SEISMIC ANALYSIS
AND AN IMPROVED SEISMIC DESIGN PROCEDURE
FOR GRAVITY RETAINING WALLS

by

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ABSTRACT

A prediction rule for the relative displacement induced in a retaining wall during earthquake is formulated. This is deduced from a detailed analysis using Newmark's sliding block model and Zarrabi's modified sliding block model. It allows for the time variation of the dynamic active earth pressure, the orientation of the wall, shaking characteristics as well as incorporating the vertical acceleration. Tilting displacement has been justifiedly ignored. The prediction rule can be updated and refined as more results for Zarrabi's model are available. Correlation from results of Newmark's model may also be utilized.

A simple yet practical and rational procedure to the design of gravity retaining walls against earthquake has been described herein. The procedure is based on the limiting displacement approach proposed by Richards and Elms but utilizes the prediction rule formulated in this study. The level of confidence on the limiting displacement criterion is chosen to be above 95%. The expected displacement can be evaluated explicitly. The procedure is, however, restricted in application to dry non-liquefying backfill.

Whereas the proposed procedure provides a rational approach to the seismic design of gravity retaining walls and offers a significant improvement over Richards and Elms's design procedure, the lack of field and experimental validation requires that it should be used with caution and good judgement.

Thesis Supervisor: Robert V. Whitman
Title: Professor of Civil Engineering

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<u>Nomenclature</u>

A	Coefficient of absolute maximum horizontal ground acceleration
Bn	Normal force at the base of the wall
D	Relative displacement subscripts -- $_L$ Limiting displacement n Newmark's model no Newmark's model and kv=0 z Zarrabi's model
Em	Logarithmic of the model parameter
Eo	Uncertainty function due to orientation of the wall
Es	Uncertainty function due to shaking characteristics
Ev	Uncertainty function due to correction of including the vertical ground acceleration
Ez	Uncertainty function due to correlation from Newmark's model to Zarrabi's model
H	Height of the wall
I	Inertia force of the wall
Ka	Static active earth pressure coefficient
Kae	Dynamic active earth pressure coefficient
M	Model parameter
N	Coefficient of limiting acceleration of the wall
Pae	Dynamic active earth pressure
Q	Modified model parameter
Rv	Correlation function for inclusion of vertical ground acceleration
Rw	Correlation function from Newmark's model to Zarrabi's model
T	Time step in accelerograms
V	Absolute maximum horizontal velocity of the ground

W Weight of the soil wedge during sliding

Ww Weight of the wall

g Universal gravitational constant

i Slope angle of backfill

kh Coeffieient of horizontal acceleration of ground

kh' Coefficient of horizontal acceleration of soil wedge

kh" Coefficient of horizontal acceleration of the wall

kn' Coefficient of soil wedge acceleration normal to the rupture plane

kn" Coefficient of wall acceleration normal to the inside face of the wall

kt' Coefficient of soil wedge acceleration tangential to the rupture plane

kt" Coefficient of wall acceleration tangential to the inside face of the wall

kv Coefficient of vertical acceleration of ground

kv' Coefficient of vertical acceleration of the soil wedge

kv" Coefficient of vertical acceleration of the wall

q Logarithmic value of Q

ψ Arc tan [kh/(1-kv)]

α Arc tan [kh'/(1-kv')]

ξ Arc tan [kh"/(1-kv")]

β Inclination of the inside of the wall

δ Wall friction angle

θ Inclination of the rupture plane

ϕ Dynamic internal friction angle of backfill

ϕ_b Dynamic base friction angle of the wall

γ Unit weight of the backfill

Chapter I

Introduction

1.1 Background

Retaining walls are among the most common of Civil Engineering structures. Yet, there is no universally accepted and rational approach to the design of retaining walls against earthquakes. Large movements and outright failures of retaining walls still occur during every major earthquake. Although such failures seldom directly endanger human lifes and these occurrences usually pass relatively unnoticed, a systematic, rational seismic design method is urgently needed.

The classical approach to seismic design of retaining walls with non-liquefying backfills is to treat the problem as one of pseudo-dynamic static force equilibrium. The dynamic active earth pressure is determined by the Mononobe-Okabe equation with the expected ground acceleration. This approach is uneconomical if the inertia force of the wall is included in the calculation. There have been attempts to modify this approach to make it practical but none has been rational enough to produce consistent designs.

Recently, a very simple, rational approach to the design of retaining walls has been suggested by Richards and Elms (1979) in New Zealand; it involves a deformation criterion rather than a force equilibrium criterion. Certain relative displacement is allowed to develop between the wall and the underlying ground. The design criterion is to keep this relative displacement less than a limiting value. The principle of this approach is very sound, and when fully developed, it should lead to rational and economical seismic designs of gravity retaining walls. The need for such an approach, based upon a limiting displacement criterion, has also been emphasized in a recent state-of-the-art paper by Prakesh (1977).

However, in its original version, Richards and Elms' design procedure has made several simplifications. These include neglecting the effect of vertical acceleration, neglecting tilting displacements, ignoring the time variation of the dynamic earth pressure and an arbitrarily selected upper bound envelop as prediction rule. As a result, a conservative factor of safety is recommended.

Zarrabi(1979) and Nadim(1980) eliminated some of the theoretical and conceptual shortcomings in computing the deformations induced during earthquakes. However, their studies have been limited to a few earthquake records only. More extensive study in the seismic response of retaining walls is most desirable and refinement of Richards and Elms' design procedure should be made before it can be adopted into applicable design codes and standards.

1.2 Objectives and Outline of the Study

The principal objectives of this thesis are (1) to investigate the seismic behavior of gravity retaining walls; (2) to formulate a representative and reliable prediction rule; and (3) to determine the appropriate factor of safety to be employed with the prediction rule in order to achieve a required confidence level in design.

This study adopts the limiting displacement approach as the basis for seismic design of gravity retaining walls. The principle behind the limiting displacement approach is both logical and rational. It is also consistent with the strategy of seismic design of other structures to produce economical designs. The proposed design procedure follows closely to Richards and Elms' design procedure but attempts to eliminate most of its potential shortcomings, which will be discussed in detail later.

This is the most complete text of the thesis available. The following page(s) were not included in the copy of the thesis deposited in the Institute Archives by the author: p. 13.

mind. The results are grouped into four major factors: orientation of the wall, the shaking charactertics, the inclusion of the vertical ground acceleration and the correlation for converting the computed results from Newmark's model to Zarrabi's model.

