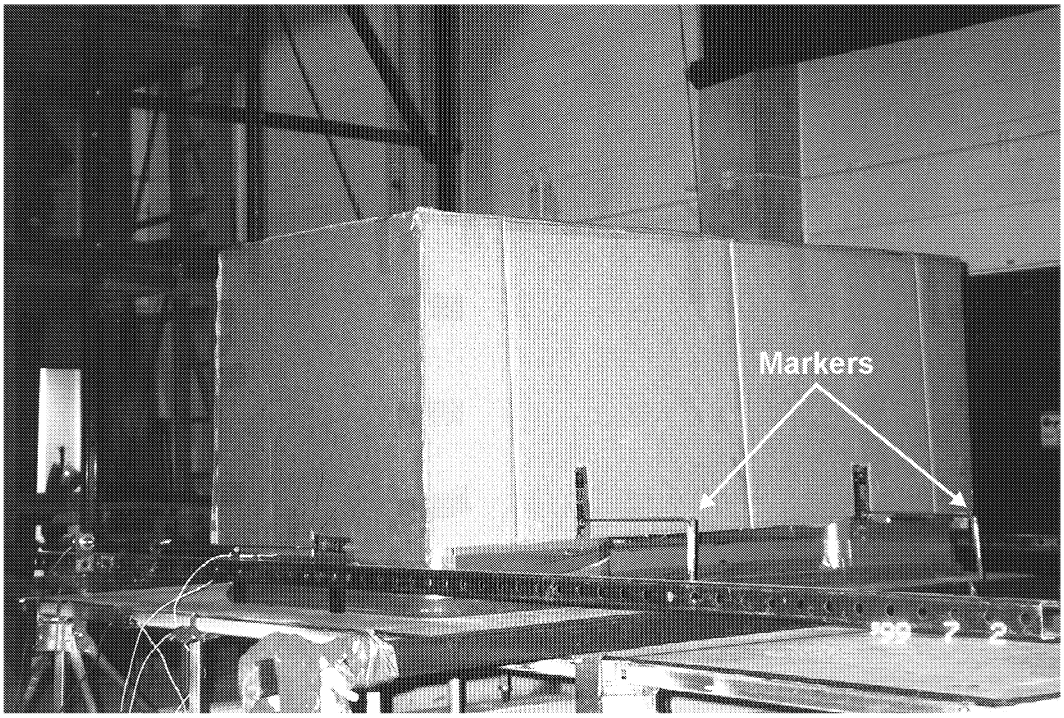
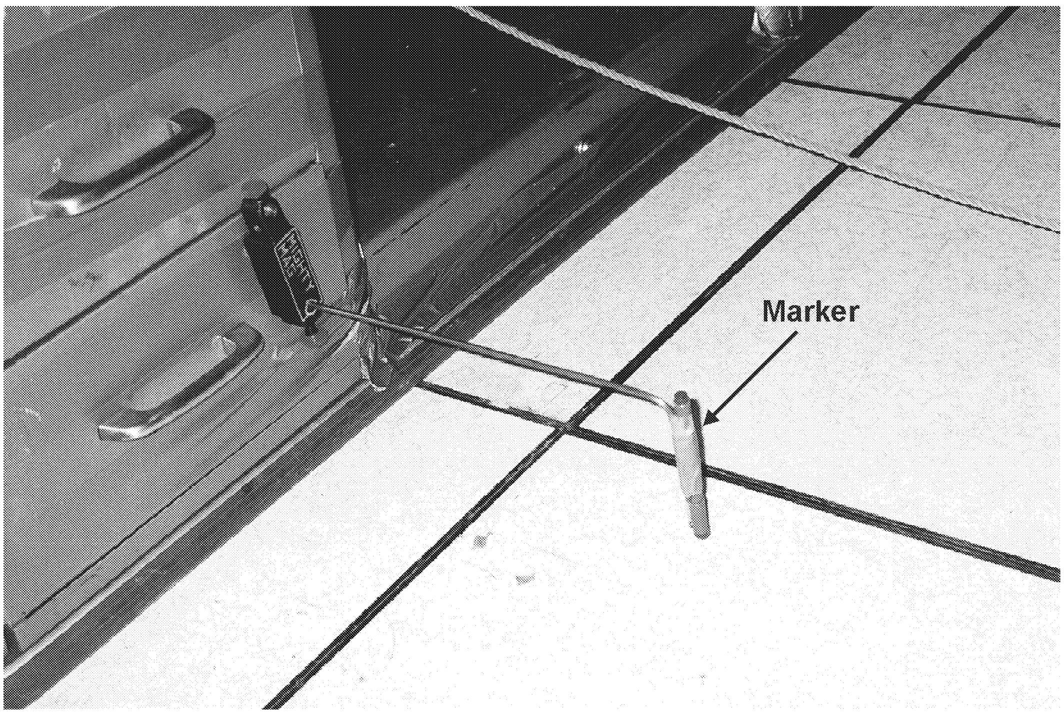


Figure 3.5(e) Front View of LVDT



(a)



(b)

Figure 3.6 Locations of Permanent Markers

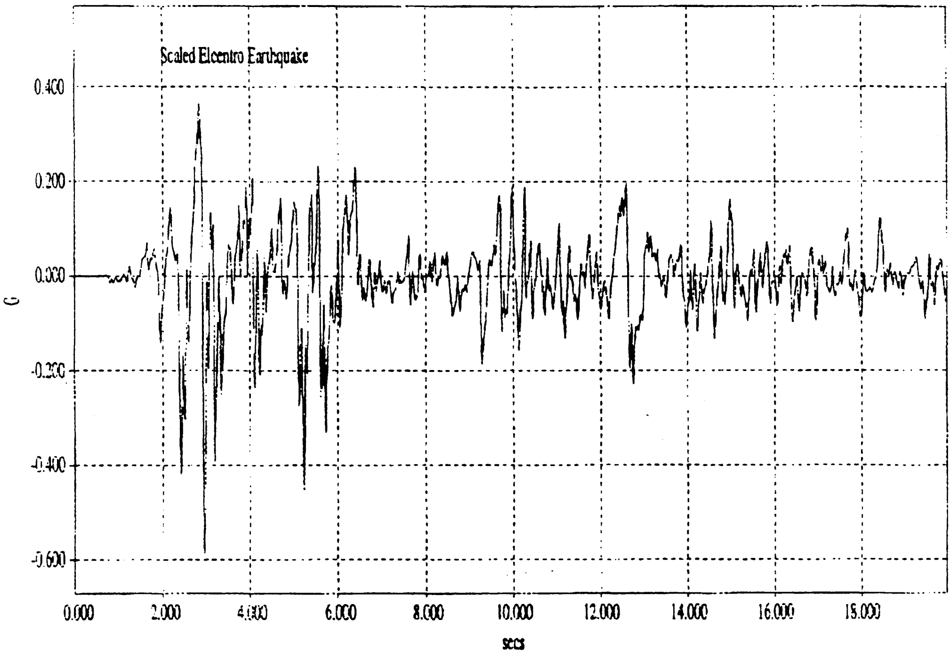


Figure 3.7 Scaled El Centro Earthquake Time History

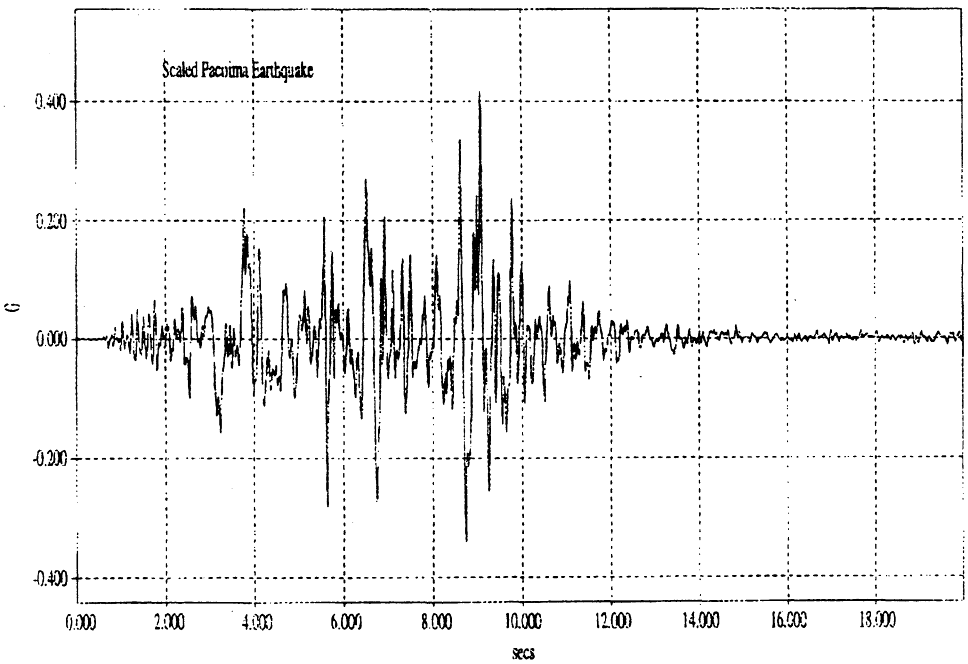


Figure 3.8 Scaled Pacoima Earthquake Time History

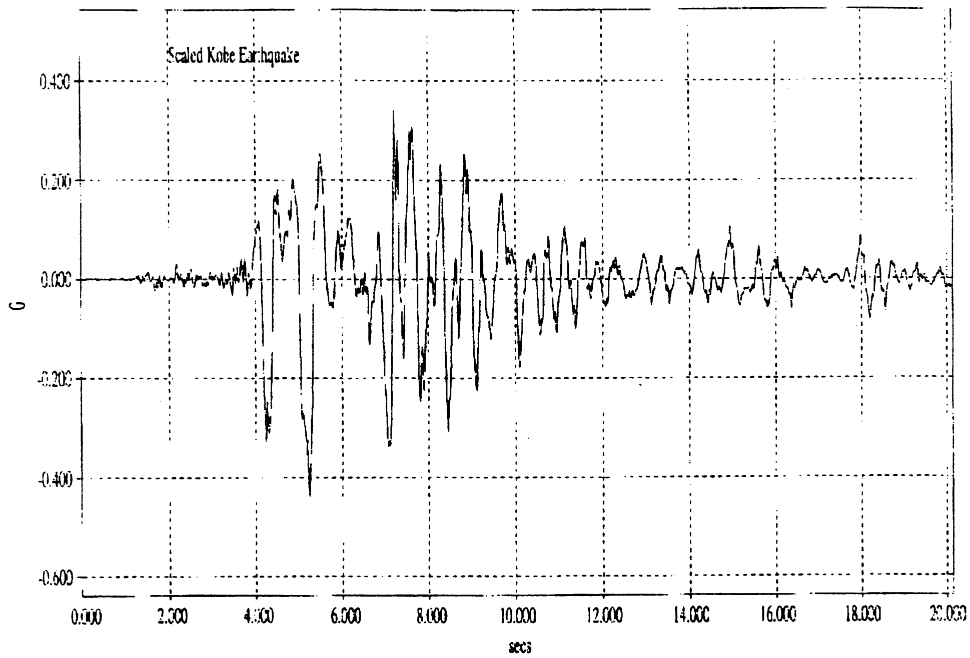


Figure 3.9 Scaled Kobe Earthquake Time History

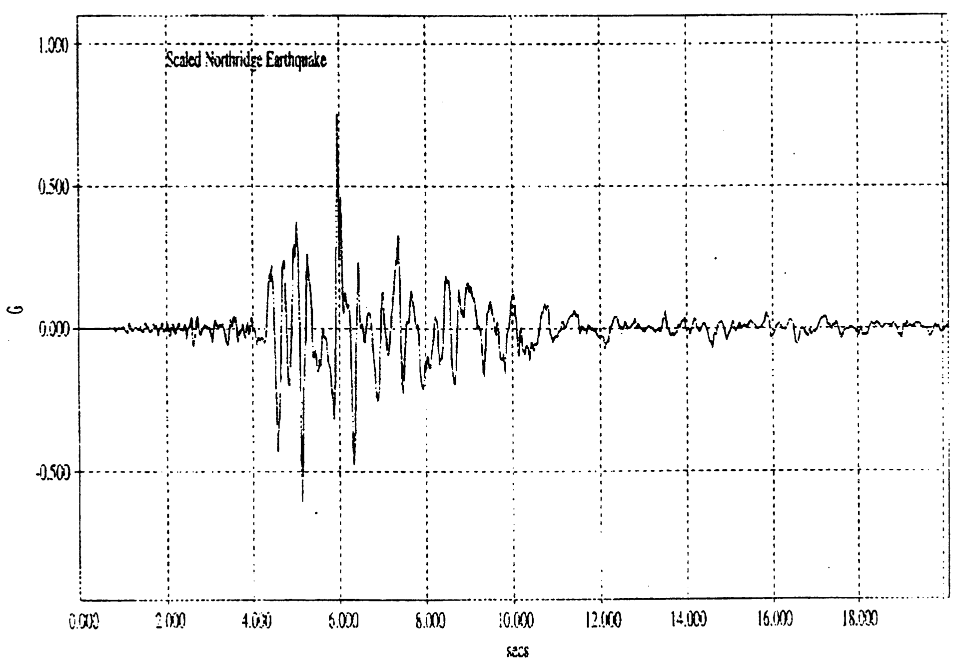


Figure 3.10 Scaled Northridge Earthquake Time History

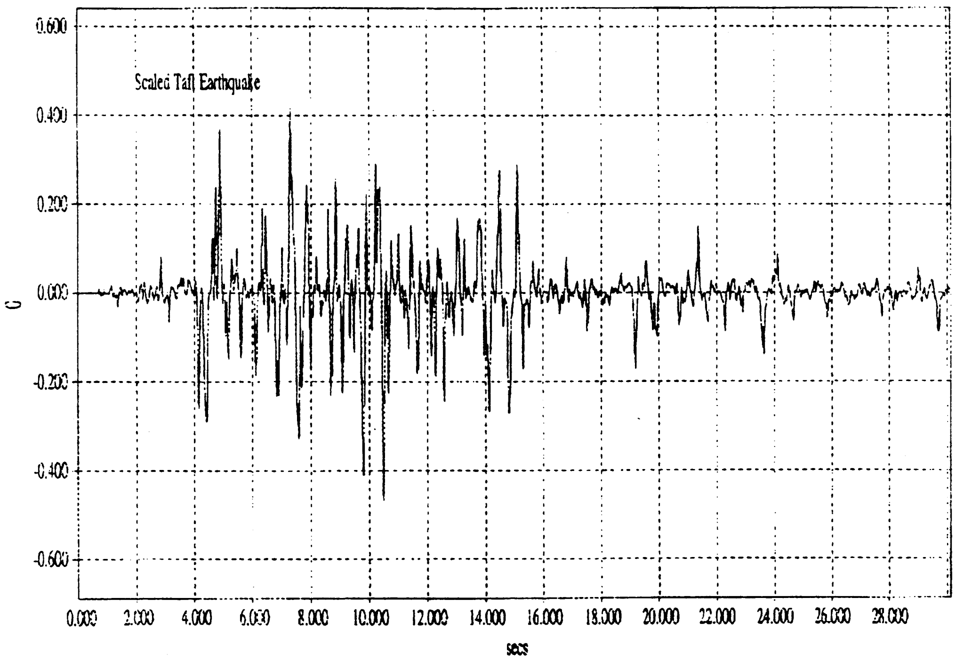


Figure 3.11 Scaled Taft Earthquake Time History

3.2 Determination of Coefficient of Static Friction

Determination of the static coefficient of friction for the two sliding surfaces is a very important part of this experiment in the sense that, with the static coefficient of friction determined, comparison between the experimental and analytical results become possible and this leads to the evaluation of accuracy of the analytical solution. There were two tests conducted for the determination of static coefficient of friction : the pulling test and the tilting test as described below.

3.2.1 The Pulling Test

The schematic representation of the test setup is shown in Figure 3.12. The determination of the static coefficient of friction is based on the following equation which described the relationship between the static frictional force, F_s, and the normal force, N :

$$F_s = \mu_s N \tag{3.1}$$

where μ_s is the coefficient of static friction.

In this test, a rope was tied to the sliding block, which was pulled during the test. A load cell was used to measure the force applied in pulling the sliding block, F_s. The block was pulled until it started to slide. The weight of the sliding block, N, was then measured. A total of five tests were repeated to obtain an accurate static coefficient of friction, which in this case is 0.143.

3.2.2 The Tilting Test

A schematic representation of the test setup in the tilting test is shown in Figure 3.13. Equation (3.2) shown below was used to determine the static coefficient of friction, which is a simpler experiment than the pulling test.

$$\mu_3 = \tan\theta \tag{3.2}$$

where θ is the angle between the tilted surface and the original surface.

In this case, the whole equipment setup, the sliding block and the raised floor surface, was tilted slowly at one side by a crane, as shown in Figure 3.14, until the block started to slide. The angle at which the rigid block started to slide was measured using an angle measuring instrument shown in Figure 3.15. Two repeated tests were done. A result of 0.455 for the static coefficient of friction was obtained.