A simple equation is derived to estimate the relative displacement that would be predicted by the Newmark's model. A correlation factor for estimating relative displacement predicted by Zarrabi's model is developed. The variance of relative displacement is evaluated and the confidence level of limiting displacement is formulated. A simple and practical seismic design method is then proposed for retaining walls.

1.3 Organization of the Thesis

This thesis presents the development of a seismic design procedure for gravity retaining walls via a detailed study of the sliding behavior of retaining walls during earthquake. Chapter 2 summarizes the state-of-the-art in seismic analysis and design of retaining walls. Chapter 3 descirbes the sliding block models used in this study while the solution procedure is discussed in Chapter 4. The results are summarized and analyzed in Chapter 5. Through a study of variance in the relative displacement formulation, an improved seismic design procedure is presented in Chapter

6. The merits and performance of the proposed design procedure are evaluated. Richards and Elms' design procedure is also reviewed in the light of the computed results in this study. This thesis concludes with a brief discussion of the future research to be pursued.

Chapter II

State-of-the-Art of Seismic Design of Retaining Walls

2.1 Introduction

This chapter summarizes the present state-of-the-art of seismic design for gravity retaining walls. The classical design procedures are based on a force equilibrium approach in which the shear force at the base of the wall never exceeds the maximum shear resistance. On the other hand, the new design procedure proposed by Richards and Elms is based on a limiting displacement criterion where some yielding is allowed but should be under tolerable limit. Both approachs are discussed in detail. Recent developments in seismic analysis are also described in order to introduce the basic concepts and background that are important to a complete understanding of this study.

2.2 The Force Equilibrium Design Approach

2.2.1 Dynamic Equilibrium

Mononobe(1929) and Okabe(1926) extended Coulomb's theory to the dynamic case of a retaining wall with dry backfill. They obtained the following equation:

$$Pae = 0.5\ \gamma H^2\ (1-kv')\ Kae \qquad \text{.... (2.1)}$$

where $$Kae = \frac{\cos^2(\phi-\alpha-\beta)}{\cos\alpha\cos^2\beta\cos(\alpha+\beta+\delta)\left[1+\sqrt{\dfrac{\sin(\phi+\delta)\sin(\phi-\alpha-i)}{\cos(i-\beta)\cos(\alpha+\beta+\delta)}}\right]^2}$$

and kv' = vertical acceleration coefficient of soil wedge

kh' = horizontal acceleration coefficient of soil wedge

α = arc tan$\left[kh'/(1-kv')\right]$

γ = unit weight of soil

H = height of wall

ϕ = angle of internal friction

δ = angle of friction acting between backfill and wall

β = angle between inside face of the wall and vertical

Figure 2.1 illustrates the structural and geometric parameters used in the above equation (equation 2.1). Figure 2.2 shows a typical variation of Kae with kh. The equation is commonly referred to as the Mononobe-Okabe

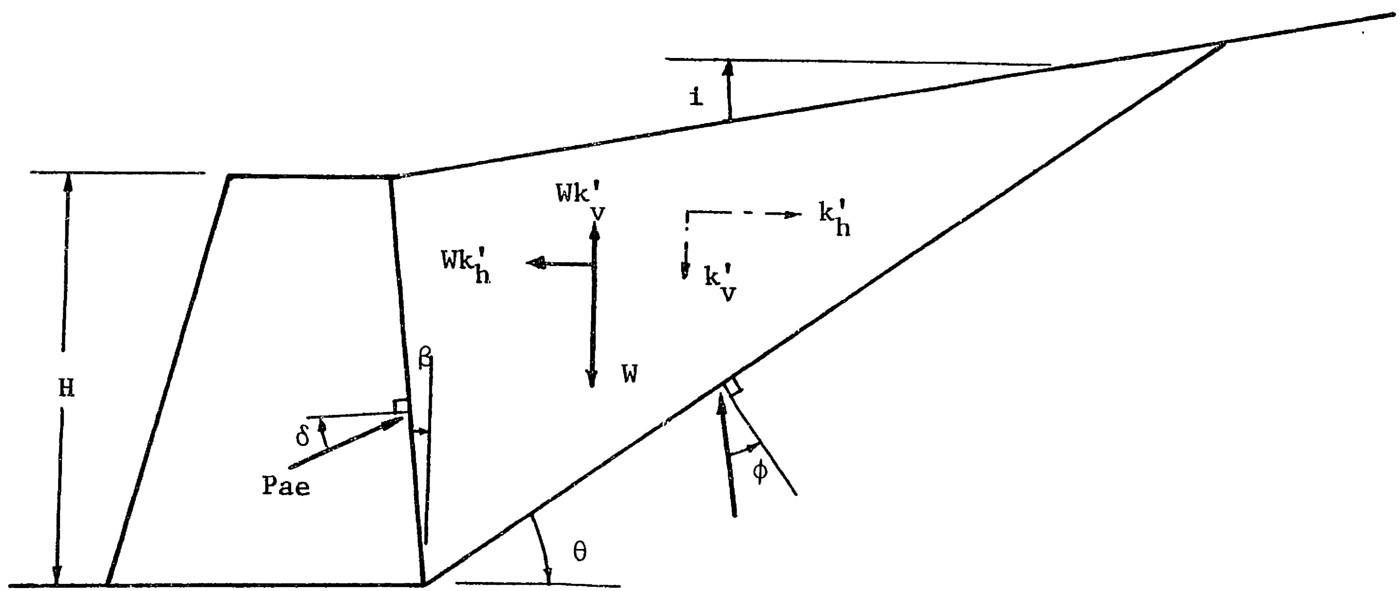

Figure 2.1 Structural and geometrical parameters for Mononobe-Okabe Equation

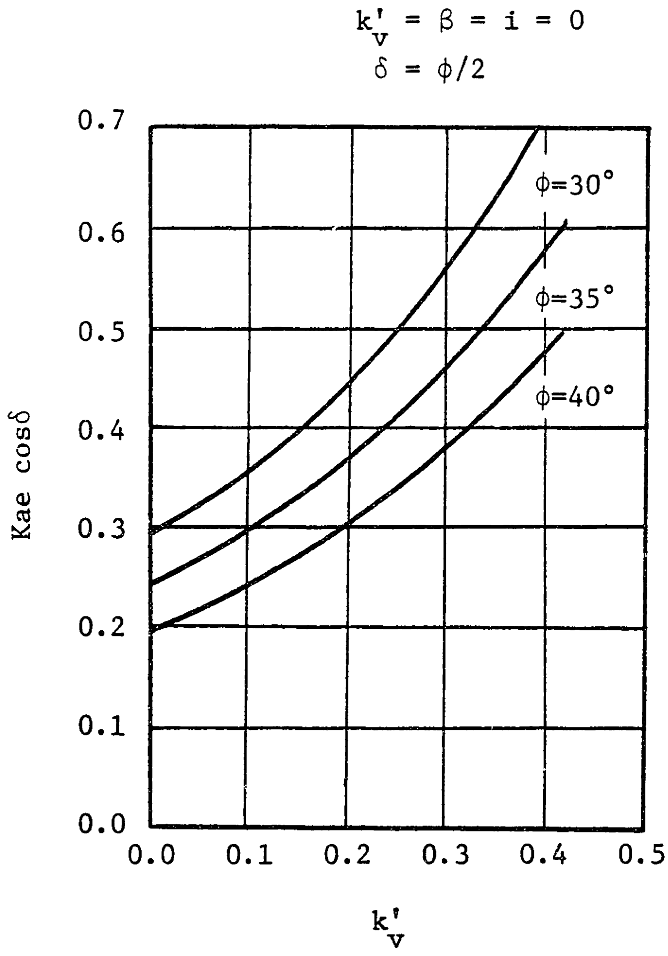

Figure 2.2 Dynamic lateral pressure by Mononbe-Okabe Equation

equation. The inclination of the rutpure plane is calculated by:

$$\vartheta = \phi - \alpha + \tan^{-1}\left[\frac{-P + \sqrt{P\,(P+Q)\,(1+QR)}}{1 + R\,(P+Q)}\right] \quad \ldots. (2.2)$$

where $P = \tan(\phi-\alpha-i)$

$Q = \cot(\phi-\alpha-\beta)$

$R = \tan(\alpha+\beta+\delta)$

Model tests performed by various researchers showed that the lateral dynamic pressure agrees reasonably well with the Mononobe-Okabe equation. (The principal sources for the information of these model test programs are Seed and Whitman, 1970, and Wood, 1973.) This equation has been widely used in seismic designs.

Seed and Whitman(1970) investigated the sensitivity of the Mononobe-Okabe equation to the input parameters. They observed that the soil friction angle, ϕ, and the slope inclination, i, have significant effects on Pae while the influence of the vertical ground shaking, kv, and the wall friction angle, δ, are small. For a horizontal backfill, vertical wall, and $\phi=35^\circ$. for soil backfill, they approximated the total dynamic horizontal force as:

$$Pae = 0.5\ \gamma H^2\ (Ka + 0.75\ kh') \quad \ldots. (2.3)$$

where Ka = Static active pressure coefficient

Based on the these observations they recommended using the approximate expression (equation 2.3) as a basis for simple design procedures.

2.2.2 Classical Seismic Design Methods

The Mononobe-Okabe equation enables the engineer to determine the dynamic active earth pressure against retaining walls during earthqake. The design of the wall is usually based on the no yielding criterion under the dynamic forces.

Consider the free body diagram of the wall as shown in Figure 2.3. Pae is the active total earth pressure computed by the Mononobe-Okabe equation from the soil wedge. I is the induced inertia force due to the ground motion and Ww is the weight of the wall. Bn is the vertical resultant of all forces at the base of the wall while S is the resultant in the horizontal direction. S is limited to the maximum shear resistance that can be mobilized which is Bn tan(ϕb). All forces in the figure except the weight of the wall are functions of the time varying ground motion. The usual design criterion is to have the wall weight large enough so that the horizontal resultant of P and I is always less than Bn tan(ϕb) throughout the whole excitation. However, if

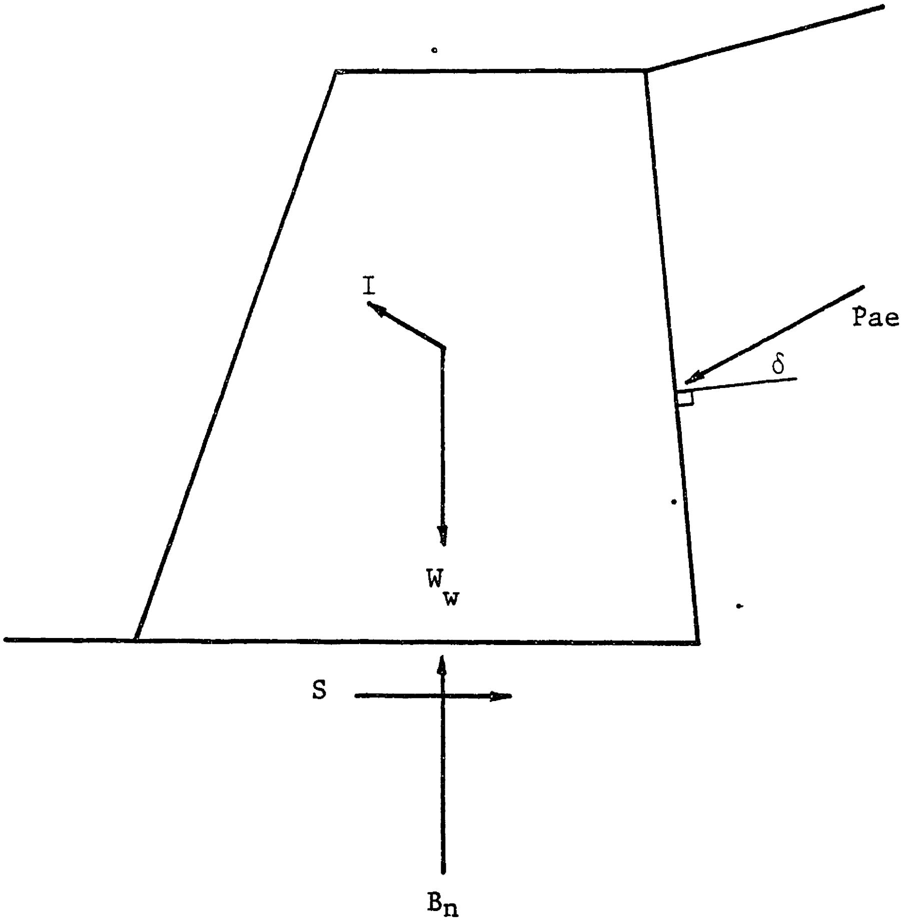

Figure 2.3 Free body diagram of retaining wall

used with the expected ground acceleration, this procedure leads to uneconomical designs. At the extreme, there is a critical acceleration above which no-yielding is not possible and this procedure simply cannot be applied.