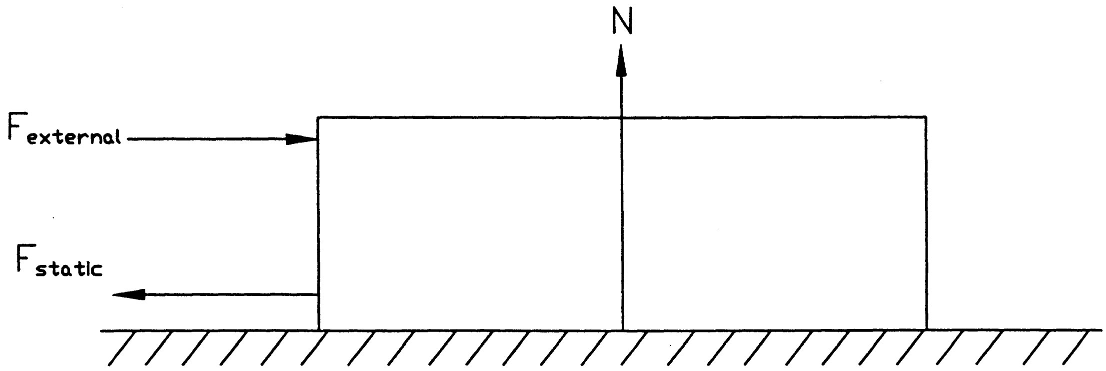


Figure 3.12 The Pulling Test Assembly

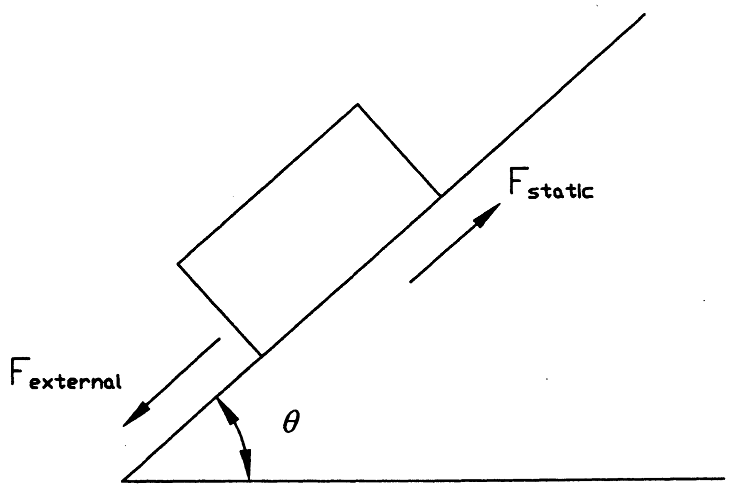


Figure 3.13 The Tilting Test Assembly

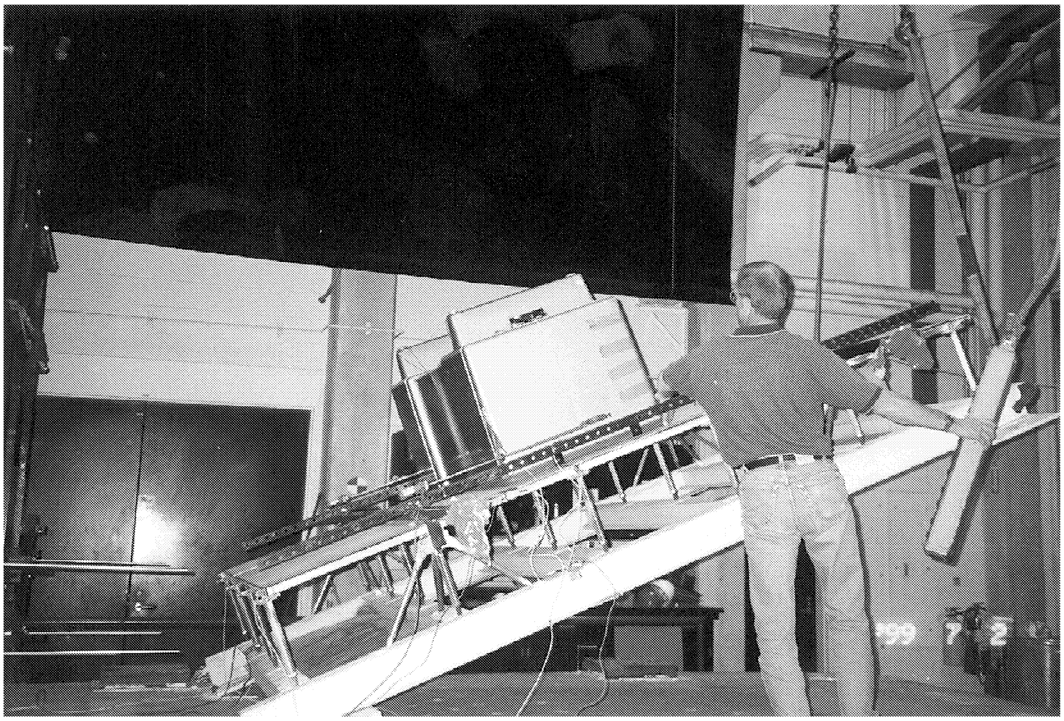
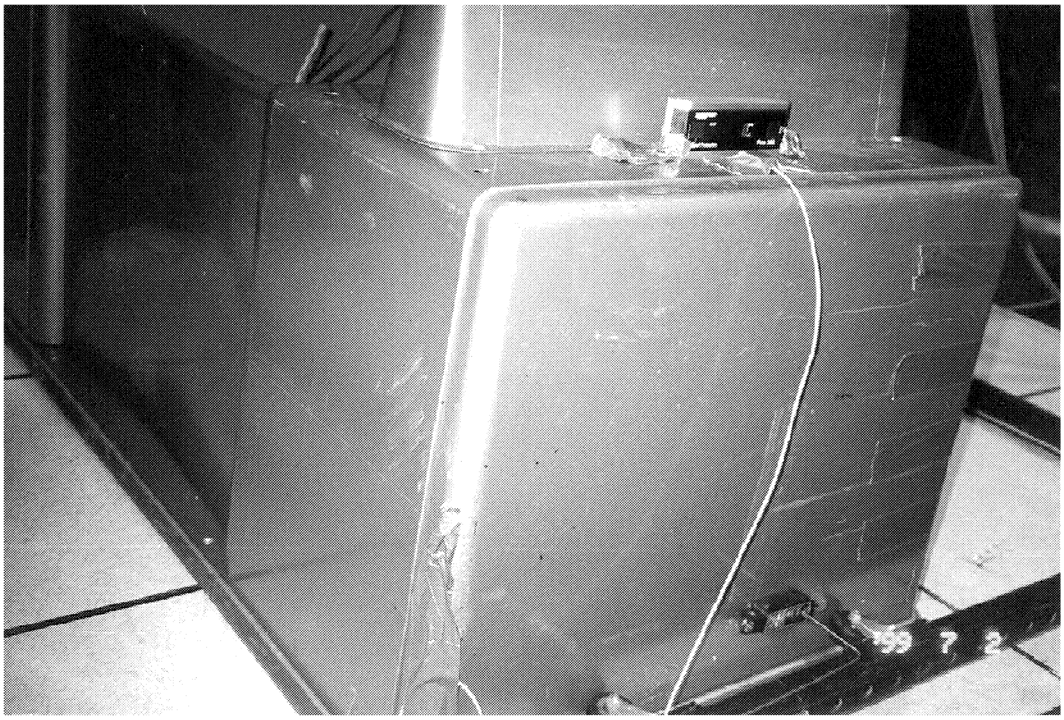


Figure 3.14 The Tilting Test Procedure

(a)



(b)
Figure 3.15 Instrument for Angle Measurement

3.2.3 Average Static Coefficient of Friction

Due to the fact that the results obtained for the static coefficient of friction in the two tests described above were significantly different, averaging the results obtained from both tests was necessary. The averaged value of the coefficient of static friction was taken as 0.3.

3.3 Summary of Experimental Results

There were five different sets of acceleration time history inputs used in the experiments. They are the acceleration time history records from El Centro, Kobe, Pacoima, Northridge and Taft earthquakes.

Horizontal and vertical excitations were considered in the experiments, as considered in the analytical calculations. In every of the five excitation inputs mentioned above, five different horizontal intensities, which represented by the peak PGA ranging from 0.3g to 0.7g, were tested. As for the vertical acceleration inputs, they were scaled from the horizontal acceleration inputs. There were four different scale factors used in the vertical accelerations : 0,1/4,1/3 and ½..Table 3.1 illustrates these combinations clearly. For each of the combinations of the HPGA and VPGA in each set of the time history inputs (i.e. El Centro Earthquake, Kobe Earthquake,...etc), two or three repeated test were done for the sake of accuracy of the results.

3.3.1 Sliding Performance of Free-Standing Rigid Block

Once sliding is initiated, there are three parameters which affect the sliding response of the free-standing rigid block. They are the peak horizontal and vertical excitations, and the dynamic coefficient of friction. These three parameters were investigated in the experiments.

Figures 3.16~3.20 show relative displacement and absolute acceleration time histories from the five time history earthquake inputs mentioned before. The HPGA considered here is 0.7 g, with a VPGA of 0.23g, which is 1/3 of the horizontal PGA.

The block average relative peak displacements for each of the combinations of HPGA and VPGA are shown in Table 3.2, together with the corresponding average absolute accelerations at which threshold displacements occur. In addition, based on an approximate correlation between static and dynamic friction coefficients found in TABLE C1. (Dimarogonas, 1996) in Appendix C, an assumed coefficient of dynamic friction of 0.21 which was estimated from the determined coefficient of static friction between the tested sliding surfaces was used as a parameter in the analytical solution procedure for comparison. A summary of these results is presented in Table 3.3.

3.3.2 Experimental Failure Curves

There were eight different failure thresholds considered in the experimental analysis, as in the analytical solutions. They are relative displacements of 0.1 inch, 0.2 inch, 0.5 inch, 0.75 inch, 1 inch, 2 inches, 2.5 inches and 3 inches. The fragility curves for failure threshold of 1 inch and 2

Table 3.2 Summary of Experimental Results

Average Peak Displacement, inch

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7
0	0.1473	0.43132	0.763692	1.813846	3.029818
1/4	0.1326	0.4463	0.821385	2.064538	3.192909
1/3	0.1309	0.4042	0.876	2.317769	3.215273
1/2	0.1292	0.418	0.882462	2.287846	3.843091

Average Acceleration at which Peak Displacement Occurs, g

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7
0	0.2187	0.2052	0.231538	0.256923	0.196909
1/4	0.1929	0.2462	0.237154	0.241692	0.21
1/3	0.2346	0.2423	0.214692	0.231	0.246636
1/2	0.2191	0.2601	0.186846	0.255846	0.163091

Table 3.3 Summary of Analytical Solution for $\mu_d = 0.21$

Average Peak Displacement, inch

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.027586	0.208377	0.665909	1.385792	2.317321	3.39103	4.598406	5.894688
1/4	0.034412	0.2584	0.835573	1.805412	3.065873	4.564104	6.245473	8.093002
1/3	0.038549	0.296323	0.979537	2.11098	3.573012	5.342662	7.355268	9.50258
1/2	0.053762	0.4073	1.350192	2.929514	4.9672	7.415218	10.16441	13.09147

Average Acceleration at which Peak Displacement Occurs, g

Horizontal Peak Ground Acceleration, g

k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.220012	0.220102	0.220313	0.220662	0.221277	0.221902	0.222909	0.222913
1/4	0.219328	0.219373	0.220117	0.222542	0.224652	0.227457	0.229738	0.232046
1/3	0.216208	0.218529	0.220116	0.223239	0.225861	0.228754	0.232716	0.237841
1/2	0.215276	0.218409	0.220737	0.22343	0.225846	0.233291	0.237565	0.244355