One common modified approach is to determine the total static and dynamic thrust from the backfill using the Mononobe-Okabe equation, but to ignore any inertia forces I upon the retaining wall itself. With this approach, reasonable designs sometimes result even when realistically high values for the designed horizontal ground acceleration are included. However, because the inertia of the wall is neglected this approach is irrational and cannot consistently lead to satisfactory designs.

Another common approach considers both dynamic thrust from the backfill and inertia loading upon the wall, using horizontal ground accelerations that are some fraction of those that may realistically occur. Inasmuch as there are no generally accepted rules for selecting the reduced accelerations to be used with this approach, it too cannot consistently lead to satisfactory designs.

2.3 The Limiting Displacement Design Approach

2.3.1 Basic Concepts

Richards and Elms (1979) noted that using the Mononobe-Okabe equation and including the wall inertia would lead to uneconomical design. They outlined a new design procedure with the failure (design) criterion based on limiting relative displacements rather than the conventional no yielding criterion. The principle of this approach is to recognize that although at some instances during the ground motion the conventional factor of safety is less than unity, this does not necessarily mean that the wall has "failed". Rather, some relative displacement occurs between the wall and underlying ground which is not catastrophic in many cases. The design criterion is to keep this relative displacment less than a limiting value. This approach in effect provides a rational guideline for selecting the reduced accelerations to be used in the second approach to design described in last section. The reduced acceleration for design is termed the limiting acceleration, Ng, where g is the gravitational acceleration and N is a dimensionless coefficient.

2.3.2 Richards and Elms' Design Procedure

Richards and Elms proposed to treat a retaining wall as a sliding block and use Newmark's sliding block model to analyze the behavior of the wall during earthquakes. The envisioned sliding mode is depicted in Figure 2.4. One simplification is to assume that the dynamic active earth pressure remains constant after sliding has been initiated. Based on the results from Franklin and Chang's (1977)

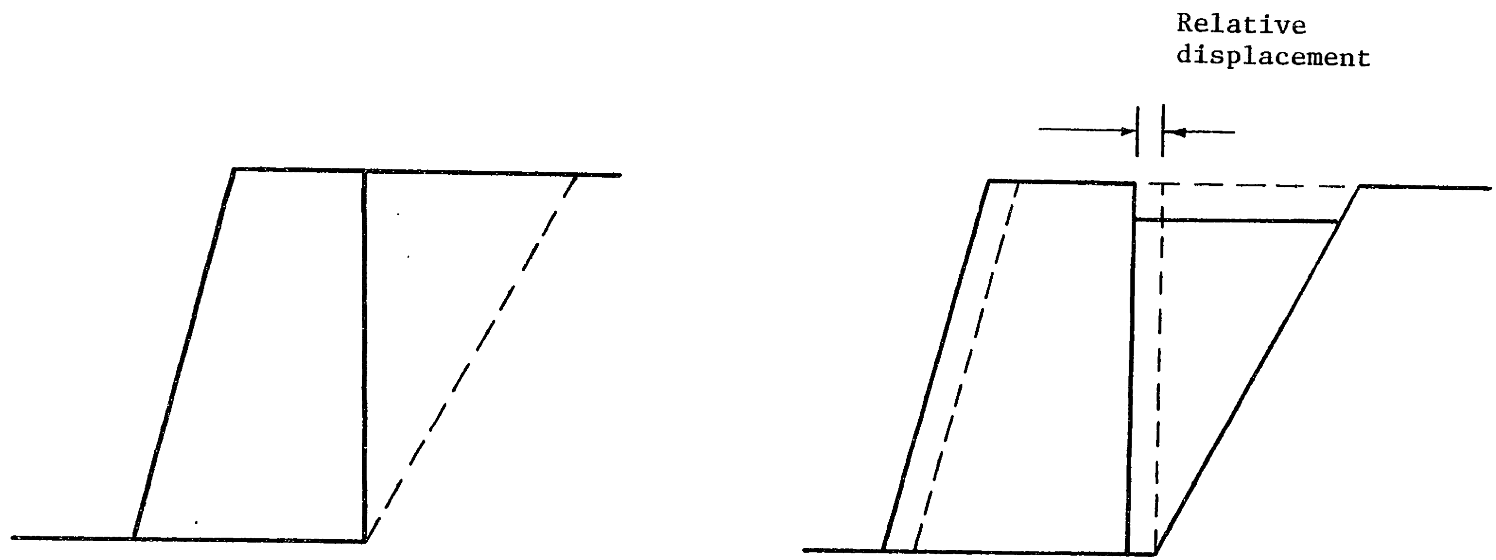

Figure 2.4 Sliding model for retaining walls

analysis, Richards and Elms suggested an empirical equation (equation 2.4) as the upper bound envelop curve for the permanent relative displacement.

$$D = 0.087 \frac{V^2}{Ag} \left(\frac{N}{A} \right)^{-4} \qquad \text{.... (2.4)}$$

where Ag = Absolute maximum horizontal ground acceleration

V = Peak horizontal ground velocity

This equation predicts higher displacement when compared to Newmark's original prediction (see Section 3.2.2) simply due to inclusion of the destructive San Fernando and synthetic earthquakes in the data set of Franklin and Chang.

Considering only the sliding mode of failure, Richards and Elms' design procedure employs equation 2.4 as the prediction equation for the seismic design of gravity retaining wall. The steps in Richards and Elms' design procedure are:

1. Determine the design maximum ground acceleration, design maximum ground velocity and allowable relative displacement.

2. Use equation 2.4 to calculate the limiting acceleration, Ng, for the design.

3. Detail the wall as outlined in conventional approach, including the inertia I on the wall, using Ng as the input acceleration. The required weight of the wall is evaluated.

4. Apply a factor of safety of 1.5 to the weight of the wall.

To illustrate the procedure, assume that a wall is to be designed for an earthquake with a peak acceleration of 0.4g and a peak velocity of 400 mm/s. The permissible displacement is to be less than 50 mm. From equation 2.4, the limiting acceleration for purposes of design is 0.206g. From conventional design (see Section 3.3), the necessary weight of wall would be $1.29(0.5\gamma H^2)$ or $0.645\gamma H^2$ per unit length. Finally, the design weight of the wall is increased to $0.968\gamma H^2$ which is 1.5 times the calculated required value. Thus the actual limiting acceleration is 0.298g. The anticipated permanent displacement is less than 12mm.