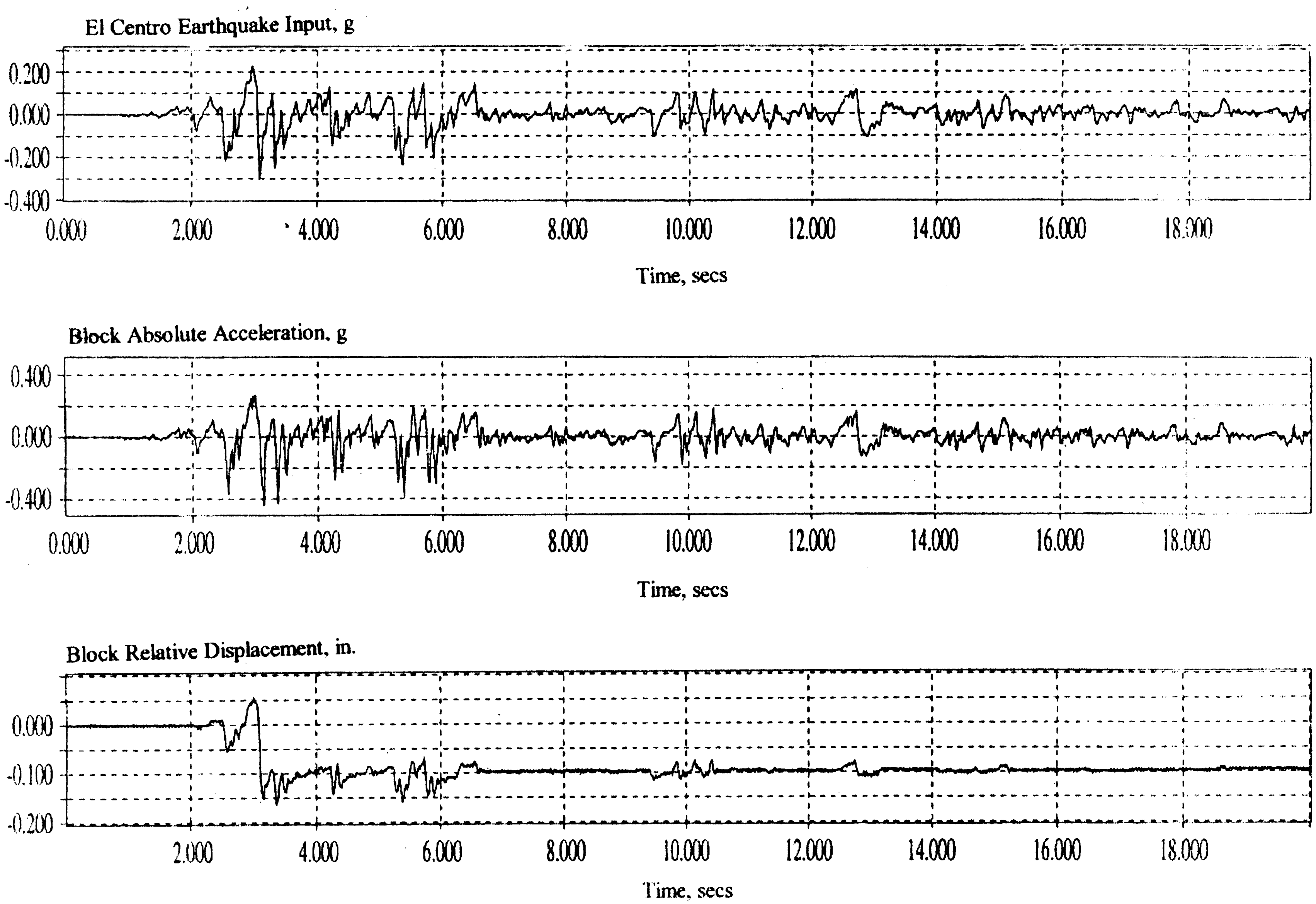


Figure 3.16 Typical Experimental Result from El Centro Earthquake Input

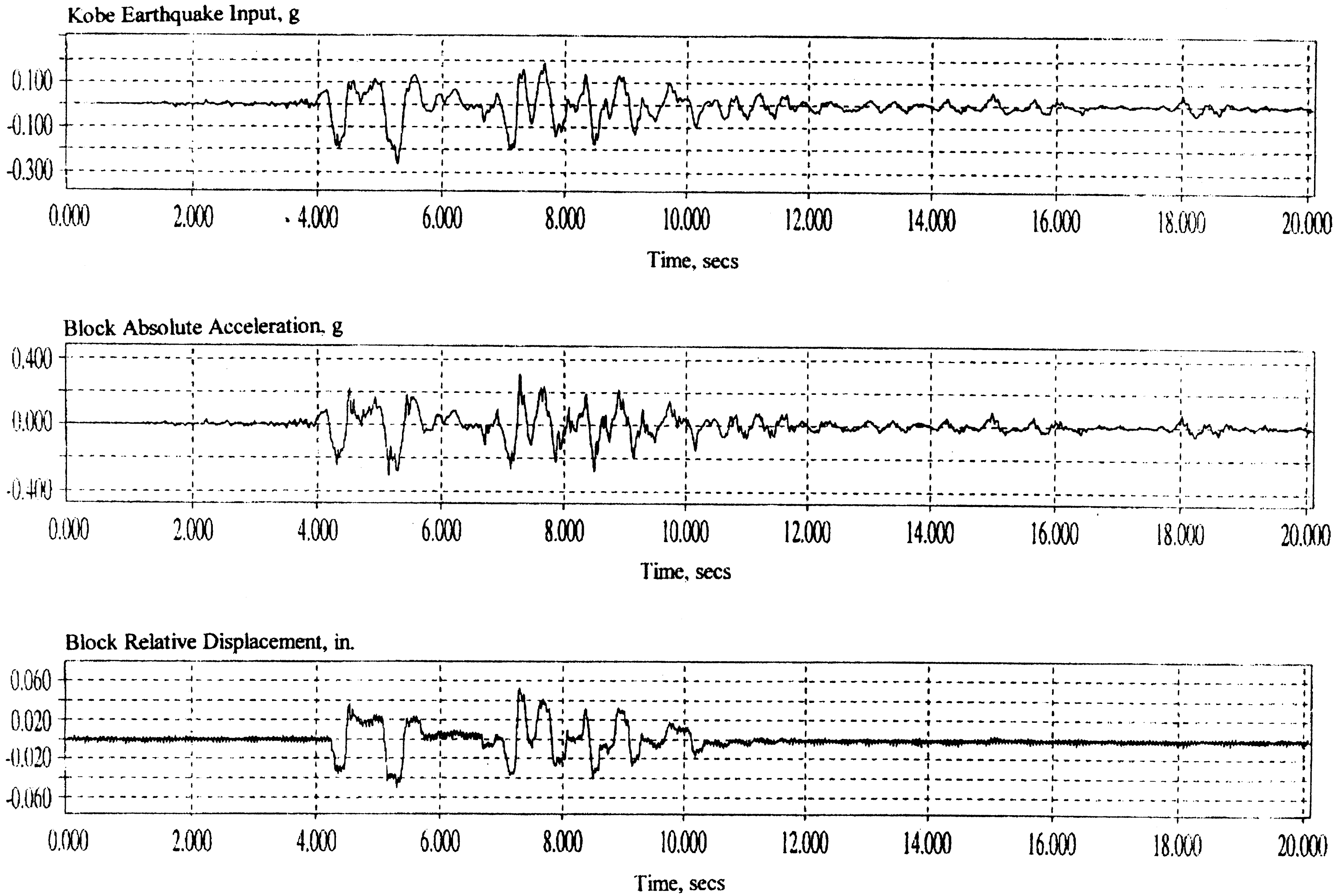


Figure 3.17 Typical Experimental Result from Kobe Earthquake Input

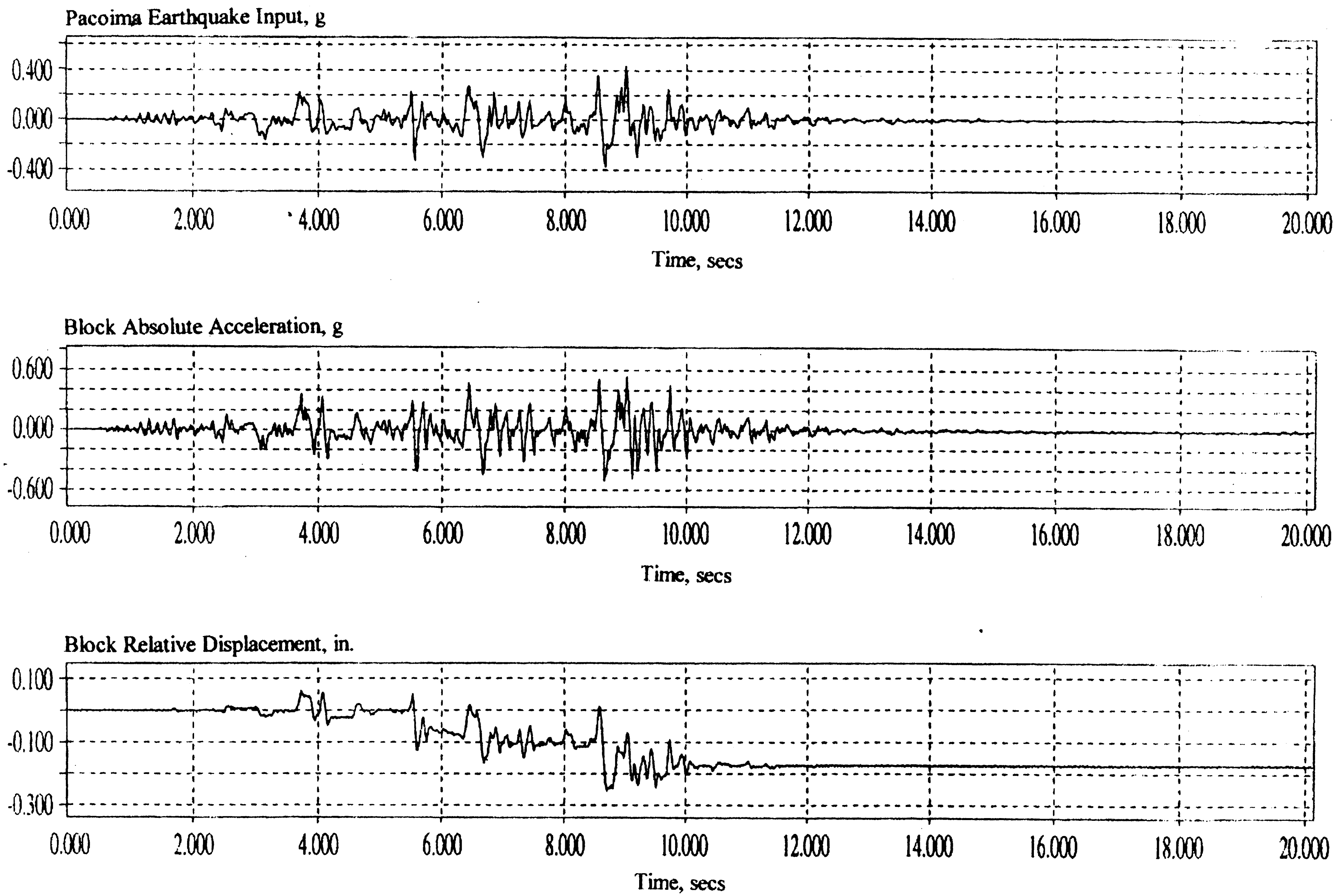


Figure 3.18 Typical Experimental Result from Pacoima Earthquake Input

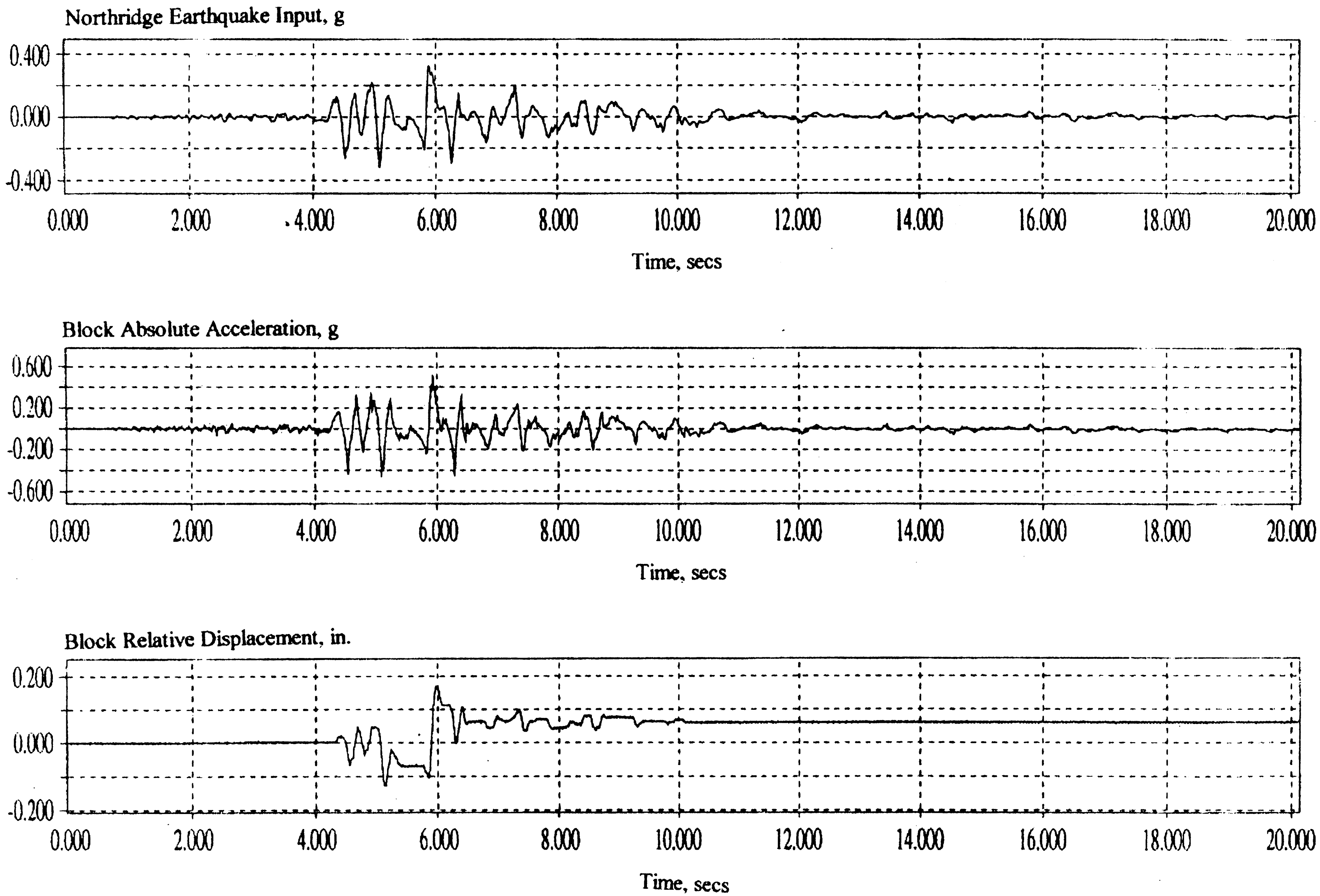


Figure 3.19 Typical Experimental Result from Northridge Earthquake Input

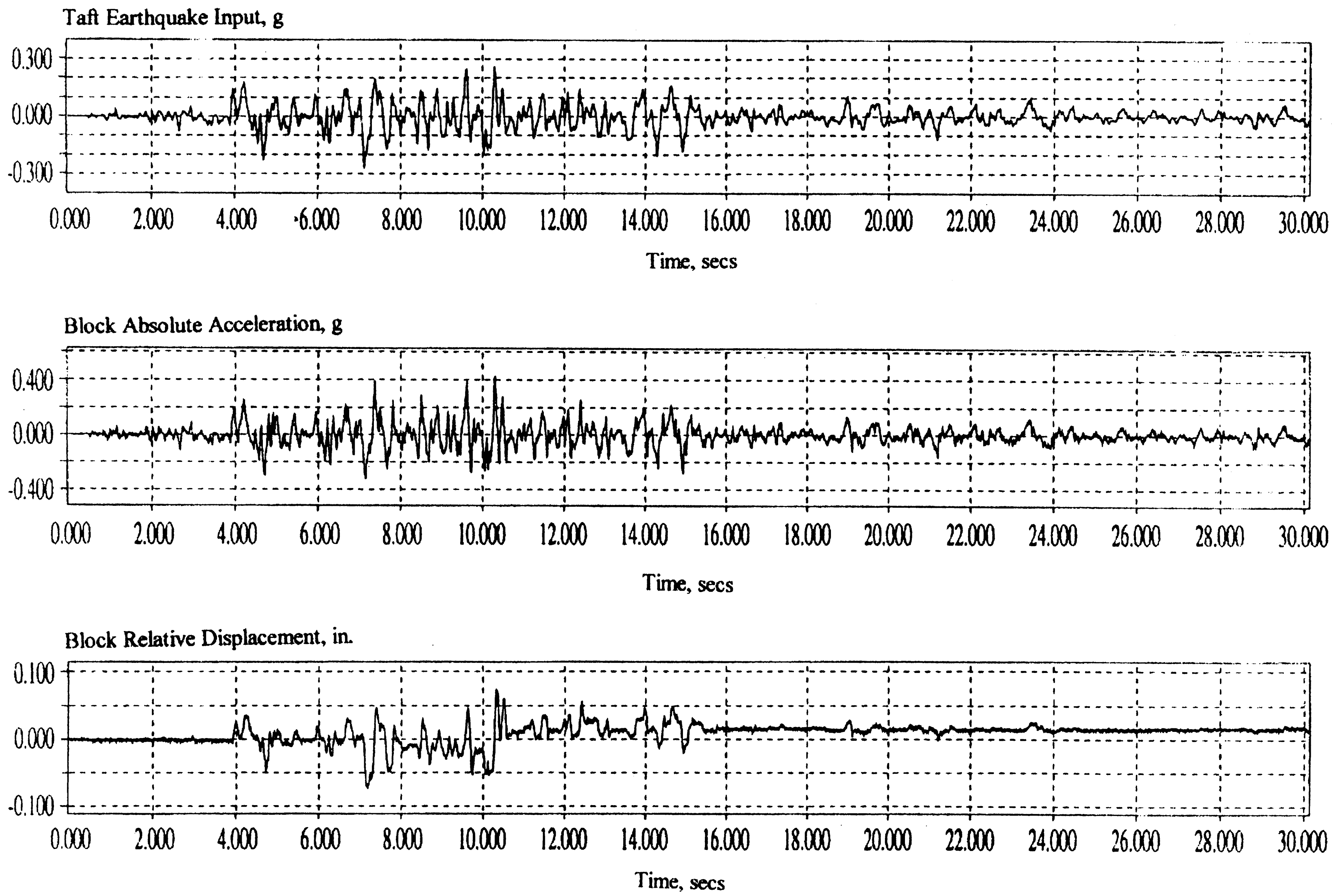


Figure 3.20 Typical Experimental Result from Taft Earthquake Input

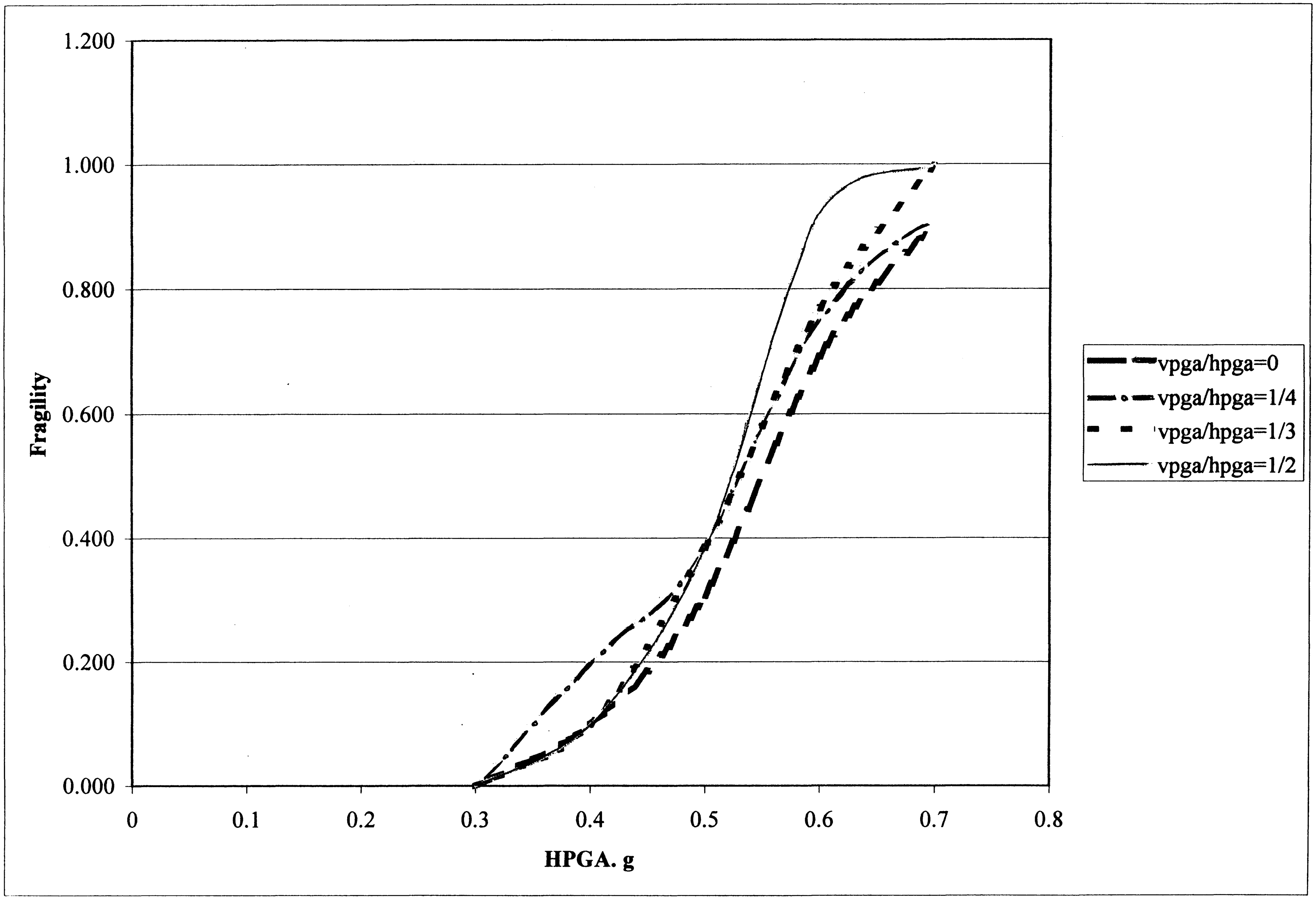


Figure 3.21 Experimental Fragility Curves for Failure Threshold = 1 inch

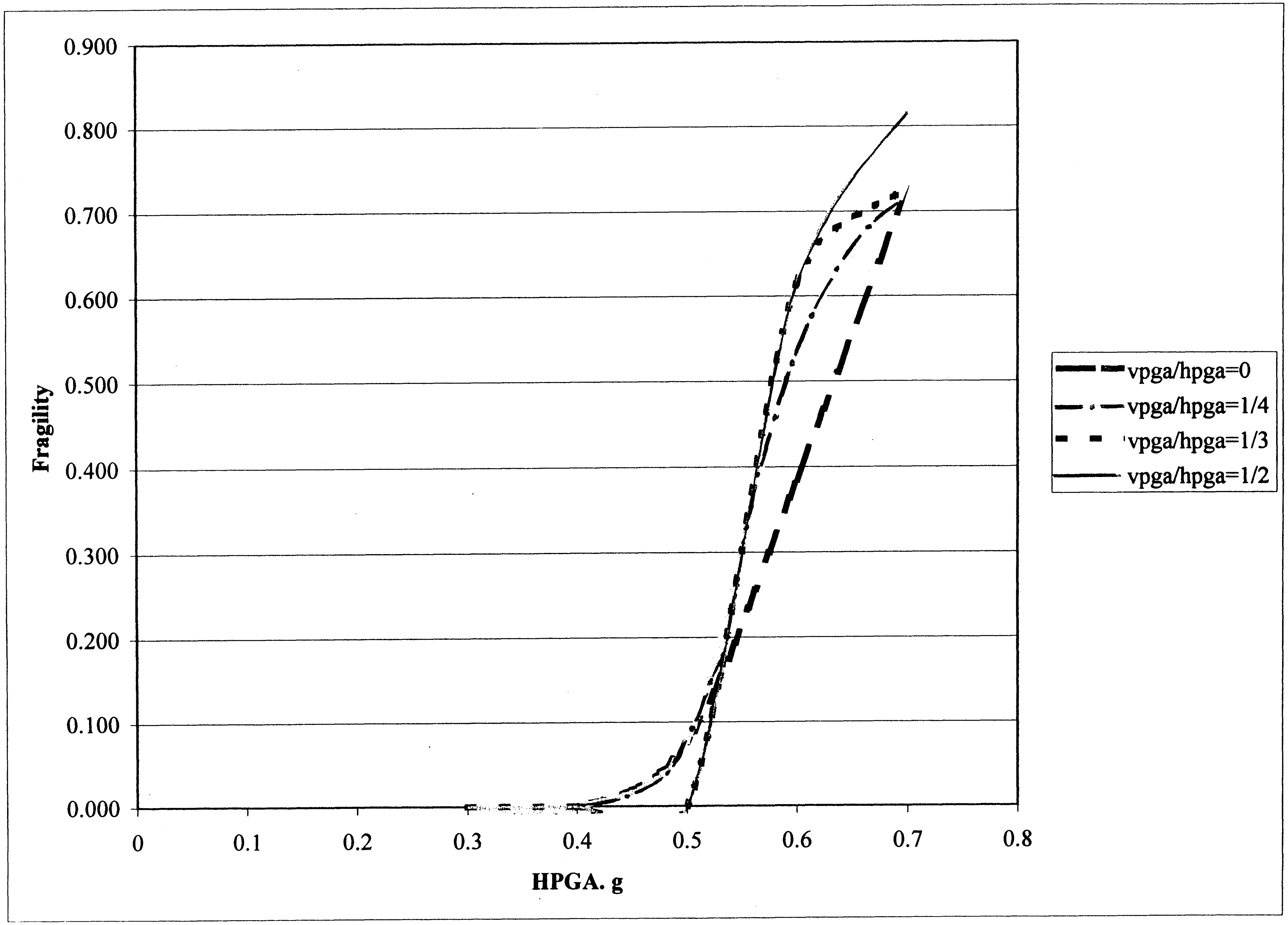


Figure 3.22 Experimental Fragility Curves for Failure Threshold = 2 inches

inches are shown in Figure 3.21 and 3.22, respectively. A comprehensive presentation of the probabilities of failure for all of the failure thresholds considered is given in Table 3.4.

3.3.3 Discussion of Results

The results obtained from the experiments are somewhat similar to the results obtained analytically. Most of the threshold displacements increase as magnitudes of the horizontal and vertical excitation inputs increase. Moreover, the insensitivity of the absolute acceleration at which threshold displacement occurs to the change of horizontal and vertical input excitations once again revealed in the experimental results, as in the analytical solutions. However, some experimental results show that, for a specific HPGA and coefficient of dynamic friction, the peak displacements do not always increase as the VPGA increases, as in the analytical results.

The experimental coefficient of dynamic friction was obtained through multiplying a scale factor to the coefficient of static friction obtained experimentally due to the fact that the coefficient of dynamic friction was difficult to determine by experimental means. Comparison of the analytical and experimental results is illustrated in more detail in the next section.

3.4 Comparison of Analytical and Experimental Results

Based on the displacement failure thresholds, it can be seen from the analytical and experimental results that, as the coefficient of dynamic friction increases, the free-standing rigid block will have less vulnerability in resisting earthquake excitation. In other words, it will perform better in resisting earthquake load with a larger coefficient of dynamic friction of the contact surfaces. However, as the HPGA and VPGA of an excitation increase, the rigid block will have a larger probability of failure for a given sliding failure mode.

On the other hand, it was found that the fragility curves are not necessary to be constructed base on the threshold displacement together with the absolute accelerations at which threshold displacements occur for a specific dynamic friction coefficient. This is due to the fact that from a summary of those average absolute acceleration results for each of the cases considered in Section 2, it could be seen that no matter how the HPGA or VPGA changes, the average absolute accelerations for each cases remain almost unchanged. The experimental results produce a somewhat similar pattern in this case.

As for a comparison of the analytical and experimental results, Figures 3.23 and 3.24 show the results for the displacement thresholds of 1 inch and 2 inches, respectively, obtained analytically and experimentally for a coefficient of dynamic friction of 0.3. As can be noticed in these figures, there is quite a difference between the analytical and experimental solutions. This difference can be explained by the use of the experimentally obtained static friction coefficient, 0.3, as the dynamic friction coefficient in obtaining analytical results.

The coefficient of friction determined in the experiments is for the static case. This value was used in the analytical solution procedure despite the fact that the dynamic friction coefficient, which is supposed to be smaller than 0.3, should be used in the analytical solution procedure.

Therefore, we can see from Figures 3.23 and 3.24 that the analytical failure curves are lower than those experimental solutions. This 'lower position' suggests that the probabilities of failure, determined analytically, are supposed to be higher than what are shown in Figures 3.23 and 3.24 if a proper coefficient of dynamic friction is used.

The proper coefficient of dynamic friction, which should be input into the analytical solution procedure, is supposed to be smaller than the determined static coefficient of friction of 0.3. Due to the fact that there is no suitable experimental procedure that we could perform to determine the dynamic coefficient of friction, a coefficient of 0.7 of the static coefficient of friction, which is 0.21, is taken to be the dynamic coefficient of friction. This value was selected based on Table C1 (Dimarogonas, 1996) for similar sliding surfaces. These analytical solutions obtained based on the scaled coefficient of dynamic friction of 0.21 agree well enough with the experimental results as shown in Figures 3.25 and 3.26 for the displacement failure thresholds of 1 inch and 2 inches.

Table 3.4 Experimental Probabilities of Failure

vpga/hpga = 0

Threshold Sliding Distance, in

PGA	0.1	0.2	0.5	0.75	1	2	2.5	3
0.300	0.700	0.400	0.000	0.000	0.000	0.000	0.000	0.000
0.400	0.800	0.700	0.400	0.200	0.100	0.000	0.000	0.000
0.500	1.000	0.846	0.538	0.385	0.308	0.077	0.000	0.000
0.600	1.000	1.000	0.846	0.692	0.692	0.385	0.308	0.154
0.700	1.000	1.000	1.000	0.909	0.909	0.727	0.455	0.364

vpga/hpga = 1/4

Threshold Sliding Distance, in

PGA	0.100	0.200	0.500	0.750	1.000	2.000	2.500	3.000
0.300	0.500	0.200	0.000	0.000	0.000	0.000	0.000	0.000
0.400	0.700	0.700	0.200	0.200	0.200	0.000	0.000	0.000
0.500	1.000	0.923	0.538	0.385	0.385	0.077	0.000	0.000
0.600	1.000	1.000	0.923	0.769	0.769	0.538	0.385	0.231
0.700	1.000	1.000	1.000	1.000	0.909	0.727	0.545	0.545

vpga/hpga = 1/3

Threshold Sliding Distance, in

PGA	0.100	0.200	0.500	0.750	1.000	2.000	2.500	3.000
0.300	0.500	0.200	0.000	0.000	0.000	0.000	0.000	0.000
0.400	0.700	0.700	0.200	0.200	0.100	0.000	0.000	0.000
0.500	1.000	1.000	0.538	0.462	0.385	0.000	0.000	0.000
0.600	1.000	1.000	0.923	0.923	0.769	0.615	0.538	0.308
0.700	1.000	1.000	1.000	1.000	1.000	0.727	0.545	0.545

vpga/hpga = 1/2

Threshold Sliding Distance, in

PGA	0.100	0.200	0.500	0.750	1.000	2.000	2.500	3.000
0.300	0.500	0.200	0.000	0.000	0.000	0.000	0.000	0.000
0.400	0.800	0.700	0.300	0.200	0.100	0.000	0.000	0.000
0.500	1.000	1.000	0.615	0.538	0.385	0.000	0.000	0.000
0.600	1.000	1.000	1.000	0.923	0.923	0.615	0.538	0.231
0.700	1.000	1.000	1.000	1.000	1.000	0.818	0.545	0.545

Table 3.5 Analytical Probabilities of Failure for $\mu_d = 0.21$

vpga/hpga = 0

PGA	0.1 in	0.2 in	0.5 in	0.75 in	1 in	2 in	2.5 in	3 in
0.3	0.011111	0	0	0	0	0	0	0
0.4	0.855556	0.411111	0	0	0	0	0	0
0.5	1	0.977778	0.644444	0.322222	0.166667	0	0	0
0.6	1	1	0.955556	0.844444	0.7	0.133333	0.066667	0.033333
0.7	1	1	1	1	0.977778	0.566667	0.344444	0.2
0.8	1	1	1	1	1	0.855556	0.688889	0.555556
0.9	1	1	1	1	1	0.988889	0.911111	0.822222
1	1	1	1	1	1	1	0.988889	0.944444

vpga/hpga = 1/4

PGA	0.1 in	0.2 in	0.5 in	0.75 in	1 in	2 in	2.5 in	3 in
0.3	0.044444	0	0	0	0	0	0	0
0.4	0.877778	0.522222	0.1	0.011111	0	0	0	0
0.5	1	1	0.711111	0.477778	0.311111	0.011111	0	0
0.6	1	1	1	0.9	0.788889	0.366667	0.211111	0.133333
0.7	1	1	1	1	0.955556	0.733333	0.533333	0.455556
0.8	1	1	1	1	1	0.911111	0.844444	0.733333
0.9	1	1	1	1	1	0.977778	0.966667	0.888889
1	1	1	1	1	1	1	1	0.988889

vpga/hpga = 1/3

PGA	0.1 in	0.2 in	0.5 in	0.75 in	1 in	2 in	2.5 in	3 in
0.3	0.077778	0	0	0	0	0	0	0
0.4	0.9	0.588889	0.155556	0.033333	0	0	0	0
0.5	1	1	0.788889	0.611111	0.433333	0.044444	0.011111	0
0.6	1	1	0.988889	0.933333	0.844444	0.488889	0.322222	0.188889
0.7	1	1	1	1	0.988889	0.811111	0.722222	0.555556
0.8	1	1	1	1	1	0.922222	0.877778	0.855556
0.9	1	1	1	1	1	0.977778	0.944444	0.911111
1	1	1	1	1	1	1	1	0.966667

vpga/hpga = 1/2

PGA	0.1 in	0.2 in	0.5 in	0.75 in	1 in	2 in	2.5 in	3 in
0.3	0.111111	0.011111	0	0	0	0	0	0
0.4	0.977778	0.855556	0.255556	0.088889	0.011111	0	0	0
0.5	1	1	0.944444	0.855556	0.666667	0.144444	0.055556	0.011111
0.6	1	1	1	0.988889	0.966667	0.744444	0.622222	0.433333
0.7	1	1	1	1	1	0.966667	0.922222	0.811111
0.8	1	1	1	1	1	0.988889	0.977778	0.966667
0.9	1	1	1	1	1	1	1	0.977778
1	1	1	1	1	1	1	1	1

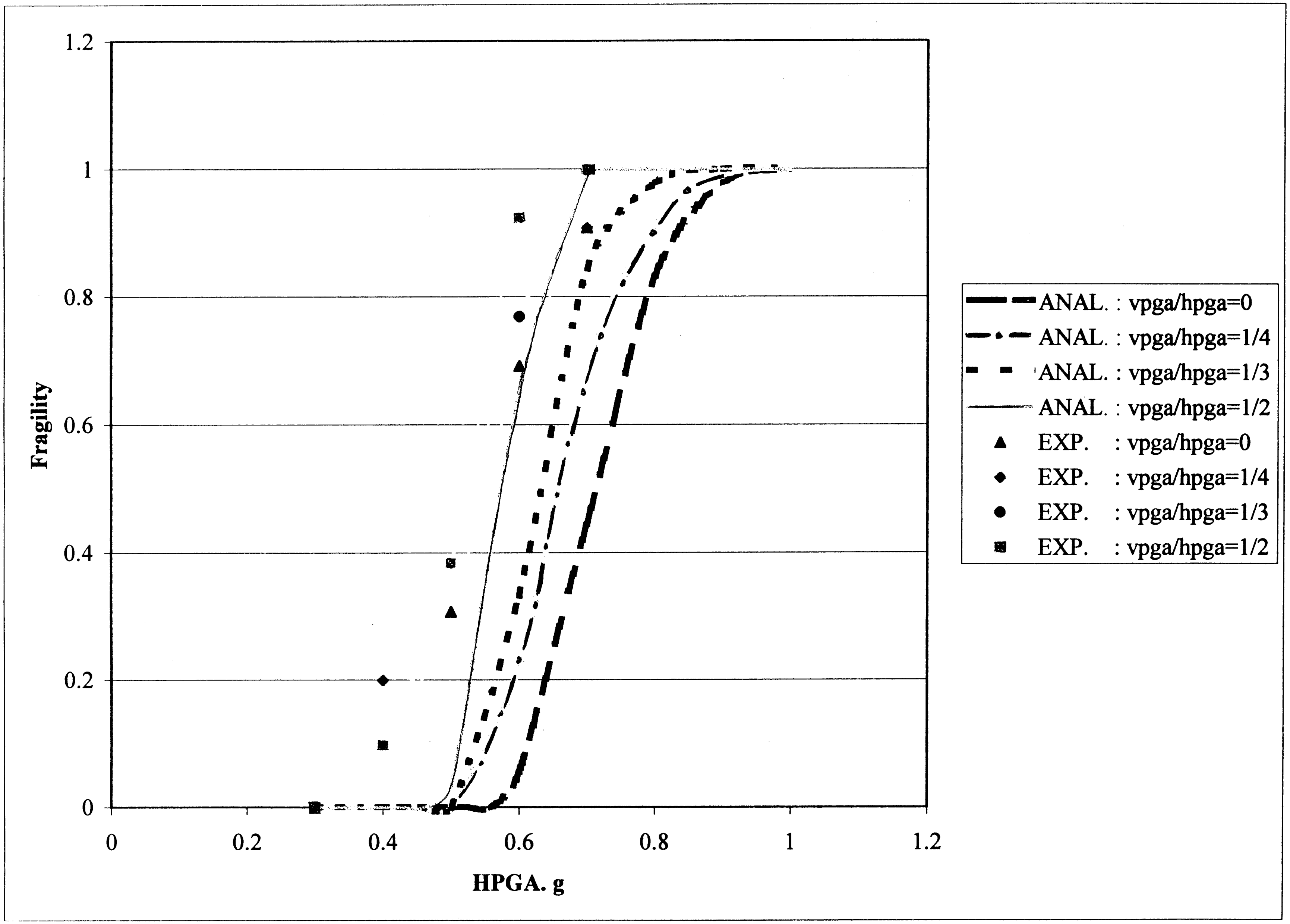


Figure 3.23 Comparison of Experimental and Analytical Fragility Curves with $\mu_d = 0.3$, Failure Threshold = 1 inch

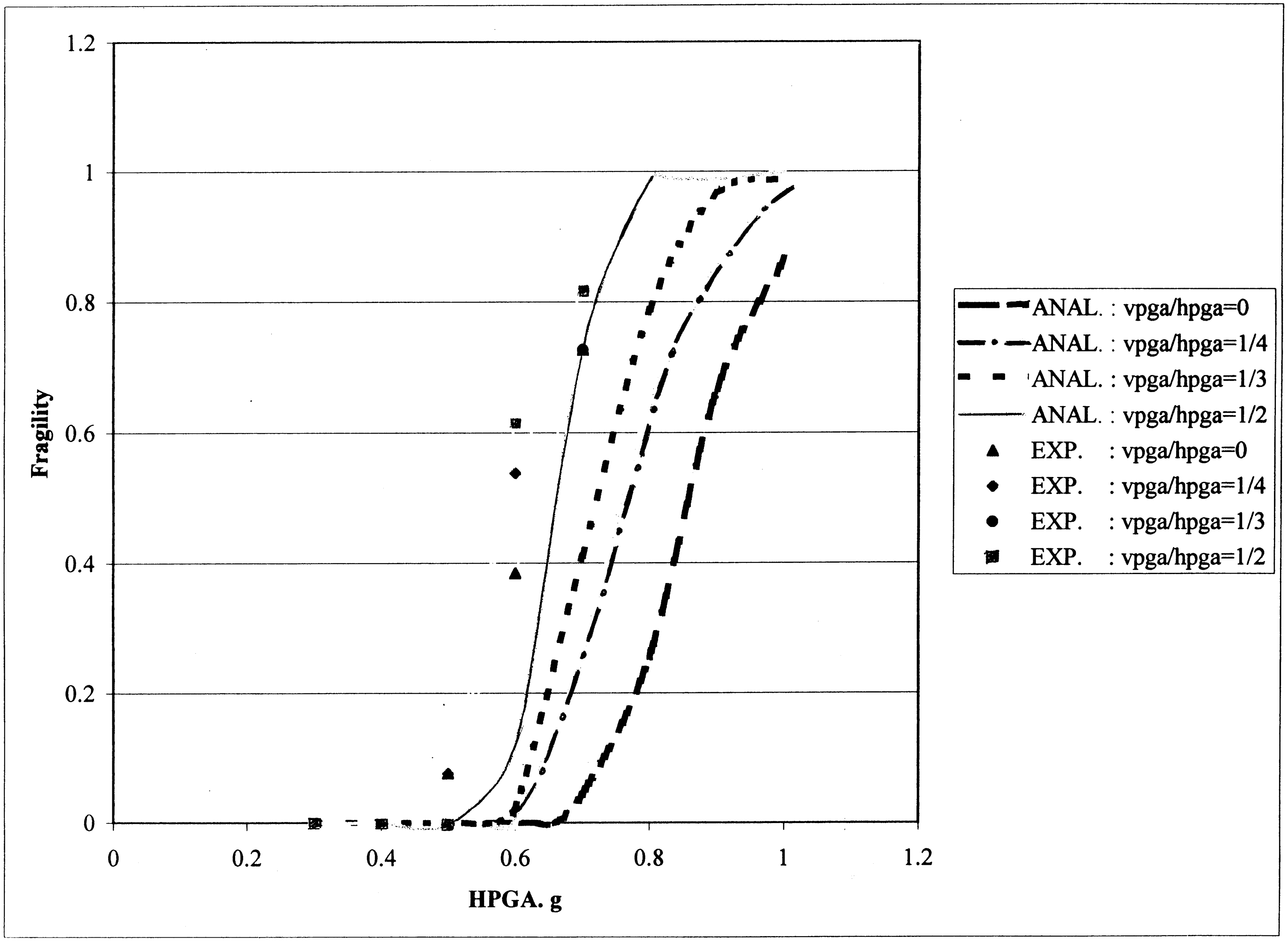


Figure 3.24 Comparison of Experimental and Analytical Fragility Curves with $\mu_d = 0.3$, Failure Threshold = 2 inches

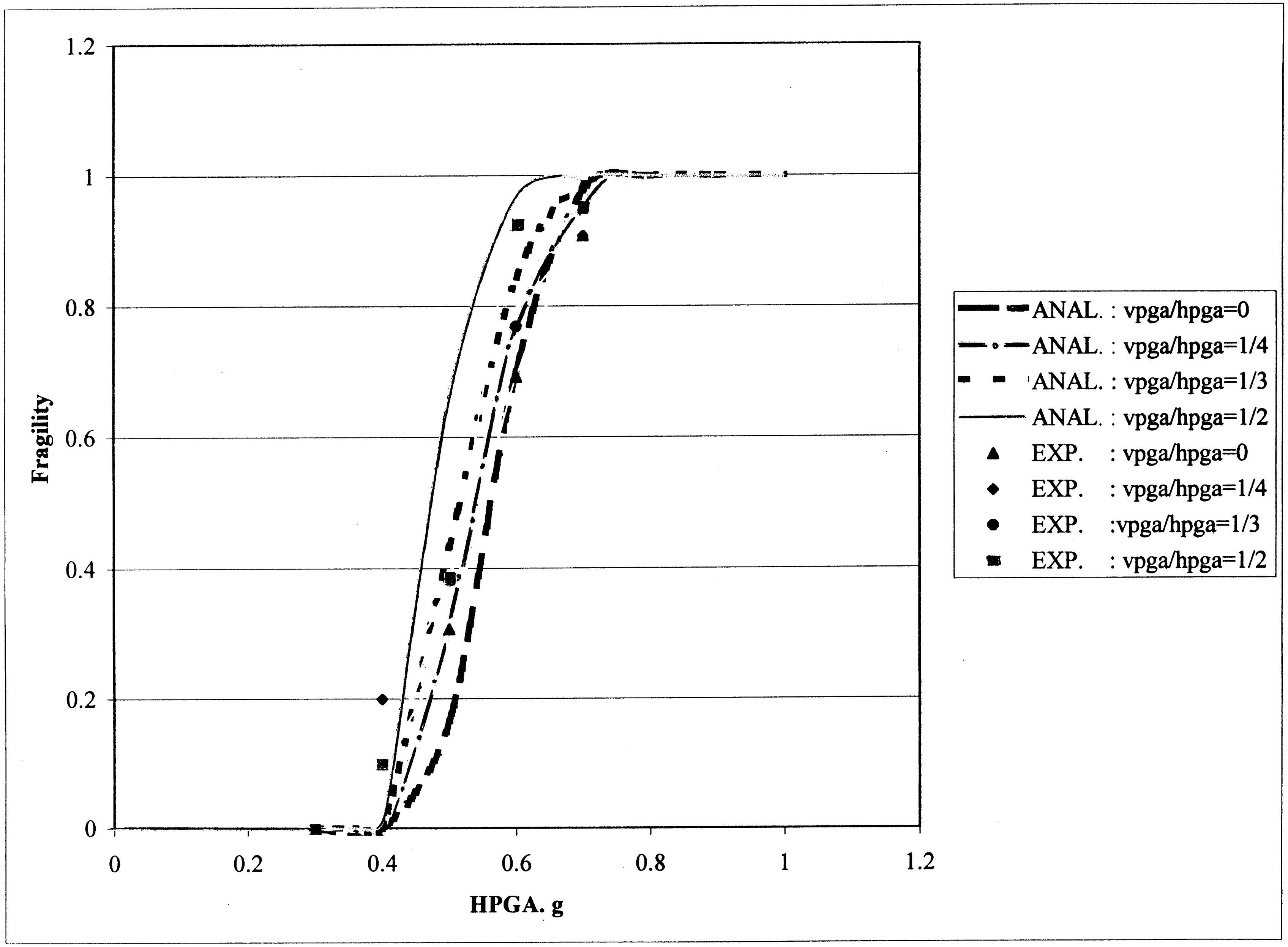


Figure 3.25 Comparison of Experimental and Analytical Fragility Curves with $\mu_d = 0.21$, Failure Threshold = 1 inch