2.3.3 <u>Shortcomings in Richards and Elms' Procedure</u>

Richards and Elms' design procedure is an oversimplification of the problem. Their data base rests on some doubtful assumptions. For example, Franklin and Chang studied one accelerogram at a time. Apparently, they have neglected the vertical acceleration of the ground in their analysis. Moreover, an inherent assumption is that the maximum absolute acceleration happens to align with one of the recording instruments. Since Ag is defined as the absolute maximum acceleration, clearly, this assumption cannot be valid when applied to BOTH accelerograms of the same earthquake recorded at one station. In the author's opinion, the three accelerograms of each earthquake should be scaled by the SAME scaling factor so as to have the absolute maximum acceleration as specified.

Even when there is no vertical ground motion, once the backfill begins to slip, compatibility of movements requires the backfill to have a different vertical acceleration, (kv')g. This vertical acceleration is a function of the input ground motion, (kv, kh) and the inclination of the failure plane. Figure 2.5 illustrates the compatibility requirement. The primary effect of the vertical backfill acceleration is to make the dynamic active earth pressure dependent on kh and kv. As a result, the instantaneous wall acceleration, (kh")g, is also a function of kv and kh. At this point, we have to redefine the limiting acceleration Ng as the intantaneous acceleration of the wall during sliding when there is NO vertical acceleration. The general instantaneous wall acceleration during sliding, (kh")g, is termed the threshold or cut-off acceleration instead.

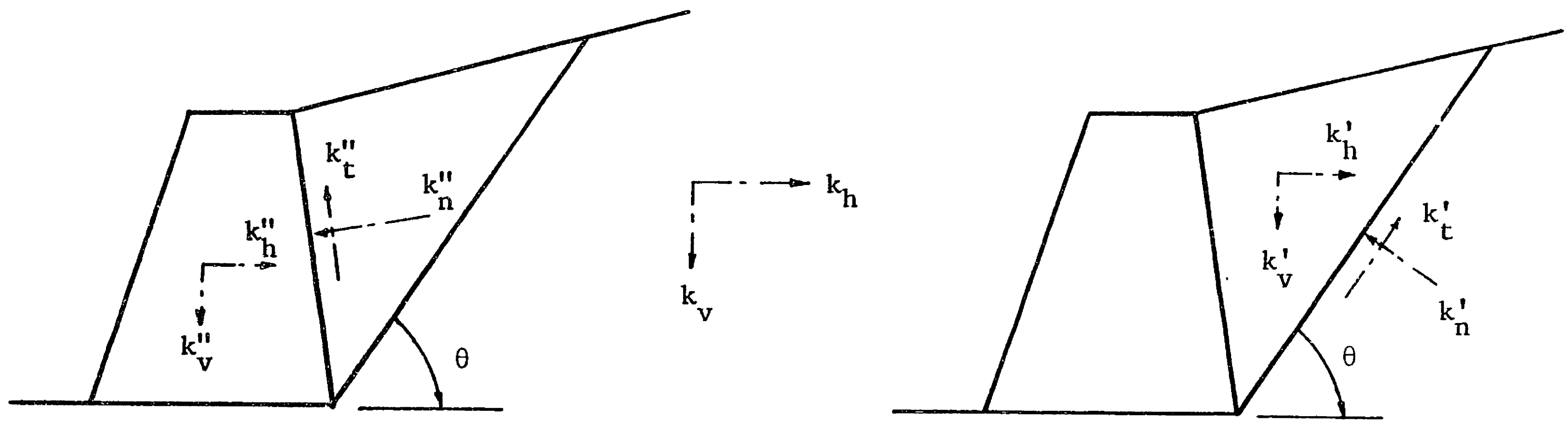

Figure 2.5 Compatibility requrements at interfaces

Richards and Elms recommended conservative application of the procedure because the assumptions and simplifications used to derive the prediction equation may not be conservative. These potential shortcomings are :

1. Vertical ground accelerations are neglected in the analysis.

2. The time variation of dynamic earth pressure is not taken into account.

3. Inconsistent normalization of earthquake accelerograms.

4. The dynamic soil friction angles are assumed to equal the static friction angles.

5. Tilting displacements have not been considered.

6. There are uncertainties in the design ground motion.

7. The prediction rule is empirical in nature; the confidence level cannot be readily evaluated.

Despite all these shortcomings, the principle underlying the approach is still very sound so as to have acceptable performance with economical designs. More study and possible refinement of the method are needed before the procedure can be incorporated into applicable standards and codes.

2.4 Recent Developments in Seismic Analysis

2.4.1 Modelling of Sliding Behavior

Zarrabi(1979) extended the analysis of relative displacement, coupling the simple sliding block model with the Mononobe-Okabe equation to account for the time-varying dynamic earth pressure. In his modified model, the failure soil wedge is considered as a second block sliding down along the failure plane; see Figure 2.5. At every time step, the compatibility and equilibrium requirements across the interfaces are satisfied by recalculating the inclination of the rupture plane. Effectively, some of the simplications in Richards and Elms' design procedure have been eliminated. He concluded that:

1. The effect of excluding vertical ground acceleration in the analysis is insignificant at low N/A. At high N/A, the error is of the order of 10 to 30% on the unsafe side.

2. Newmark's model always underestimates the relative displacement comparing to his modified model under the same† conditions (i.e. either including or excluding the vertical acceleration).

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†Zarrabi compares the case of his model including vertical acceleration to the case of Newmark's model with kv=0.

3. The effect of internal friction for the backfill is negligible in the analysis with the same N, but affects the weight of the wall and hence the N value.