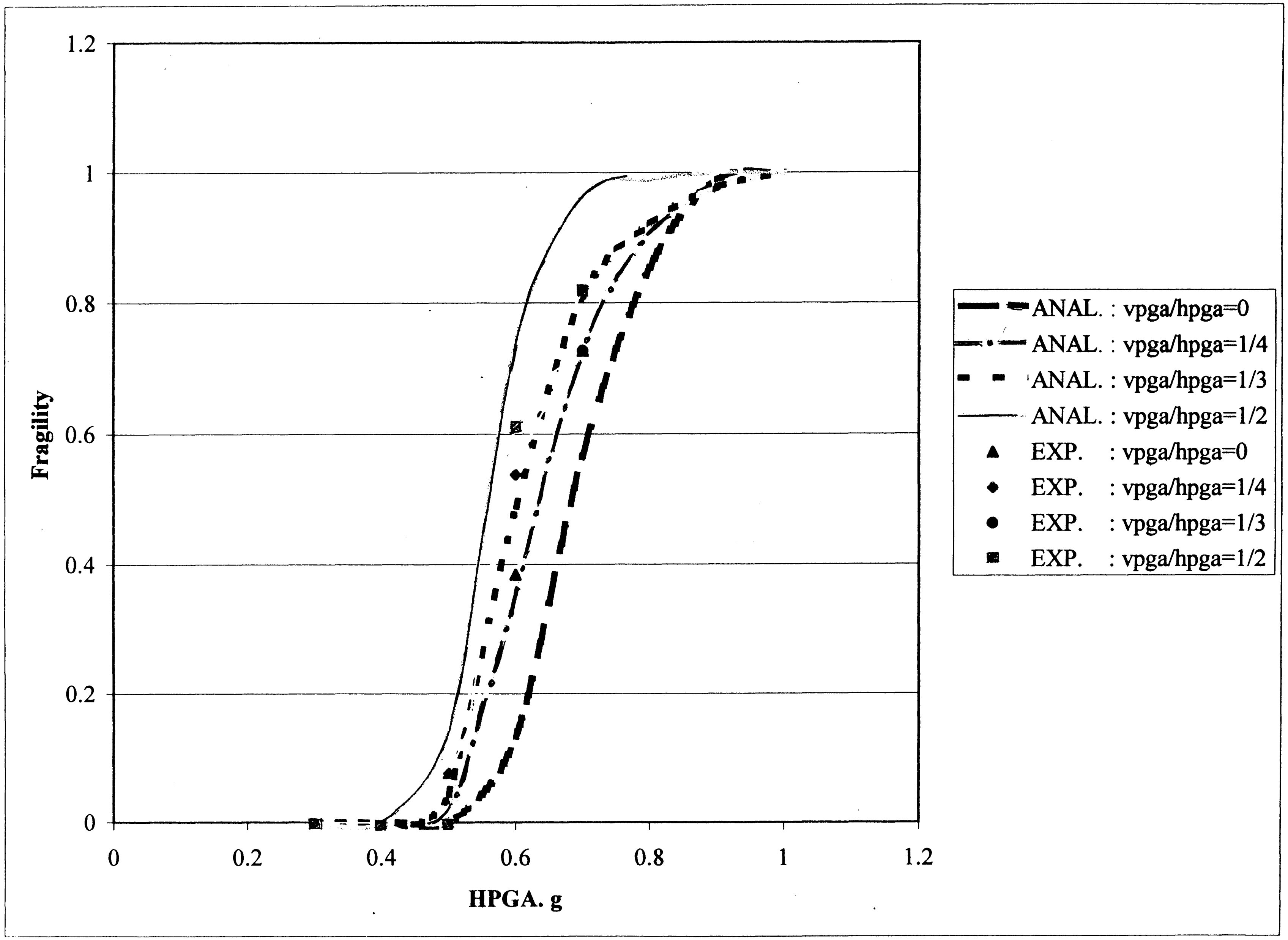


Figure 3.26 Comparison of Experimental and Analytical Fragility Curves with $\mu_d = 0.21$, Failure Threshold = 2 inches

SECTION 4
CONCLUSION

4.1 Conclusion

A free-standing rigid block resting on a rigid supporting base subjected to horizontal and vertical base excitations is an excellent model of an unrestrained block-type equipment under seismic excitations. There are, basically, four types of response of this rigid block that can be initiated under base excitations, depending on the excitation level, the aspect ratio (b/h), and the static friction coefficient. They are the at-rest state, sliding motion, rocking motion, and jumping motion. A graphical representation of sliding and rocking motion types can be used to determine the motion of the free-standing rigid block once the peak value of the base excitation level is known. This representation is developed by assigning static friction coefficient as the abscissa and aspect ratio as the ordinate.

A combined analytical and experimental approach has been implemented to assess the fragility of free-standing rigid block under pure sliding motion. The equation of sliding motion has been derived in term of horizontal force balance. SIMQKE was used to generate base excitations, for the analytical solution procedure, based on the response spectrum specified by NEHRP. On the other hand, the base excitations used in the experiments were from past earthquake data. A comparison of the analytical and experimental results was made possible by multiplying a scale factor into the experimentally determined static friction coefficient, in order to match the dynamic friction coefficient used in the analytical solution procedure.

Three sensitive parameters have been studied in this research. They are the coefficient of dynamic friction, the HPGA and the VPGA. From the results obtained, both analytical and experimental, relative displacement increases as the HPGA and VPGA increases and decreases as the coefficient of friction increases, as expected. On the other hand, the absolute acceleration at which threshold acceleration occurs is insensitive to changes as the HPGA and VPGA change while the coefficient of dynamic friction remains unchanged. However, it increases as the coefficient of dynamic friction increases, and in fact, it has an almost perfectly correlation with the dynamic friction coefficient.

4.2 Recommendations for Future Research

Theoretical assumptions were made in this research in order to simplify the problem and obtain analytical solutions. In regards to this, investigation and modifications of the theoretical model should further be implemented to verify its validity and to improve upon performance predictions. This section addresses some specific issues for future improvements on this analytical model and accuracy of results.

4.2.1 Sliding-Rocking Motion Type and Jumping Motion Type

It was assumed in this research that the restraining moment is large enough to prevent rocking motion of a sliding block and no jumping will occur during sliding. However, in realistic situations, these assumptions may not always be true. Rocking motion may also occur if the restoring moment is not large enough and jumping will happen if VPGA is too large. Thus, these motion types may also need to be incorporated into this study. In this case, the equation of sliding motion may break down and new equations of motion need to be derived, which may be much more complicated than the equation of sliding motion.

4.2.2 Deviation from Horizontal Supporting Base

The surface of supporting base was assumed to be horizontal in this research. This assumption may not be valid in realistic situations, and thus introducing the sliding angle parameter in the equation of motion is necessary to better predict the sliding performance of unrestrained block-type equipment.

4.2.3 Experimental Estimation of Dynamic Friction Coefficient

Determination of the actual dynamic friction coefficient experimentally is an important subject in validating the accuracy of the analytical model in this research. Due to this importance, further effort should be concentrated on the method for this determination.

SECTION 5
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APPENDIX A DISCRETE SYSTEM ANALYSIS FOR SLIDING PROBLEM

```
/* slide-stick program for a block on ground attached with tendons */ /*
Written by Rahul Rana, Modified by Woon Hui Chong */

#include<stdio.h>
#include<math.h>

main(){

FILE *f1;
FILE *f2;
FILE *f10;
/*FILE *f5;*/
/*FILE *f3;
FILE *f4;
FILE *f5;
FILE *f6;
FILE *f7;
FILE *f8;
FILE *f9;*/

int i,j,k,N,NUM,n,l,parts;
int counter,stick,sgn,index,loop;

float quake[1024];
float s1,sd1,s2,sd2,sdd2,z2,zd2,zdd2,xg1,xg2,P1,Q2,Teq,ratio;
float
a,b,c,d,e,blah,tau,one,two,peak_displ,peak_vel,peak_acc,peak_displ_acc;
float minvel,DT,dt,mu,W,Wd,xi,T,D,theta,M;

char c1[]={'s','i','m','1','0','h','.','h','s','t','\0'};
char infile[20], outfile[20];
printf("enter the inputfile name:\n");
scanf("%s",infile);
printf("enter the outputfile name:\n");
scanf("%s",outfile);

f10=fopen(outfile,"w+");
f2=fopen(infile,"r");

for(loop=10;loop<100;loop++)

{

c1[3]=(loop/10)+48;
c1[4]=loop%10+48;

if ((f1=fopen(c1,"r"))==NULL) {
  printf("sorry, cannot open file %s\n",c1);
}

/*f3=fopen("summary29","w");

f4=fopen("p_disp29","w");*/
/*f5=fopen("p_acc29","w");*/
/*f6=fopen("p_vel29","w");

f7=fopen("disp29_h","w");
f8=fopen("acc29_h","w");
f9=fopen("vel29_h","w");
*/
fscanf(f2,"%f %f %f %d",&minvel,&DT,&dt, &NUM);
/* minvel: If velocity falls below minvel, block is considered stuck. */
/* DT: The excitation data interval */
/* dt: Interval of integration */
/* NUM: total number of points to read from file 'excitation' */
```

```
n=ceil(DT/dt);
/* Input data file should have DT and dt such that DT/dt is an integer. 'ceil'
   is used here since DT/dt will be float which otherwise can't be assigned
   to int variable n */

N=(NUM-1)*n+1;

fscanf(f2,"%f %f %f %f %d",&mu,&W,&one,&two,&parts);

/* mu: coeff of friction */
/* W: natural frequency */
/* xi: damping ratio */

fscanf(f2,"%f %f %f %f %f",&T,&D,&a,&M,&ratio);
theta=a*M_PI/180.0;

/* T: Pretension in cable */
/* D: depth */
/* a: angle in degrees, theta: angle in radians.*/
/* M: Block mass */
/* Vertical ground acc = horizontal ground acc (file 'excitation') * ratio */

Teq=2*T*sin(theta);

for (i=0;i<NUM;i++){
  fscanf(f1,"%f %f",&a,&b);
  quake[i]=b*0.3;
}

for (l=0;l<=parts;l++) {     /* looping over damping ratio */

peak_displ=peak_acc=peak_vel=0.0;

xi=one+(two-one)*l/parts;

Wd=W*sqrt(1-xi*xi);

blah=xi*W*dt;

stick=1; s1=sd1=xg1=0.0; index=0;

if ((parts==1) && (l==0)) {
/* save time-history if no damping ratio looping is done */

/*fprintf(f7, "%5.2f %10.5f\n", 0.0, 0.0);
fprintf(f8, "%5.2f %10.5f\n", 0.0, 0.0);
fprintf(f9, "%5.2f %10.5f\n", 0.0, 0.0);
*/
}

counter=0;      /* counter for when to store results. the big for loop follows*/
for (k=0;k<N;k++){

/* now xg2 by interpolation of quake[] vector */

  xg2=9.81*(quake[index]+(quake[index+1]-quake[index])*counter/n);

if (stick == 1) {                         /* block is sticking */
    d=mu*(9.81+(Teq/M)+(xg1*ratio)); e=fabs(W*W*s1+xg1);

/* vertical acceleration = xg1*ratio. Teq is equivalent pretension in cable. */

    if (d < e) {
      stick=0; sgn=((xg1 > 0)? -1:+1);
    }
    else {
```

```
      s2=s1; sd2=0.0; sdd2=0.0;
     }
   } /* if stick == 1 */

   if (stick == 0) {                        /* block is sliding */
     P1=-(xg1+mu*(9.81+Teq/M+xg1*ratio)*sgn);
     Q2=-(xg2-xg1)-mu*sgn*(xg2-xg1)*ratio;
     c=pow(M_E,-blah);

     z2=c*(-((1-2*xi*xi)/(W*W*Wd*dt))*sin(Wd*dt)+((2*xi)/(W*W*W*dt))*cos(Wd*dt))*Q2 + c*((1/Wd

     s2 = z2 + (1/(W*W))*(P1+(1-(2*xi)/(W*dt))*Q2);

     zd2 = -xi*W*z2 + Wd*c*(-((1-2*xi*xi)/(W*W*Wd*dt))*cos(Wd*dt)-((2*xi)/(W*W*W*dt))*sin(Wd*d

     sd2 = zd2 + Q2/(W*W*dt);

     zdd2 = -2*xi*W*zd2 - W*W*z2;

     sdd2 = zdd2;
     if (fabs(sd2)<minvel) stick=1;     /* if vel < minvel, block sticks */
   }

   counter++;
   if (counter == n) {
     index++;

     if ((parts==1) && (l==0))
  { /* save time-history if no damping ratio looping is done */

       tau=DT*index;
   /*    fprintf(f7, "%5.2f %10.5f\n", tau,s2);
       fprintf(f8, "%5.2f %10.5f\n", tau,(sdd2+xg2)/9.81);
       fprintf(f9, "%5.2f %10.5f\n", tau,sd2);
     */}
   }
   if (counter==n) counter=0;

 a=peak_displ;b=peak_vel;c=peak_acc;
 d=sdd2+xg2;
 if (fabs(s2) > fabs(a)) { peak_displ=fabs(s2); peak_displ_acc=fabs(d);}
 if (fabs(sd2) > fabs(b)) peak_vel=fabs(sd2);

 if (fabs(d) > fabs(c)) peak_acc=fabs(d);

   xg1=xg2; s1=s2; sd1=sd2; sgn=((sd2 > 0)? 1:-1);

 } /* The big for loop */

 fprintf(f10,"%10.5f %14.7f %14.7f\n",xi,peak_displ,peak_displ_acc);
 /*fprintf(f4,"%10.5f %14.7f\n",xi,peak_displ);*/
 /*fprintf(f5,"%10.5f %14.7f\n",xi,peak_acc/9.81);*/
 /*fprintf(f6,"%10.5f %14.7f\n",xi,peak_vel);
 */

 }/* looping over damping ratio */

 fclose(f1);

 }
 fclose(f2);
 /*fclose(f3);
 fclose(f4);
 fclose(f5);
 fclose(f6);
 fclose(f7);
```

```
fclose(f8);
fclose(f9);*/
fclose(f10);

}
```

APPENDIX B SIMQKE PROGRAM

```
      PROGRAM SIMQK
C
C     - SIMULATION OF EARTHQUAKE GROUND MOTIONS -
C
C     DEVELOPED BY - E. H. VANMARCKE, C. A. CORNELL,
C                    D. A. GASPARINI AND S. N. HOU
C                    DEPARTMENT OF CIVIL ENGINEERING
C                    MASSACHUSETTS INSTITUTE OF TECHNOLOGY
C                    CAMBRIDGE, MASSACHUSETTS 02139
C
C     PROGRAM DATE - AUGUST 1969, REVISED SEPTEMBER 1976
C
C     NOTES - THIS SOURCE DECK HAS BEEN MODIFIED FOR A CDC6400
C           - DUMMY SUBROUTINE PLOT CALLS (SC4020) HAVE BEEN INSERTED
C
C     installiert auf VAX-11/780, H.G.Hartmann, 1-Jun-1988
C           - Bestimmung der Zufallszahl ver{ndert
C           - umgestellt von Inch auf Meter
C           - Eingabe eines Beschleunigungsspektrums m|glich
C
C INPUT PARAMETERS REQUIRED
C
C  IX--A STARTER FOR THE RANDOM NUMBER GENERATOR-IT MUST BE ODD
C  NPA---NUMBER OF DIFFERENT MOTIONS REQUIRED
C  ICASE---=1 FOR STATIONARY CASE
C  TL - THE LARGEST PERIOD VALUE FOR RESPONSE CALCULATIONS
C  TS - THE SMALLEST VALUE
C  TMIN,TMAX---OPTIONAL MINIMUM AND MAXIMUM PERIODS TO DETERMINE FREQUEN
C  CONTENT OF THE MOTION. DEFAULT USES TS AND TL
C  NCYCLE---THE NUMBER OF ITERATIONS TO BE PERFORMED IS ONE LESS
C  THAN THIS NUMBER--IF NCYCLE = 1, NO ITERATION IS MADE
C  DELT -- TIME INTERVAL USED BETWEEN POINTS
C  NDAMP---NUMBER OF DIFFERENT DAMPINGS TO BE CONSIDERED
C  AMOR---ARRAY CONTAINING THE DAMPING VALUES
C  TRISE --- RISE TIME
C  TLVL --- INTERVAL AT THE HIGHEST AMPLITUDE
C  NGWK -- DEFINES TYPE OF SPECTRAL DENSITY FUNCTION USED
C  IF NGWK = 0 , THE PROGRAM GENERATES ITS OWN POWER SPECTRUM.
C  IF NGWK IS NOT = 0, THEN A PIECEWISE LINEAR POWER SPECTRUM
C  WILL BE PROVIDED BY USER AND NGWK = NUMBER OF POINTS THAT DEFINE IT.
C  IF NGWK IS NEGATIVE, THEN GWK WILL BE READ ALONG WITH PERIODS FOR
C  RESPONSE CALCULATIONS
C  ABS(NKK) = NUMBER OF POINTS FOR RESPONSE CALCULATIONS.
C  IF NKK IS POSITIVE, THE PROGRAM WILL GENERATE A STRING OF POINTS
C  ON A LOGARITHMIC SCALE FROM TS TO TL.
C  IF NKK IS NEGATIVE, THE USER PROVIDES A LIST OF POINTS.
C  (TSV,SV0) - POINTS WHICH DEFINE DESIRED VELOCITY RESPONSE SPECTRUM
C  NRES---NUMBER OF POINTS WHICH DEFINE DESIRED VEL.RESPONSE SPECTRUM
C  IF NRES < 0, INPUT OF ACC. RESPONSE SPECTRUM
C  IF NRES = 0, NO DATA NEED BE GIVEN(NO CYCLING ONLY).
C  (W0,GWK0) - POINTS THAT DEFINE POWER SPECTRUM IF NGWK IS NOT = 0.
C  TQ---OPTIONAL ARRAY OF PERIOD VALUES FOR RSPONSE CALCULATIONS.
C  AGMX --- MAX GROUND ACC  INPUT UNIT IN M/S**2
C  DUR --- DURATION
C  UNITS   SECONDS,METER ---UNLESS SPECIFIED OTHERWISE
C
      INTEGER*4 IX
      DIMENSION TQI(150)
      DIMENSION RR(300)
      DIMENSION YTITL(9),TITLO(9)
      DIMENSION TIT(9),TIM(9),TIMX(9),TIMY(9),TIX(9),TITX(9),TITY(9)
      DIMENSION ACCG(8001),WB(300),GWK(300),TIME(3001),FRQ(300),
     1          TQ(300),PLTVMX(10,300),AMOR(10),TITLE(20),IBUF(2000),
     2          FQ(1500),GWG(1500),PA(1500),DW(1500),TMD(10,300),
     $          W0(300),GWK0(300),SV(300),TSV(1010),SV0(1010),SI(300)
     *          ,ANEWGK(300)
```

```
      DIMENSION PERCEN(300)                                              SIMQ  62
C-----------------------------------------------------------------------
      DIMENSION SAY(1010),VELROD(10)
      CHARACTER*10 filename

      EQUIVALENCE(TIME(1),FQ(1)),(TIME(1501),DW(1)),(GWG(1),PLTVMX(1))  SIMQ  63
      DATA TIX/ 4H    ,4H    ,4HRESP,4HONSE,4H SPE,4HCTRU,4HM   ,4H    ,SIMQ  64
     1         4H    /                                                   SIMQ  65
      DATA TIM/ 4H    ,4H    ,4HACCE,4HLERO,4HGRAM,4H    ,4H    ,4H    ,SIMQ  66
     1         4H    /                                                   SIMQ  67
      DATA BLANK / 4H    /                                               SIMQ  68
      DATA TIT/ 4HRESP,4HONSE,4H SPE,4HCTRU,4HM  D,4HAMPI,4HNG ',4H    ,SIMQ  69
     1         4H    /                                                   SIMQ  70
      DATA TITX/4H    ,4H  NA,4HTURA,4HL PE,4HRIOD,4H    ,4H(SEC,4HONDS,SIMQ  71
     1         4H)   /                                                   SIMQ  72
      DATA YTITL/ 4H    ,4HG(W),4H   - ,4H(M**,4H2/SE,4HC**3,4H)   ,
     1           4H    ,4H    /                                          SIMQ  73
      DATA TITLO/ 4HSPEC,4HTRAL,4H DEN,4HSITY,4H FUN,4HCTIO,4HN   ,     SIMQ  74
     1           4H    ,4H    /                                          SIMQ  75
      DATA TITY/4H    ,4H    ,4HMAXI,4HMUM ,4HVELO,4HCITY,4H  (M,4H/SEC,SIMQ  76
     1         4H)   /                                                   SIMQ  77
      DATA TIMX/4H    ,4H    ,4HTIME,4H (SE,4HCOND,4HS)  ,4H    ,4H    ,SIMQ  78
     1         4H    /                                                   SIMQ  79
      DATA TIMY/4H    ,4HACCE,4HLERA,4HTION,4H    ,4H G'S,4H    ,4H    ,SIMQ  80
     1         4H    /                                                   SIMQ  81
      DATA BETAS,BETAL/0.005,0.2/,PI/3.14159/                            SIMQ  82
      ICONT=0                                                            SIMQ  83
      OPEN(UNIT =5,FILE='sim.inp',STATUS='OLD',FORM='FORMATTED')
      OPEN(UNIT =6,FILE='SIM.OUT',status='unknown')
      OPEN(UNIT=11,FILE='SIM.POW',status='unknown')
      OPEN(UNIT=12,FILE='SIM.ACC',status='unknown')
      OPEN(UNIT=13,FILE='SIM.RES',status='unknown')
C                                                                        SIMQ  84
C    REQUIRED INPUT PARAMETERS                                           SIMQ  85
C                                                                        SIMQ  86
 9003 READ (5,1) TITLE                                                   SIMQ  87
C     CALL STOIDV ('M5324-9950',9,0)                                     SIMQ  88
C-----------------------------------------------------------------------
      READ (5,9920) TS,TL,TMIN1,TMAX1,YMIN,YMAX,IUNIT                    SIMQ  89
      IF(IUNIT.EQ.1) THEN
        sclrod=9.81
      ELSE
        sclrod=386.4
      ENDIF
C
      READ (5,3020) ICASE,TRISE,TLVL,DUR,AO,ALFAO,BETAO,IPOW              SIMQ  90
      READ (5,129) DELT,AGMX,IIX,NDAMP,NCYCLE,NPA,NKK,NRES,NGWK,IPCH     SIMQ  91
C-----------------------------------------------------------------------
      AGMX=AGMX*sclrod
C
      IF(IPCH.EQ.1)
     *OPEN(UNIT=10,FILE='PUNCH',STATUS='UNKNOWN')
C                                                                        SIMQ  93
C    FIRST DAMPING VALUE MUST BE ONE WHICH IS CYCLED ON.                 SIMQ  94
C    THE FIRST CURVE VALUE WILL BE PLOTTED (RESPONSE SPECTRUM)           SIMQ  95
C                                                                        SIMQ  96
      READ(5,7020) (AMOR(I),I=1,NDAMP)                                   SIMQ  97
      WRITE (6,2) TITLE                                                  SIMQ  98
      WRITE(6,30) DELT                                                   SIMQ  99
C                                                                        SIMQ 100
      IF (NKK.LE.0) GO TO 6301                                           SIMQ 101
C                                                                        SIMQ 102
C    OPTIONS 1 AND 2                                                     SIMQ 103
      CALL PLTX2(TS,TL,TQ,NKK)                                           SIMQ 104
      GO TO 3                                                            SIMQ 105
C                                                                        SIMQ 106
```

```
C     OPTION 3
 6301 NKK=-NKK
C
C     OPTIONAL INPUT PARAMETERS IF NKK IS NEGATIVE.
C     GWK IS REQUIRED ONLY IF NGWK IS NEGATIVE.
C
      READ (5,13) (TQ(I),I=1,NKK)
      READ (5,888)(GWK(NKK-I+1),I=1,NKK)
      READ (5,7020) N2,N3
   14 READ (5,4262) TC,GWC
      IF (TC.GT.50.0) GO TO 5
      DO 9 I=1,NKK
      IF (ABS(TC-TQ(I)).LT.0.0002) GO TO 11
    9 CONTINUE
      GO TO 14
   11 GWK(NKK-I+1)=GWC
      GO TO 14
    5 CONTINUE
      IF (N2.EQ.0) GO TO 3
      DO 10 I=1,N3
      READ (5,7020) TQ1,TQ2,RATIO
      DO 10 J=1,NKK
      IF(TQ(J).GT.TQ1.AND.TQ(J).LT.TQ2) GWK(NKK-J+1)=GWK(NKK-J+1)*RATIO
   10 CONTINUE
    3 DO 4325 I=1,NKK
      J=NKK-I+1
      FRQ(I)=1./TQ(I)
4325  WB(J)=6.2832/TQ(I)
      IF (TMIN1.EQ.0.)  TMIN1=TS
      WL=6.2832/TMIN1
      IF (TMAX1.EQ.0.)  TMAX1=TL
      WS=6.2832/TMAX1
C
C     WEND --- THE HIGHEST FREQUENCY FOR GROUND MOTION
C     WBEGIN --- THE LOWEST FREQUENCY FOR GROUND MOTION
C     THE FOLLOWING OPTIONS FOR COMPUTING WEND AND WBEGIN MAY BE
C     ELIMINATED SINCE BETAL AND BETAS HAVE BEEN DEFINED INTERNALLY BY
C     THE PROGRAM TO BE 0.2 AND 0.005 RESPECTIVELY
C
      WEND=2.0*WL
      IF ((5.0*BETAL).GE.1.0) WEND=WL*(1.+5.*BETAL)
      WBEGIN=WS*.5
      IF (BETAL.LT.0.05)  WBEGIN=WS*(1.-10.*BETAL)
      IF(ICASE.GT.1) GO TO 42
C
C     NO INTENSITY ENVELOPE USED
      WRITE(6,134)
      GO TO 38
   42 WRITE(6,135)
   38 WRITE(6,106)AGMX
      IF (NRES.EQ.0) GO TO 6022
C-------------------------------------------------------------------
C
C  IOP = 1  MEANS THE INPUT ARE DISPLACEMENT SPECTRUM
C  IOP = 2  MEANS THE INPUT ARE VELOCITY SPECTRUM
C  IOP = 3  MEANS THE INPUT ARE ACCELERATION SPECTRUM
C  SAY(I)  VALUE OF THE GIVEN SPECTRUM ( D or V or A)
          READ(5,*)IOP
          READ(5,*)(TSV(I),SAY(I),I=1,NRES)
C
C-------------------------------------------------------------------
      CALL CONVERT (TSV,SAY,NRES,IOP,SV0)
      CALL POLATE(NRES,NKK,TSV,SV0,TQ,SV)
      WRITE(6,107) TRISE,TLVL,DUR
      WRITE(6,6016)
6022  IF (NGWK.EQ.0) GO TO 4260
```

```
      IF(NGWK.LT.0) GO TO 9703                                          SIMQ 163
C                                                                       SIMQ 164
C     OPTIONAL INPUT OF ORIGINAL POWER SPECTRUM IF NGWK IS POSITIVE     SIMQ 165
C     IF TQ WAS READ IN PREVIOUSY FOR NKK NEGATIVE, THIS OVERIDES POWER SIMQ 166
C     SPECTRUM 'GWK' READ IN WITH 'TQ'.                                 SIMQ 167
C                                                                       SIMQ 168
C                                                                       SIMQ 169
C     OPTIONAL INPUT OF DESIRED RESPONSE VELOCITY                       SIMQ 170
C     SPECTRUM IF CYCLING IS USED.                                      SIMQ 171
C                                                                       SIMQ 172
      READ (5,4262) (W0(I),GWK0(I),I=1,NGWK)                            SIMQ 173
      CALL POLATE(NGWK,NKK,W0,GWK0,WB,GWK)                              SIMQ 174
 9703 DO 8011 I=1,NKK                                                   SIMQ 175
      J=NKK+1-I                                                         SIMQ 176
      GWK0(I)=GWK(I)                                                    SIMQ 177
 8011 WRITE(6,4340) TQ(I),FRQ(I),GWK(J)                                 SIMQ 178
      GO TO 6007                                                        SIMQ 179
 4260 T=(DUR+TLVL)/2.                                                   SIMQ 180
      BETA=AMOR(1)                                                      SIMQ 181
      CALL SVGW(NKK,WB,GWK0,SV,T,BETA,16.0,0.6,0.368,GSUM,WCP,QP,RR)    SIMQ 182
      INULL=0
      DO 6001 LLL=1,NKK                                                 SIMQ 183
      LL1=NKK-LLL+1                                                     SIMQ 184
      WRITE(11,889)FRQ(LL1),GWK0(LLL)
 6001 WRITE(6,8901)TQ(LL1),FRQ(LL1),GWK0(LLL),RR(LLL)                   SIMQ 185
      WRITE(11,27) INULL
      WRITE (6,8902) WCP,QP                                             SIMQ 186
C     SET THE MAXIMUM VALUE OF SPECTRAL DENSITY FUNCTION FOR PLOT       SIMQ 187
      XMAX= 0.0                                                         SIMQ 188
      DO 327 I12= 1,NKK                                                 SIMQ 189
      IF (XMAX-GWK0(I12)) 326,327,327                                   SIMQ 190
  326 XMAX=GWK0(I12)                                                    SIMQ 191
  327 CONTINUE                                                          SIMQ 192
      IF (XMAX-70.0) 329,328,328                                        SIMQ 193
  328 XLAI=XMAX/100.                                                    SIMQ 194
      NDUM=(IFIX(XLAI)+1)*100                                           SIMQ 195
      XMAX=FLOAT(NDUM)                                                  SIMQ 196
      GO TO 330                                                         SIMQ 197
  329 XMAX=70.0                                                         SIMQ 198
  330 CONTINUE                                                          SIMQ 199
      CALL GWPLOT (NKK,0.01,4.0,0.0,XMAX,TQ,GWK0,TITX,TITLO,YTITL)      SIMQ 200
      AREA=SQRT(GSUM)                                                   SIMQ 201
      WRITE(6,6008) AREA                                                SIMQ 202
6007  ITOTAL=NDAMP*NKK                                                  SIMQ 203
      IX=(IIX/2)*2+1                                                    SIMQ 204
C---------------------------------------------------------------------- SIMQ 205
C     LOOP OVER NPA, NUMBER OF ARTIFICIAL EARTHQUAKES DESIRED           SIMQ 206
C----------------------------------------------------------------------
      DO 585 NTOTAL=1,NPA                                               SIMQ 207
C----------------------------------------------------------------------
C     Open output files for time-history and response spectras
      WRITE(filename,9901) NTOTAL+9,'h.hst'
      OPEN(UNIT=20,FILE=filename,STATUS='UNKNOWN')
      WRITE(filename,9901) NTOTAL+9,'d.spc'
      OPEN(UNIT=21,FILE=filename,STATUS='UNKNOWN')
      WRITE(filename,9901) NTOTAL+9,'v.spc'
      OPEN(UNIT=22,FILE=filename,STATUS='UNKNOWN')
      WRITE(filename,9901) NTOTAL+9,'a.spc'
      OPEN(UNIT=23,FILE=filename,STATUS='UNKNOWN')
9901  FORMAT('sim',I2,5A)

      WRITE(6,60) IX                                                    SIMQ 208
      DO 8608 I=1,NKK                                                   SIMQ 209
 8608 GWK(I)=GWK0(I)                                                    SIMQ 210
      MM=1                                                              SIMQ 211
      AREAG=0.                                                          SIMQ 212
```

```
      SIGMS=0.                                                          SIMQ 213
      NFQ=0                                                             SIMQ 214
      W=WBEGIN                                                          SIMQ 215
 4080 DELW=BETAS*W                                                      SIMQ 216
      W=W+DELW                                                          SIMQ 217
      CALL DUMMY(W,FOUT,NKK,WB,GWK,MM)                                  SIMQ 218
      NFQ=NFQ+1                                                         SIMQ 219
      GWG(NFQ)=FOUT                                                     SIMQ 220
      FQ(NFQ)=W                                                         SIMQ 221
      DW(NFQ)=DELW                                                      SIMQ 222
      AREAG=AREAG+GWG(NFQ)*DELW                                         SIMQ 223
      SIGMS=SIGMS+GWG(NFQ)*DELW*W*W                                     SIMQ 224
      IF (W.LT.WEND) GO TO 4080                                         SIMQ 225
C                                                                       SIMQ 226
C    LOOP OVER NCYCLE, TO SMOOTHEN RESPONSE SPECTRUM FOR TARGET DAMPING SIMQ 227
      DO 100 ICYCLE=1,NCYCLE                                            SIMQ 228
C                                                                       SIMQ 229
C    W IS LOWEST FREQUENCY REPRESENTED IN GROUND MOTION.                SIMQ 230
C                                                                       SIMQ 231
      IF (ICYCLE.LE.1) GO TO 1116                                       SIMQ 232
      AREAG=0.                                                          SIMQ 233
      MM=1                                                              SIMQ 234
      DO 6703 I=1,NFQ                                                   SIMQ 235
      W=FQ(I)                                                           SIMQ 236
      CALL DUMMX(W,FOUT,NKK,WB,GWK,MM)                                  SIMQ 237
      GWG(I)=FOUT                                                       SIMQ 238
 6703 AREAG=AREAG+DW(I)*GWG(I)                                          SIMQ 239
 1116 DO 1117 IP=1,NFQ                                                  SIMQ 240
 1117 GWG(IP)=GWG(IP)*DW(IP)*2.                                         SIMQ 241
      IF(ICYCLE.GT.1) GO TO 8603                                        SIMQ 242
C                                                                       SIMQ 243
C    COMPUTE AVERAGE FREQUENCY AND PERIOD                               SIMQ 244
C                                                                       SIMQ 245
      SIGMS=SIGMS/AREAG                                                 SIMQ 246
      WA=SQRT(SIGMS)                                                    SIMQ 247
      TA=6.2832/WA                                                      SIMQ 248
C                                                                       SIMQ 249
C    DEFINE SLOPES OF ENVELOPE                                          SIMQ 250
C                                                                       SIMQ 251
      IF (ICASE.GT.2) GO TO 6                                           SIMQ 252
      IF(TRISE.GT..0) GO TO 33                                          SIMQ 253
      TRISE=0.25*DUR                                                    SIMQ 254
      TLVL=0.                                                           SIMQ 255
   33 IF(ICASE.LE.1) GO TO 7                                            SIMQ 256
    8 FTC1=1./TRISE                                                     SIMQ 257
      FTC2=-1./(DUR-TRISE-TLVL)                                         SIMQ 258
      GO TO 6                                                           SIMQ 259
    7 FTC1=0.5                                                          SIMQ 260
      FTC2=0.                                                           SIMQ 261
    6 WRITE(6,114) WA,TA,NFQ,WBEGIN,WEND                                SIMQ 262
C                                                                       SIMQ 263
C    COMPUTE RANDOM PHASE ANGLES                                        SIMQ 264