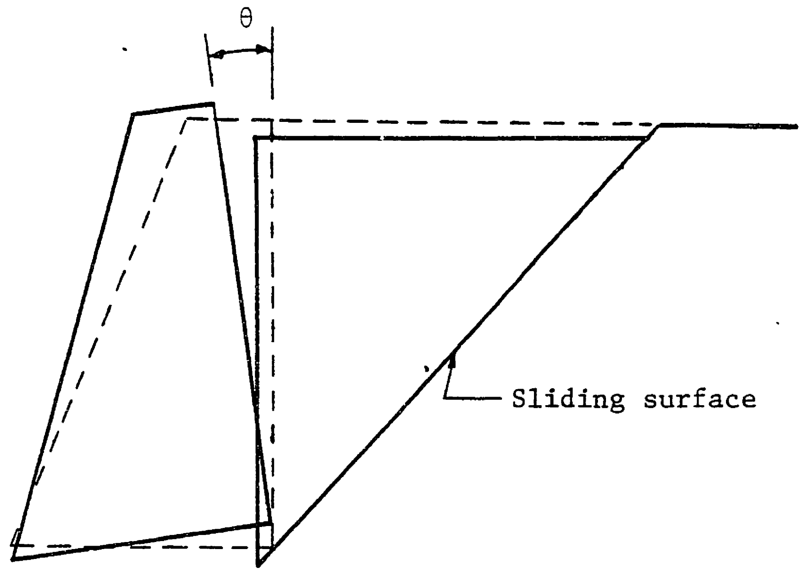
4. Richards and Elms' design procedure is very conservative when using a dynamic factor of safety of 1.5 on the weight of the wall. The expected relative displacement is lower than the permissible relative displacement determined by Richards and Elms' design procedure (equation 2.4) by one order of magnitude.

Model tests reported by Lai(1979) showed that the accuracy of Zarrabi's model is better than Newmark's model.

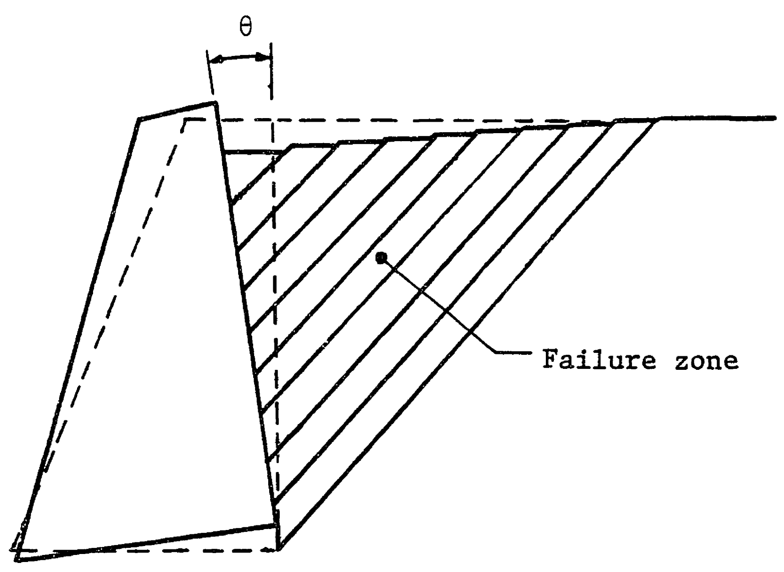
2.4.2 Modelling of Coupled Sliding and Tilting Behavior

Nadim (1980) extended the analysis further by considering the sliding as well as tilting behavior of retaining walls during earthquakes. Figure 2.6 shows the tilting model used in his formulation. His preliminary results suggested that:

1. When (N/A) for sliding, $(N/A)_s$, is less than (N/A) for tilting, $(N/A)_t$, no tilting will occur.



(a) Compatibility not satisfied



(b) Compatibility satisfied

Figure 2.6 Tilting models for retaining walls

2. When (N/A) for sliding is greater than 1.15 times of (N/A) for tilting, the displacements are primarily tilting. He observed that the tilting displacement for the upper third point of the wall is roughly equal to the displacement for the sliding only mode.

3. For $1.15>(N/A)s/(N/A)t>1$, a sliding block model with an equivalent (N/A) may be used to estimate the displacement at the top of the wall. The equation for the equivalent (N/A) is:

$$(N/A)eq = 2.5\ (N/A)t - 1.5\ (N/A)s \qquad \text{....(2.5)}$$

These results suggest that the sliding mode governs the seismic response of gravity retaining walls when $(N/A)s < 1.15(N/A)t$. However, both Zarrabi and Nadim considered a few specific cases only; their data bases are limited. It is desirable to carry out more extensive study with these extensions and to refine the design procedure of Richards and Elms.

Chapter III

The Sliding Block Models for Retaining Walls

3.1 Introduction

In this chapter, the mathematical details of the sliding block models used in this study are presented. Newmark's model was originally developed for modelling the response of dams during earthquakes. Adaptation for modelling the response of retaining walls is described. Zarrabi's improvement of the model is briefly discussed. The expressions he derived are rearranged for better understanding and efficient handling. Nadim's work on the tilting mode is, however, beyond the scope of the present study and so has been omitted.

3.2 Newmark's Sliding Block Concept

3.2.1 The Theory

In his Rankine lecture, Newmark(1965) presented the sliding block concept for calculating the relative displacement induced in dams during earthquakes. The sliding block model has been widely used in seismic analysis of dams since then.

Newmark's model is that of a block sitting on a moving plane, as shown in Figure 3.1. The plane is subjected to both horizontal and vertical accelerations. For simplicity, let us assume no vertical acceleration for the time being. The shear force developed at the interface between the block and the plane induces the driving force to accelerate the block. This shear force is limited to the maximum frictional resistance that can be mobilized at the interface. Hence, the horizontal acceleration of the block is limited. Since there is no vertical acceleration, by definition, the maximum acceleration that the block can achieve is the limiting acceleration, Ng. When the horizontal acceleration of the plane exceeds this limiting acceleration, the block can no longer accelerate with the plane and relative displacement develops. Upon retardation, the plane slows down and at some instance, the velocity of the block is equal to that of the plane. The block and the plane thus reunite. For most engineering applications,

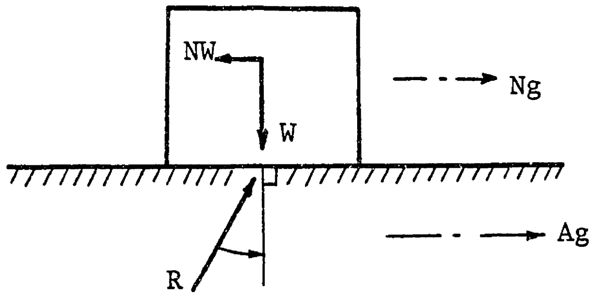


Figure 3.1 Block on moving plane

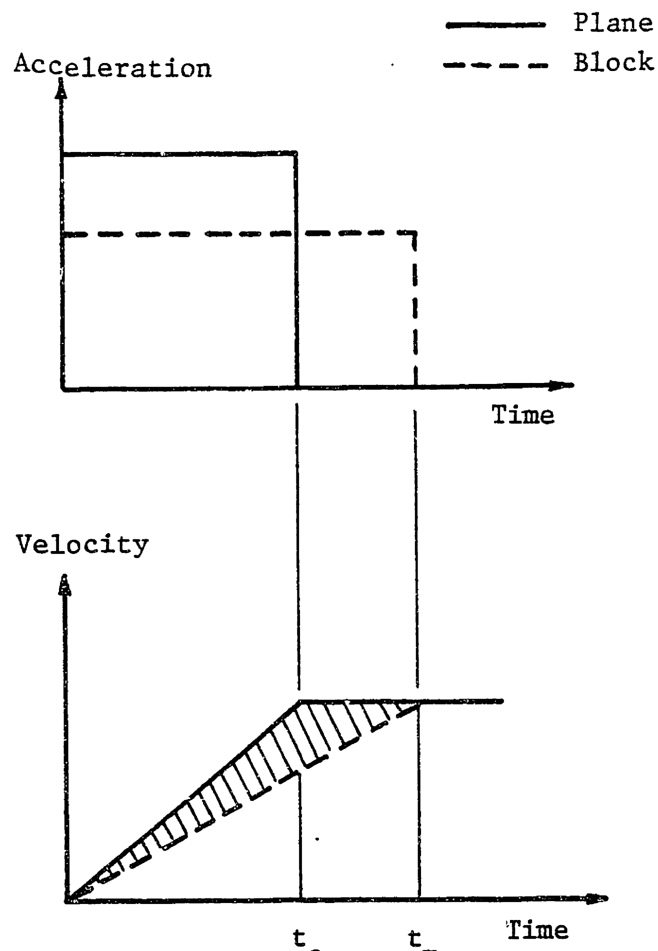


Figure 3.2 Development of relative displacement

relative displacement can only develop in one direction only. In these cases, the N value for sliding towards the restricted direction is taken as infinity.

Consider a one-way sliding block sitting on a horizontal ground, and the plane being subjected to a single rectanglular pulse of horizontal ground acceleration with value Ag and duration t_o, Figure 3.2. The instantaneous ground velocity is given by :

$$Vg = Agt \qquad \text{for } t \leq t_o$$

Since the acceleration of the block is limited to the limiting acceleration, Ng, the block velocity is given by :

$$Vb = Ngt \qquad \text{for } t \leq tm$$

$$tm = At_o/N, \text{ the instance when the velocities become equal}$$

for any t smaller than tm. The relative displacement occurring during this time interval is equal to the area surrounded by the two velocity profiles, i.e., the area of the shaded triangle in Figure 3.2. Denoting this area by D, by geometry :

$$D = \frac{V^2}{2Ng}\left(1 - \frac{N}{A}\right)$$

where V is the maximum ground velocity and D is the relative displacement for a single rectangular pulse.

For different forms of pulses, the velocities are obtained by integration, numerically if necessary. The relative displacement is calculated likewise.

As a result, there is a finite relative displacement between the plane and the block. At some other stages of the shaking, the process occurs again and again; see Figure 3.3. The total permanent relative displacement is the sum of these incremental displacements. A typical time history of displacement during an earthquake is illustrated in Figure 3.4.

3.2.2 Previous Work

Newmark concluded that, based on four selected normalized earthquake motions (Ferndale, Eureka, Olympia and El Centro), the effective number of rectangular pulses is close to A/N. As a result, he proposed equation 3.1 to estimate the permanent relative displacement of a sliding block possessing unsymmetrical resistance.

$$D = \frac{V^2}{2Ng}\left(1 - \frac{N}{A}\right)\frac{A}{N} \qquad \ldots\ (3.1)$$

Franklin and Chang(1977) extended the data base for Newmark's estimation and checked on the validity of equation 3.1. They analyzed a total of 169 horizontal and 10 vertical strong motion records from 27 earthquakes and 10