C                                                                       SIMQ 265
      DO 31 I=1,NFQ                                                     SIMQ 266
C*IBM*IY=IX*65539                                                       SIMQ 267
C     IY=IX*16777219                                                    CDC ONLY
C     IF (IY.GE.0.) GO TO 32                                            SIMQ 268
C*IBM*IY=IY+2147483647+1                                                SIMQ 269
C     IY=IY+140737488355327+1                                           CDC ONLY
C  32 YFL=IY                                                            SIMQ 270
C*IBM*YFL=YFL*.4656613E-9                                               SIMQ 271
C     YFL=YFL*.71054273576010E-14                                       CDC ONLY
cc      CALL RANDOM(YFL)
      YFL=RAN(IX)
      PA(I)=6.2832* YFL                                                 SIMQ 272
C  31 IX=IY                                                             SIMQ 273
```

```
   31 CONTINUE
C
C    ACCELERATION COMPUTATIONS
C
 8603 NACCG=DUR/DELT+1.000001
      IF(NCYCLE.LE.ICYCLE) GO TO 9801
      WRITE(6,9008) ICYCLE,TQ(1)
      WRITE (6,9567)
9801  DO 1114 KK=1,NACCG
 1114 ACCG(KK)=0.
      KCHEK=1000
      DO 12   LM=1,NFQ
      IF (GWG(LM).LT.0.0) WRITE (6,3000) GWG(LM),LM
      GWG(LM)=ABS(GWG(LM))
      AA=SQRT(GWG(LM))
      ALFA=FQ(LM)*DELT
      SINA=SIN(ALFA)
      COSA=COS(ALFA)
      SN=SIN(PA(LM))
      CN=COS(PA(LM))
      SNA=SINA*CN+COSA*SN
      CNA=COSA*CN-SINA*SN
      ACCG(2)=AA*SNA+ACCG(2)
      DO 12   KK=3,NACCG
      IF (KK.GE.KCHEK) GO TO 5012
      SNO=SNA
      SNA=SNA*COSA+CNA*SINA
      CNA=CNA*COSA-SNO*SINA
      GO TO 12
 5012 KCHEK=KCHEK+1000
      SNA=SIN(PA(LM)+(KK-1)*ALFA)
      CNA=COS(PA(LM)+(KK-1)*ALFA)
   12 ACCG(KK)=AA*SNA+ACCG(KK)
C
      GO TO (3003,3003,3004,3007),ICASE
C
C    TRAPEZOIDAL INTENSITY ENVELOPE
 3003 IF(ICASE.LE.1) GO TO 18
      TX=TRISE
      GO TO 19
   18 TX=2.
C
C    DEFINE MAXIMUM HEIGHTS IN TERMS OF SLOPES
C
   19 DO 16 KK=2,NACCG
      TI=(KK-1)*DELT
      IF (TI.GT.TX) GO TO 15
      FT=FTC1*TI
      GO TO 16
   15 IF(ICASE.LE.1) GO TO 28
      IF((TI-TX-TLVL).GT.0.) GO TO 29
   28 FT=1.
      GO TO 16
   29 FT=1.+(TI-TX-TLVL)*FTC2
C
C    COMPUTE ACCELERATION
C
   16 ACCG(KK)=ACCG(KK)*FT
      GO TO 3011
C
C    EXPONENTIAL INTENSITY ENVELOPE
 3004 DO 3006 KK=2,NACCG
      TI=(KK-1)*DELT
      FT=AO*(EXP(-ALFAO*TI)-EXP(-BETAO*TI))
 3006 ACCG(KK)=ACCG(KK)*FT
      GO TO 3011
```

```
C
C     COMPOUND INTENSITY ENVELOPE
 3007 DO 3010 KK= 2,NACCG
      TI=(KK-1)*DELT
      IF(TI.GE.TRISE) GO TO 3008
      FT=(TI/TRISE)**IPOW
      GO TO 3010
C 3008 IF ((TI-TLVL-TRISE).LT.0.) GO TO 3009
 3008 IF (TI.LE.TLVL) GO TO 3009
      FT=EXP(-ALFAO*(TI-TLVL))
      GO TO 3010
 3009 FT=1.0
 3010 ACCG(KK)=ACCG(KK)*FT
 3011 CONTINUE
C
C     COMPUTE MAX GROUND ACCELERATION BEFORE BASELINE CORRECTION
C
   20 AMAXIM=0.
      DO 5000 I=1,NACCG
      IF(ABS(ACCG(I)).LT.ABS(AMAXIM)) GO TO 5000
      AMAXIM=ACCG(I)
      TMAXIM=(I-1)*DELT
 5000 CONTINUE
      IF (NCYCLE.GT.ICYCLE) GO TO 8504
      WRITE(6,5200) AMAXIM,TMAXIM
 8504 T1=-DELT*0.5
C
C     JUSTIFY ACCG TO ZERO FINAL VELOCITY
C
      BETA1=0.
      BETA2=0.
      BETA3=0.
      VEL=0.
      DO 4300 IZ=1,NACCG
      VEL=VEL+ACCG(IZ)*DELT
      T1=T1+DELT
      BETA1=BETA1+VEL*T1
      BETA2=BETA2+VEL*T1*T1
 4300 BETA3=BETA3+VEL*T1*T1*T1
      BETA1=BETA1*DELT/(T1*T1*T1)
      BETA2=BETA2*DELT/(T1*T1*T1*T1)
      BETA3=BETA3*DELT/(T1*T1*T1*T1*T1)
      C1=300.*BETA1-900.*BETA2+630.*BETA3
      C2=(-1800.*BETA1+5760.*BETA2-4200.*BETA3)/T1
      C3=(1890.*BETA1-6300.*BETA2+4725.*BETA3)/(T1*T1)
      DO 4310 IZ=1,NACCG
      TI=(IZ-1)*DELT
 4310 ACCG(IZ)=ACCG(IZ)-C1-C2*TI-C3*TI*TI
C
C     GET MAXIMUM GROUND ACCELERATION
C
      GAMX=ACCG(1)
      VEL=0.
      VAMX=0.
      DISP=0.
      DMAX=0.
      LL1=0
      GAMX=ABS(GAMX)
      DO 59 LL=2,NACCG
      GAMY=ABS(ACCG(LL))
      VEL=VEL+ACCG(LL)*DELT
      DISP=DISP+VEL*DELT
      DAMY=ABS(DISP)
      VAMY=ABS(VEL)
      IF (DAMY.LE.DMAX) GO TO 52
   53 DMAX=DAMY
```

```
   52 IF (VAMY.LE.VAMX) GO TO 56
      VAMX=VAMY
   56 IF(GAMY.LE.GAMX) GO TO 59
   58 GAMX=GAMY
      LL1=LL
   59 CONTINUE
C
C     NO SCALING OF THE ENTIRE TIME HISTORY IS DONE BUT PEAKS ARE
C     ADJUSTED IN ORDER TO HAVE ONLY ONE PEAK EQUAL TO THE SPECIFIED
C     MAXIMUM GROUND ACCELERATION.
      TTT=ABS(GAMX/AGMX)
      IF(TTT.LE.1.) GO TO 1112
      DO 111 K1=1,NACCG
      DAR=ABS(ACCG(K1))-AGMX
      IF(DAR.LE.0.) GO TO 111
      ACCG(K1)=ACCG(K1)/TTT
  111 CONTINUE
      GO TO 1113
 1112 ACCG(LL1)=ACCG(LL1)/TTT
C-----------------------------------------------------------------------
 1113 GAMX=AGMX/sclrod

      LIM=NDAMP
      IF (ICYCLE.LT.NCYCLE) LIM=1
C
C     CHECK ACCG DIMENSIONS
C
      ICK=NACCG+2.*TQ(NKK)/DELT
      IF (ICK.GE.8000) WRITE (6,34) ICK
      IF (ICK.GE.8000) GO TO 9003
C
C     RESPONSE CALCULATION AND PLOTTING
C
      CALL SPECT(PLTVMX,TMD,ACCG,NACCG,DELT,TQ,NKK,AMOR,LIM)
      IF(IPCH.EQ.1) THEN
       WRITE(10,27) ICYCLE
       WRITE(10,13)(TQ(I),I=1,NKK)
       WRITE(10,888)(GWK(NKK-I+1),I=1,NKK)
      ENDIF
      IF(NCYCLE.LE.ICYCLE) GO TO 44
C
C     CYCLING PROCEDURE WHICH MODIFIES G(W) TO SMOOTHEN THE CALCULATED
C     RESPONSE SPECTRUM
C
      SUMPOS = 0.
      SUMNEG = 0.
      DO 43 I=1,NKK
      AMULT=SV(I)/PLTVMX(1,I)
      RATIOS = ABS (1./AMULT)*100.
      PERCEN(I) =      RATIOS - 100.
      WRITE(6,8901) TQ(I),FRQ(I),GWK(NKK-I+1),SV(I),PLTVMX(1,I),
     * PERCEN(I),TMD(1,I),I
      J=NKK-I+1
10002 ANEWGK(J) = GWK(J)*AMULT*AMULT
      AINCRM = ANEWGK(J)-GWK(J)
      IF (AINCRM.GE.0.) SUMPOS = SUMPOS+AINCRM
      IF (AINCRM.LT.0.) SUMNEG = SUMNEG-AINCRM
   43 CONTINUE
      IF (SUMNEG.LE.1.E-8) GO TO 213
      FACTOR = SUMPOS/SUMNEG
      WRITE (6,10000) SUMPOS,SUMNEG,FACTOR
      DO 211  I=1,NKK
  211 GWK(I) = ANEWGK(I)
      GO TO 100
C
C     OPTION THAT MAKES NO CHANGES IN POSITIVE INCREMENTS WHEN SUMNEG
```

```
C     IS LESS THAN 1.0E-8                                                SIMQ 467
C                                                                        SIMQ 468
  213 DO 214  I=1,NKK                                                    SIMQ 469
  214 GWK(I) = ANEWGK(I)                                                 SIMQ 470
      GO TO 100                                                          SIMQ 471
C                                                                        SIMQ 472
C     WRITE MAXIMUM RESPONSE VALUE                                       SIMQ 473
C                                                                        SIMQ 474
   44 CONTINUE
C-----------------------------------------------------------------------
      GAMXM=GAMX*sclrod

      WRITE(6,120)GAMXM,VAMX,DMAX                                        SIMQ 475
      DO 17 I=1,NACCG                                                    SIMQ 476
   17 ACCG(I)=ACCG(I)                                                    SIMQ 477
      WRITE(6,5203)  (ACCG(I),I=1,NACCG)                                 SIMQ 478
CRRR  Output for the time history
      DO I=1,NACCG
cc        WRITE(12,4111)  (I-1)*DELT,ACCG(I)
CRRR
        WRITE(20,4111)  (I-1)*DELT,ACCG(I)/9.81

      ENDDO
cc      WRITE(12,4112)DELT,DMAX,VAMX,GAMXM
C-----------------------------------------------------------------------
CRRR  Changed by REV
CRRR  Loop for the frequency
      DO N=1,NKK
        FREQ=FRQ(N)
        OM=2.0*PI*FREQ
        DO LL=1,NDAMP
          VELROD(LL)=ABS(PLTVMX(LL,N))
        ENDDO
        WRITE(21,9902)  1.0/FREQ,(VELROD(LL)/OM,LL=1,NDAMP)
        WRITE(22,9902)  1.0/FREQ,(VELROD(LL),LL=1,NDAMP)
        WRITE(23,9902)  1.0/FREQ,(VELROD(LL)*OM,LL=1,NDAMP)
9902    FORMAT(1X,F12.4,10E16.6)
      ENDDO
cc      DO 9012 LL=1,NDAMP                                                 SIMQ 499
cc        WRITE(6,4535) AMOR(LL)                                             SIMQ 500
cc        CAM=AMOR(LL) * 100.                                                SIMQ 502
cc        DO 37 N=1,NKK
cc          FREQ=FRQ(N)
cc          OM=2.*PI*FREQ
cc          RVEL=ABS(PLTVMX(LL,N))
cc          RDIS=RVEL/OM
cc          RACC=RVEL*OM
cc   37   WRITE(13,889) FREQ,RDIS,RVEL,RACC
cc      WRITE(13,9016) CAM
cc 9012 WRITE (6,4340)(TQ(KK),FRQ(KK),PLTVMX(LL,KK),TMD(LL,KK),KK,        SIMQ 506
cc     $       kk=1,nkk)

      IF (NRES.EQ.0) GOTO 100                                            SIMQ 508
      WRITE(6,9567)                                                      SIMQ 509
      DO 23 I=1,NKK                                                      SIMQ 510
      AMULT=SV(I)/PLTVMX(1,I)                                            SIMQ 511
      RATIOS = ABS  (1./AMULT)*100.                                      SIMQ 512
      PERCEN(I) =       RATIOS - 100.                                    SIMQ 513
      WRITE(11,889)FRQ(NKK-I+1),GWK(I),SV(NKK-I+1),PLTVMX(1,NKK-I+1)
   23 WRITE(6,8901) TQ(I),FRQ(I),GWK(NKK-I+1),SV(I),PLTVMX(1,I),         SIMQ 514
     * PERCEN(I),TMD(1,I),I                                              SIMQ 515
      WRITE(11,27) ICYCLE
      DO 21 II=1,NDAMP                                                   SIMQ 516
      DO 21 JJ=1,NKK                                                     SIMQ 517
   21 PLTVMX(II,JJ)=ABS(PLTVMX(II,JJ))                                   SIMQ 518
      NFC=2                                                              SIMQ 519
```

```
      DO 1000 II=1,NDAMP                                                SIMQ 520
      DO 1001 J=1,NKK                                                   SIMQ 521
 1001 SI(J)=PLTVMX(II,J)                                                SIMQ 522
      XAMOR=AMOR(II)                                                    SIMQ 523
      CALL DIB2 (NFC,4,1,0,NKK,TS,TL,YMIN,YMAX,1.,1.,0,0,0,0,-2,-2,     SIMQ 524
     $TQ,SI,SV,TIX,TITX,TITY,36,36,36,0,0.,XAMOR)                       SIMQ 525
 1000 CONTINUE                                                          SIMQ 526
  100 CONTINUE                                                          SIMQ 527
C-----------------------------------------------------------------------
      CLOSE(20)
      CLOSE(21)
      CLOSE(22)
      CLOSE(23)

  585 CONTINUE                                                          SIMQ 528
C-----------------------------------------------------------------------
C     END OF LOOP OVER NPA (Number of artificial earthquakes
C-----------------------------------------------------------------------
      IF(NKK.GT.0)GOTO1100                                              SIMQ 529
 1100 CALL PLTND(KIKI)                                                  SIMQ 530
      STOP                                                              SIMQ 531
C                                                                       SIMQ 532
    1 FORMAT (20A4)                                                     SIMQ 533
    2 FORMAT(1H1,//,2X,20A4)                                            SIMQ 534
   13 FORMAT (10F8.4)                                                   SIMQ 535
   22 FORMAT (2I10)                                                     SIMQ 536
   27 FORMAT (1X,14HGWK FOR CYCLE ,I2)                                  SIMQ 537
   30 FORMAT (//,7X,17HTIME INCREMENT = ,F8.6)                          SIMQ 538
   34 FORMAT (2X,55HACCG ARRAY NOT ENOUGH FOR NACCG+2*(LARGEST PERIOD)/DSIMQ 539
     *T =,I5)                                                           SIMQ 540
   60 FORMAT (//,10X,34HA NEW PHASE ANGLE SET WITH SEED = ,I10)         SIMQ 541
  106 FORMAT (7X,30HEXPECTED MAXIMUM GROUND ACC = ,F7.2,' M/S**2')      SIMQ 542
  107 FORMAT (7X,7HTRISE =,F7.2,2X,8HTLEVEL =,F7.2,2X,10HDURATION =,F7.2SIMQ 544
     *)                                                                 SIMQ 545
  114 FORMAT (//,10X,29HCENTRAL CIRCULAR FREQUENCY = ,F10.4,13H RADIANS/SIMQ 546
     *SEC.,//,10X,17HCENTRAL PERIOD = ,F8.4,8H SECONDS,//,10X,25HNUMBER SIMQ 547
     *OF PHASE ANGLES = ,I5,//,10X,29HLOWEST FREQUENCY IN MOTION = ,F10.SIMQ 548
     *5,13H RADIANS/SEC.,//,10X,30HHIGHEST FREQUENCY IN MOTION = ,F10.5,SIMQ 549
     *13H RADIANS/SEC.)                                                 SIMQ 550
  120 FORMAT (//,10X,30HMAXIMUM GROUND ACCELERATION = ,F6.3,' M/S**2'//,SIMQ 551
     * 10X,26HMAXIMUM GROUND VELOCITY = ,F6.3,' M/S',//                 SIMQ 552
     * 10X,30HMAXIMUM GROUND DISPLACEMENT = ,F6.3,' M',//,              SIMQ 553
     * 20X,29HSIMULATED GROUND ACCELERATION,//)                         SIMQ 554
  129 FORMAT (2F10.4,I10,8I5)                                           SIMQ 555
  134 FORMAT(7X,15HSTATIONARY CASE)                                     SIMQ 556
  135 FORMAT(7X,59HNON-STATIONARY IN INTENSITY BUT STATIONARY IN FREQ SPSIMQ 557
     /ECTRUM)                                                           SIMQ 558
  301 FORMAT (8F9.5,I8)                                                 SIMQ 559
  888 FORMAT (6F13.3)                                                   SIMQ 560
  889 FORMAT (F15.5,3E15.5)
 3000 FORMAT (1X,20HGWG NEGATIVE. EQUALS ,E10.3,2X,10HFOR LM OF ,I5)    SIMQ 561
 3020 FORMAT (I5,6F10.4,I5)                                             SIMQ 562
 4111 FORMAT(F12.4,4X,E15.7)
 4112 FORMAT(2X,'DELT='F9.5', MAXD='E12.5', MAXV='E12.5', MAXA='E12.5)
 4262 FORMAT (2F10.4)                                                   SIMQ 564
 4340 FORMAT (1X,4F14.4,I10)                                            SIMQ 565
 4535 FORMAT (1H1,1X,10HDAMPING = ,F6.3,///,9X,6HPERIOD,6X,9HFREQUENCY, SIMQ 566
     * 7X,8HRESPONSE,6X,4HTIME,//)                                      SIMQ 567
 5200 FORMAT (1H ,//,10X,29HMAX. ACCEL. BEFORE CORRECTION,F12.5,//      SIMQ 568
     *          10X,7HAT TIME,F12.5,//)                                 SIMQ 569
 5203 FORMAT (5H      ,15F8.4)                                          SIMQ 570
 6008 FORMAT (/,11X,31HSTANDARD DEVIATION OF PROCESS = ,F7.4,' M/S**2') SIMQ 571
 6016 FORMAT (//,11X,23HORIGINAL POWER SPECTRUM,//,11X,6HPERIOD,8X,     SIMQ 572
     *  9HFREQUENCY,7X,8HSPECTRUM,12X,1HR,/)                            SIMQ 573
 7020 FORMAT(8G10.0)                                                    SIMQ 574
 9920 FORMAT(6G10.0,I2)                                                 SIMQ 574
```

```
 8901 FORMAT (5(4X,E14.5),4X,F14.1,4H PCT,2X,F14.3,I10)
 8902 FORMAT (//,10X,24H CENTRAL FREQUENCY WC = ,F10.3,//,10X,26H DISPER
     *SION PARAMETER Q = ,F10.3,/)
 9008 FORMAT (1H1 ,30X,12HCYCLE NUMBER ,I2,20X,25HLOWEST MODIFIED PERIOD
     * = ,F10.4,2X,7HSECONDS,//)
 9015 FORMAT(10F8.4)
 9016 FORMAT (1X,7HDAMPING,2X,F4.1,8H PERCENT)
 9102 FORMAT (F9.6,63X,I8)
 9567 FORMAT (///,9X,6HPERIOD,8X,9HFREQUENCY,4X,13HPOW.SPEC.DEN.,5X,
     * 12HDES.RESPONSE,4X,12HCAL.RESPONSE,7X,10HDIFFERENCE,9X,4HTIME,//)
10000 FORMAT (//,10X,8HSUMPOS =,F12.3,10X,8HSUMNEG =,F12.3,10X,8HFACTOR
     *=,F12.3)
C
      END
C-----------------------------------------------------------------------
      SUBROUTINE PLTX2(XMIN,XMAX,X,NPOINT)
C-----------------------------------------------------------------------
      DIMENSION X(1)
      POINT=NPOINT-1
      SPACE=ALOG10(XMAX/XMIN)/POINT
      X(1)=XMIN
      DO 1 I=2,NPOINT
      AI=I-1
      EXPO=SPACE*AI
    1 X(I)=XMIN*10.**EXPO
      X(NPOINT)=XMAX
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE POLATE (N,M,XIN,YIN,XOUT,YOUT)
C-----------------------------------------------------------------------
      DIMENSION XIN(1),YIN(1),XOUT(1),YOUT(1)
      J=1
      IF (XIN(1)-XOUT(1)) 2,2,100
    2 IF (XIN(N)-XOUT(M)) 100,3,3
    3 DO 30 I=1,M
    6 IF (XOUT(I)-XIN(J)) 5,40,4
    4 J=J+1
      GO TO 6
    5 J=J-1
      YTEST=(ALOG(YIN(J+1))-ALOG(YIN(J)))*(ALOG(XOUT(I))-ALOG(XIN(J)))/
     1 (ALOG(XIN(J+1))-ALOG(XIN(J)))+ALOG(YIN(J))
      YOUT(I)=EXP(YTEST)
      GO TO 30
   40 YOUT(I)=YIN(J)
   30 CONTINUE
      RETURN
  100 WRITE (6,20)
   20 FORMAT (1H1,1X, 53HPROGRAM STOP. FUNCTION UNDEFINED IN DESIRED INT
     1ERVAL )
      STOP
      END
C-----------------------------------------------------------------------
      SUBROUTINE SVGW(NKK,W,GW,SV,S,B,WC,Q,P,XLAM0,WCP,QP,RR)
C-----------------------------------------------------------------------
      DIMENSION GW(1),W(1),SV(1),RR(1)
      PI=3.14159
      PI2=6.2831852
      GSUM=0.
      DO 1000 I=1,NKK
      NW=NKK-I+1
      POW=2.*B*W(I)*S
      IF(POW.GT.50.0) GO TO 610
      TRANS=1.-EXP(-POW)
      GO TO 611
  610 TRANS=1.
```

```
  611 BS=B/TRANS                                                        SVGW  13
      WCYS=W(I)                                                         SVGW  14
      QYS=SQRT(4.0*BS/PI)                                               SVGW  15
      XSP=-WCYS*S/(PI2*ALOG(P))                                         SVGW  16
      RSTAR=SQRT(2.*ALOG(2.*XSP))                                       SVGW  17
      ET=-RSTAR*QYS*SQRT(PI/2)                                          SVGW  18
      ARG=2.*XSP*(1.-EXP(ET))                                           SVGW  19
      RSP=SQRT(2.*ALOG(ARG))                                            SVGW  20
      RR(I)=RSP                                                         SVGW  21
      GW(I)=(4.*BS/(W(I)*PI))*((SV(NW)*W(I)/RSP)**2-GSUM)               SVGW  22
C     IF(GW(I).LE.0.01)GW(I)=0.01                                       SVGW  23
      IF(GW(I).LE.5.E-6)GW(I)=5.E-6                                     (M)
      IF(I.GT.1)GO TO 140                                               SVGW  24
      GSUM=0.5*W(1)*GW(1)                                               SVGW  25
      GO TO 1000                                                        SVGW  26
 140  GSUM=GSUM+GW(I)*(W(I)-W(I-1))                                     SVGW  27
 1000 CONTINUE                                                          SVGW  28
      WCP=0.0                                                           SVGW  29
      QP=0.0                                                            SVGW  30
      XLAM0=0.                                                          SVGW  31
      XLAM1=0.                                                          SVGW  32
      XLAM2=0.                                                          SVGW  33
      DO 5 I=2,NKK                                                      SVGW  34
      DUMX=(GW(I)+GW(I-1))/2.                                           SVGW  35
      DUMY=W(I)-W(I-1)                                                  SVGW  36
      IF(GW(I)-GW(I-1)) 10,15,15                                        SVGW  37
   10 A=GW(I)                                                           SVGW  38
      B=GW(I-1)                                                         SVGW  39
      WBAR=DUMY*(2.*B+A)/(3.*(A+B))                                     SVGW  40
      WSTAR=W(I)-WBAR                                                   SVGW  41
      GO TO 16                                                          SVGW  42
   15 A=GW(I-1)                                                         SVGW  43
      B=GW(I)                                                           SVGW  44
      WBAR=DUMY*(2.*B+A)/(3.*(A+B))                                     SVGW  45
      WSTAR=W(I-1)+WBAR                                                 SVGW  46
   16 AREA=DUMX*DUMY                                                    SVGW  47
      XLAM0=XLAM0+AREA                                                  SVGW  48
      XLAM1=XLAM1+WSTAR*AREA                                            SVGW  49
    5 XLAM2=XLAM2+(WSTAR**2)*AREA                                       SVGW  50
      WCP=SQRT(XLAM2/XLAM0)                                             SVGW  51
      RATIO=(XLAM1**2)/(XLAM0*XLAM2)                                    SVGW  52
      QP=SQRT(1.-RATIO)                                                 SVGW  53
      RETURN                                                            SVGW  54
      END                                                               SVGW  55
C-----------------------------------------------------------------------
      SUBROUTINE GWPLOT(NKK,TS,TL,GMIN,GMAX,TQ,GW,TITX,TITLO,YTITL)     GWPL   1
C-----------------------------------------------------------------------
      DIMENSION TQ(1),GW(1),TITX(1),TITLO(1),YTITL(1)                   GWPL   2
      IF (GMAX.LE.70.0) GO TO 3                                         GWPL   3
      IF (GMAX.LE.200.0) GO TO 2                                        GWPL   4
      DY=20.0                                                           GWPL   5
      GO TO 4                                                           GWPL   6
    2 DY=10.0                                                           GWPL   7
      GO TO 4                                                           GWPL   8
    3 DY=2.0                                                            GWPL   9
    4 CONTINUE                                                          GWPL  10
C     ESTABLISH SEMILOG COORDINATES                                     GWPL  11
      CALL SMXYV(1,0)                                                   GWPL  12
C     ESTABLISH MARGINS                                                 GWPL  13
      CALL SETMIV(150,100,150,150)                                      GWPL  14
C     ESTABLISH GRID                                                    GWPL  15
      CALL GRID1V(1,TS,TL,GMIN,GMAX,1.0,DY,0,5,0,5,-2,-2)               GWPL  16
C     WRITE Y AXIS LABEL                                                GWPL  17
      CALL RITE2V(125,250,1000,90,2,28,1,YTITL,NLAST)                   GWPL  18
C     WRITE X AXIS LABEL                                                GWPL  19
      CALL RITE2V(300,125,1000,0,2,36,1,TITX,NLAST)                     GWPL  20
```

```
C       WRITE TITLE
        CALL RITE2V(250,925,1000,0,2,28,1,TITLO,NLAST)
C       JOIN POINTS WITH STRAIGHT LINES
        NKKM1=NKK-1
        DO 1 I=1,NKKM1
        X1=TQ(I)
        X2=TQ(I+1)
        II=NKK+1-I
        Y1=GW(II)
        Y2=GW(NKK-I)
C       IX1=NXV(X1)
C       IY1=NYV(Y1)
C       IX2=NXV(X2)
C       IY2=NYV(Y2)
C       CALL LINEV(IX1,IY1,IX2,IY2)
  1     CONTINUE
        RETURN
        END
C-----------------------------------------------------------------------
        SUBROUTINE DUMMY(W,FOUT,NKK,WB,GWK,MM)
C-----------------------------------------------------------------------
        DIMENSION WB(1),GWK(1)
        JAY=MM
      1 IF(W-WB(JAY)) 5,4,2
      2 JAY=JAY+1
        IF (JAY.LE.NKK) GO TO 1
        FOUT=GWK(NKK)
        GO TO 6
      4 FOUT=GWK(JAY)
        MM=JAY
        GO TO 6
      5 MM=JAY-1
        IF (MM.LE.0) GO TO 4
        SLOPE=(GWK(JAY)-GWK(JAY-1))/(WB(JAY)-WB(JAY-1))
        FOUT=GWK(JAY-1)+SLOPE*(W-WB(JAY-1))
      6 CONTINUE
        RETURN
        END
C-----------------------------------------------------------------------
        SUBROUTINE DUMMX(W,FOUT,NKK,WB,GWK,MM)
C-----------------------------------------------------------------------
        DIMENSION WB(1),GWK(1)
        JAY=MM
      1 IF(W-WB(JAY)) 5,4,2
      2 JAY=JAY+1
        IF (JAY.LE.NKK) GO TO 1
        FOUT=GWK(NKK)
        GO TO 6
      4 FOUT=GWK(JAY)
        MM=JAY
        GO TO 6
      5 MM=JAY-1
        IF (MM.LE.0) GO TO 4
        X=(WB(JAY)+WB(JAY-1))/2.
        IF(W-X) 7,7,8
      7 FOUT=GWK(JAY-1)
        GO TO 6
      8 FOUT=GWK(JAY)
      6 CONTINUE
        RETURN
        END
C-----------------------------------------------------------------------
        SUBROUTINE SPECT (VMAX,TA,GA,N,DEL,PD,IP,DMP,ID)
C-----------------------------------------------------------------------
C
C       SUBROUTINE FOR COMPUTATION OF SPECTRA FROM EARTHQUAKE RECORD
```

```
C     DIGITIZED AT EQUAL TIME INTERVALS
C
      DIMENSION VMAX(10,300),TA(10,300),GA(6001),PD(300),DMP(10),
     1          A(2,2),B(2,2),TY(3),X(3),G(2)
      DO 6 J=1,ID
      D=DMP(J)
      DO 6  K=1,IP
      P=PD(K)
      IF (P.LT.0.001) P=0.001
      W=6.2831854/P
C
C  CHOICE OF INTERVAL OF INTEGRATION
C
      DELP=P/10.
      L=DEL/DELP+1.-1.E-5
      DELT=DEL/L
C
C  COMPUTATION OF MATRICES A AND B
C
      CALL PCN04(D,W,DELT,A,B)
C
C  INITIATION
C
      X(1)=0.
      X(2)=0.
      DMAX=0.
      I=1
      DW=2.*W*D
      W2=W**2
      IA=2.*P/DELT+1.E-05
C
C  COMPUTATION OF RESPONSE
C
      L1=0
    1 SL=(GA(I+1)-GA(I))/ L
      DO 5 M=1,L
      G(1)= GA(I)+SL*(M-1)
      G(2)= GA(I)+SL*M
      TY(1)=A(1,1)*X(1)+A(1,2)*X(2)-B(1,1)*G(1)-B(1,2)*G(2)
      TY(2)=A(2,1)*X(1)+A(2,2)*X(2)-B(2,1)*G(1)-B(2,2)*G(2)
      L1=L1+1
      TIME=(L1-1)*DELT
C
C  MONITORING THE MAX. VALUES
C
      IF (ABS(TY(1)).LE.ABS(DMAX)) GO TO 2
      DMAX=TY(1)
      TD=TIME
    2 X(1)=TY(1)
    5 X(2)=TY(2)
C
C  TEST FOR END OF INTEGRATION
C
      I=I+1
      IF (I.EQ.N) GO TO 7
      GO TO 8
    7 VEND=X(2)
    8 IF (I.EQ.(N+IA)) GO TO 10
      IF (I.GE.N) GO TO 9
      GO TO 1
    9 GA(I+1)=0.
      GO TO 1
   10 CONTINUE
      VMAX(J,K)=W*DMAX
      TA(J,K)=TD
    6 CONTINUE
```

```
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE PCN04(D,W,DELT,A,B)
C-----------------------------------------------------------------------
C
C  SUBROUTINE FOR COMPUTATION OF MATRICES A AND B
C
      DIMENSION A(2,2),B(2,2)
      DW=D*W
      D2=D**2
      A0=EXP(-DW*DELT)
      A1=W*SQRT(1.-D2)
      AD1=A1*DELT
      A2=SIN(AD1)
      A3=COS(AD1)
      W2=W**2
      A4=(2.*D2-1.)/W2
      A5=D/W
      A6=2.*A5/W2
      A7=1./W2
      A8=(A1*A3-DW*A2)*A0
      A9=-(A1*A2+DW*A3)*A0
      A10=A8/A1
      A11=A0/A1
      A12=A11*A2
      A13=A0*A3
      A14=A10*A4
      A15=A12*A4
      A16=A6*A13
      A17=A9*A6
      A(1,1)=A0*(DW*A2/A1+A3)
      A(1,2)=A12
      A(2,1)=A10*DW+A9
      A(2,2)=A10
      B(1,1)=(-A15-A16+A6)/DELT-A12*A5-A7*A13
      B(1,2)=(A15+A16-A6)/DELT+A7
      B(2,1)=(-A14-A17-A7)/DELT-A10*A5-A9*A7
      B(2,2)=(A14+A17+A7)/DELT
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE DIB2 (NFC,IND,NGRAPH,NGD,NPOINT,XL,XR,YB,YT,DX,DY,
     $N,M,I,J,NX,NY,X,Y,Z,TIT,TITX,TITY,NT,NTX,NTY,NPT,PTMRK,XAMOR)
C-----------------------------------------------------------------------
      DIMENSION X(1),Y(1),Z(1),TIT(1),TITX(1),TITY(1),PTMRK(1)
      INDA=0
      GO TO (1,2,3,4),IND
    1 CALL SMXYV(0,0)
      GO TO 5
    2 CALL SMXYV(0,1)
      GO TO 5
    3 CALL SMXYV(1,0)
      GO TO 5
    4 CALL SMXYV(1,1)
    5 CONTINUE
      CALL SETMIV(150,100,150,150)
      IF(NFC-1) 11,10,20
   10 NFA=2
      GO TO 30
   20 NFA=4
   30 CALL GRID1V(NFA,XL,XR,YB,YT,DX,DY,N,M,I,J,NX,NY)
      CALL RITE2V(125,250,1000,90,2,NTY,1,TITY,NLAST)
      CALL RITE2V(300,125,1000,0,2,NTX,1,TITX,NLAST)
      CALL RITE2V(250,925,1000,0,2,NT,1,TIT,NLAST)
      CALL LABLV (XAMOR,750,880,6,1,1)
```

```
   11 CALL INCRV(8,4)                                                  DIB2  24
      NAU=NGRAPH+NGD                                                   DIB2  25
      IF(NAU) 401,401,400                                              DIB2  26
  400 DO 7 II=1,NAU                                                    DIB2  27
      NAUX=NPOINT-1                                                    DIB2  28
      DO 8 K=1,NAUX                                                    DIB2  29
      IAUX=(II-1)*NPOINT+K                                             DIB2  30
      X1=X(K)                                                          DIB2  31
      Z1=Z(K)                                                          DIB2  32
      X2=X(K+1)                                                        DIB2  33
      Z2=Z(K+1)                                                        DIB2  34
      Y1=Y(IAUX)                                                       DIB2  35
      Y2=Y(IAUX+1)                                                     DIB2  36
      IF(Y1-YT) 100,100,101                                            DIB2  37
  100 IF(Y2-YT) 110,110,103                                            DIB2  38
  103 X2=(X2-X1)*(YT-Y1)/(Y2-Y1)+X1                                    DIB2  39
      Y2=YT                                                            DIB2  40
      GO TO 110                                                        DIB2  41
  101 IF(Y2-YT) 104,104,105                                            DIB2  42
  104 X1=(X2-X1)*(YT-Y1)/(Y2-Y1)+X1                                    DIB2  43
      Y1=YT                                                            DIB2  44
      GO TO 110                                                        DIB2  45
  105 INDA=1                                                           DIB2  46
  110 CONTINUE                                                         DIB2  47
      IF(Y1-YB) 200,201,201                                            DIB2  48
  200 IF(Y2-YB) 205,203,203                                            DIB2  49
  205 INDA=1                                                           DIB2  50
      GO TO 210                                                        DIB2  51
  203 X1=(X2-X1)*(YB-Y1)/(Y2-Y1)+X1                                    DIB2  52
      Y1=YB                                                            DIB2  53
      GO TO 210                                                        DIB2  54
  201 IF(Y2-YB) 204,210,210                                            DIB2  55
  204 X2=(X2-X1)*(YB-Y1)/(Y2-Y1)+X1                                    DIB2  56
      Y2=YB                                                            DIB2  57
  210 CONTINUE                                                         DIB2  58
      IF(INDA) 303,303,302                                             DIB2  59
  303 IF(II-NGRAPH) 300,300,301                                        DIB2  60
  300 CALL LINEV(NX,NY,NX,NY)                                          DIB2  61
      CALL LINEV(NX,NY,NX,NY)                                          DIB2  62
      CALL DOTLNV(NX,NY,NX,NY)                                         DIB2  63
      GO TO 302                                                        DIB2  64
  301 CALL DOTLNV(NX,NY,NX,NY)                                         DIB2  65
      CALL DOTLNV(NX,NY,NX,NY)                                         DIB2  66
  302 INDA=0                                                           DIB2  67
    8 CONTINUE                                                         DIB2  68
    7 CONTINUE                                                         DIB2  69
  401 IF(NPT) 402,402,403                                              DIB2  70
  403 LL=NPOINT*NPT                                                    DIB2  71
      DO 500 I=1,NPOINT                                                DIB2  72
      CALL APLOTV(LL,X(I),Y(I),0,NPOINT,NPT,PTMRK,IERR)                DIB2  73
  500 CALL APLOTV(LL,X(I),Y(I),0,NPOINT,NPT,PTMRK,IERR)                DIB2  74
  402 RETURN                                                           DIB2  75
      END                                                              DIB2  76
C-----------------------------------------------------------------------
      SUBROUTINE PLTND (KIKI)                                          PLTN   1
C-----------------------------------------------------------------------
C     DUMMY PLOT SUBROUTINE                                            PLTN   2
      RETURN                                                           PLTN   3
      END                                                              PLTN   4
      SUBROUTINE SMXYV (I,J)                                           SMXY   1
C     DUMMY PLOT SUBROUTINE                                            SMXY   2
      RETURN                                                           SMXY   3
      END                                                              SMXY   4
      SUBROUTINE SETMIV (J,K,L,M)                                      SETM   1
C     DUMMY PLOT SUBROUTINE                                            SETM   2
      RETURN                                                           SETM   3
```

```
      END                                                               SETM   4
      SUBROUTINE GRID1V (NFA,XL,XR,YB,YT,DX,DY,N,M,I,J,NX,NY)           GRID   1
C     DUMMY PLOT SUBROUTINE                                             GRID   2
      RETURN                                                            GRID   3
      END                                                               GRID   4
      SUBROUTINE RITE2V (II,JJ,KK,I,J,K,IJ,IK,IL)                       RITE   1
C     DUMMY PLOT SUBROUTINE                                             RITE   2
      RETURN                                                            RITE   3
      END                                                               RITE   4
      SUBROUTINE LABLV (XAMOR,X,Y,Z,I,J)                                LABL   1
C     DUMMY PLOT SUBROUTINE                                             LABL   2
      RETURN                                                            LABL   3
      END                                                               LABL   4
      SUBROUTINE INCRV (I,J)                                            INCR   1
C     DUMMY PLOT SUBROUTINE                                             INCR   2
      RETURN                                                            INCR   3
      END                                                               INCR   4
      SUBROUTINE LINEV (N1,N2,N3,N4)                                    LINE   1
C     DUMMY PLOT SUBROUTINE                                             LINE   2
      RETURN                                                            LINE   3
      END                                                               LINE   4
      SUBROUTINE DOTLNV (N1,N2,N3,N4)                                   DOTL   1
C     DUMMY PLOT SUBROUTINE                                             DOTL   2
      RETURN                                                            DOTL   3
      END                                                               DOTL   4
      SUBROUTINE APLOTV (LL,X,Y,I,N,NPT,P,IERR)                         APLO   1
C     DUMMY PLOT SUBROUTINE                                             APLO   2
      RETURN                                                            APLO   3
      END                                                               APLO   4
C----------------------------------------------------------------------
      SUBROUTINE CONVERT(TSV,SAY,NRES,IOP,SV0)
C----------------------------------------------------------------------
      DIMENSION TSV(1010),SV0(1010),SAY(1010)
C   THIS SUBROUTINE CONVERT THE INPUT DATA FROM ACCELERATION AND
C   RESPONSE SPECTRA TO VELOCITY RESPONSE SPECTRA
C----------------------------------------------------------------------
C   TSV  = PERIOD INPUT
C   SAY  = THE INPUT ORDINATE OF THE RESPONSE SPECT IT CAN (A OR V OR D)
C   NRES = NUMBER OF DATA TO BE ENTERED
C   SV0  = THE CONVERTED VELOCITY SPECTRUM
C
C   SPEC = D  MEANS DISPLACEMENT SPECTRUM AS INPUT
C   SPEC = V  MEANS VELOCITY SPECTRUM AS INPUT
C   SPEC = A  MEANS ACCELERATION SPECTRUM AS INPUT
C   IOP  = A NUMBER WHICH STAND FOR D V OR A
C   IOP  = 1 DISP SPECT
C   IOP  = 2 VELOCITY SPECT
C   IOP  = 3 ACCELE SPECT
C
C      IF(SPEC .EQ. 'D') IOP=1
C      IF(SPEC .EQ. 'V') IOP=2
C      IF(SPEC .EQ. 'A') IOP=3
C----------------------------------------------------------------------
      OPEN(UNIT=25,FILE='target.spc',status='unknown')

      DO 62 I=1,NRES
          IF(TSV(I) .LE. 0.) TSV(I)=0.01
          W=2.*3.14159/TSV(I)
          GO TO (71,72,73) , IOP
  71      SAY(I)=W*SAY(I)
        GO TO 72
  73      SAY(I)=SAY(I)/W
  72      SV0(I)=SAY(I)
C----------------------------------------------------------------------
        WRITE(25,1000) TSV(i),SV0(i)/W,SV0(i),SV0(i)*W
1000    FORMAT(1X,F10.4,3F14.4)
```

```
   62  CONTINUE
C------------------------------------------------------------------------
       CLOSE(25)
C
       RETURN
       END
```

APPENDIX C TABLE FOR STATIC & DYNAMIC FRICTION COEFFICIENTS

Table C1 Coefficients of Friction for Selected Engineering Materials

	Static μ_s	Kinetic μ
Oil-lubricated Contacts (excluding hydrodynamic lubrication):		
Hardened Steel on Same	0.06	0.01–0.03
Soft Steel on Same	0.10	0.01–0.05
Cast Iron on Same	0.05–0.15	0.05–0.015
Cast Iron on Hardened Steel	0.08	0.01–0.05
Steel on Bronze	0.1	0.06
Leather on Metal	0.15	0.15
Ball Bearings	0.0010–0.0024	
Roller Bearings	0.0010–0.0040	
Rollers of Radius R	$0.5/R$ (R in mm)	
Dry Contacts:		
Steel on Steel	0.11–0.33	0.10–0.11
Cast Iron on Cast Iron	0.20–0.25	0.12–0.25
Cast Iron on Hardened Steel	0.18–0.20	0.16–0.20
Steel on Bronze	0.20	0.18
Leather on Metal	0.6	0.48
Rubber on Asphalt (tires)	0.5–0.8	
PTFE (Teflon) on steel	0.05	
Polyester on Steel	0.12	
Polycarbonate on Steel	0.39	

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