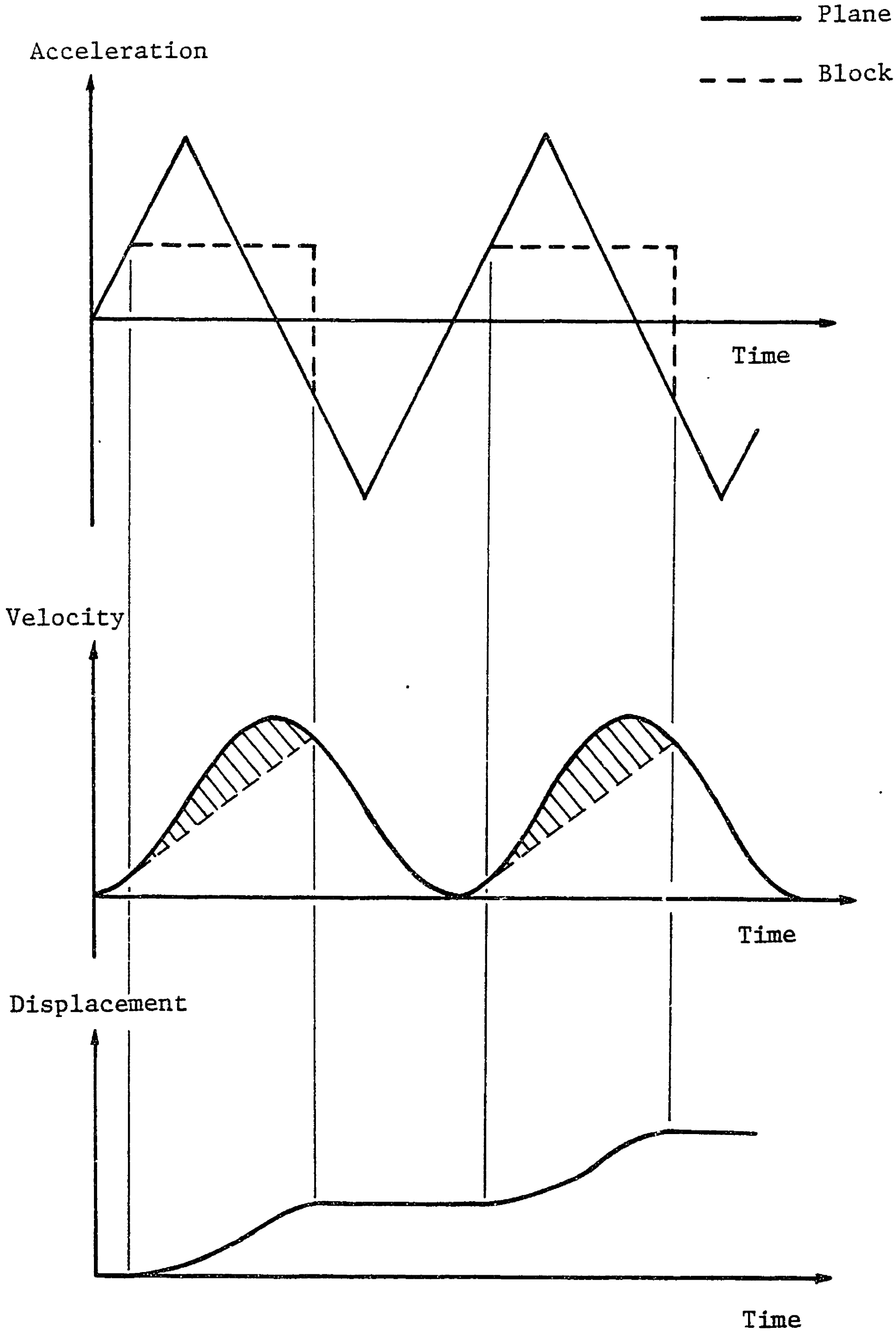


Figure 3.3 Discrete sliding processes

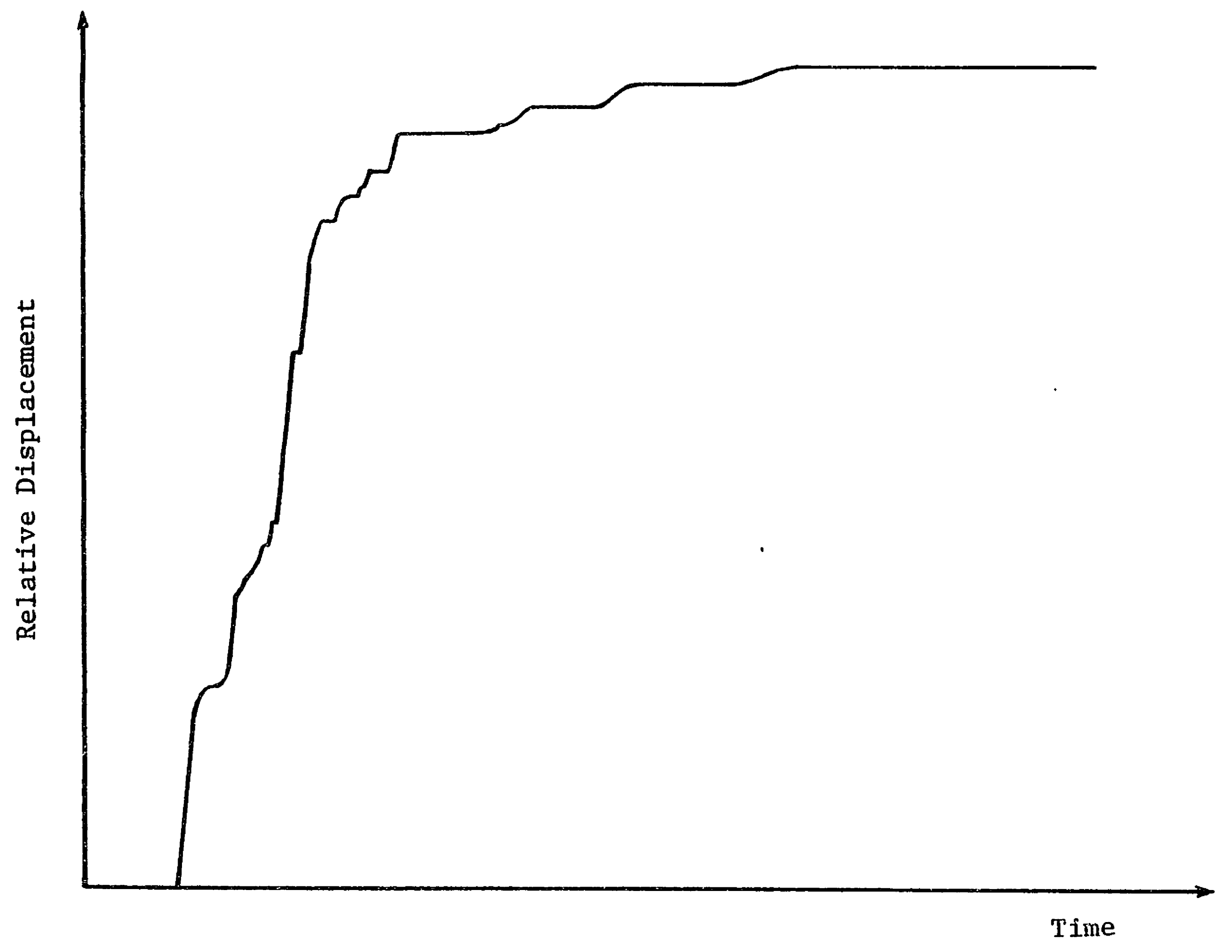


Figure 3.4 Typical Time History of Relative Displacement

synthetic accelerograms. They concluded that, except for records from the magnitude 6.5 San Fernando earthquake, all other earthquake records analyzed were near or below Newmark's estimate. The prediction rule (equation 2.4) in Richards and Elms' design procedure is determined from their published results.

3.3 The Limiting Acceleration, Ng, of Retaining Walls

The limiting acceleration for retaining walls has been defined as the maximum wall acceleration for no vertical ground shaking.

Consider the case of no vertical acceleration. Referring to Figure 3.5, relative motion will not be initiated if the horizontal ground acceleration is less than or equal to the limiting acceleration of the structural system. As long as the horizontal ground acceleration is less than this limiting value and relative motion initiated by previous shaking has stopped, the wall, the whole backfill and the ground will remain intact. In other words, $kh'' = kh' = kh$.

When the ground acceleration is just equal to the limiting value, the maximum shear resistance at the base of the wall has been mobilized. For the free body of the wall,

$$Bn = Ww + Pae \sin(\beta+\delta)$$

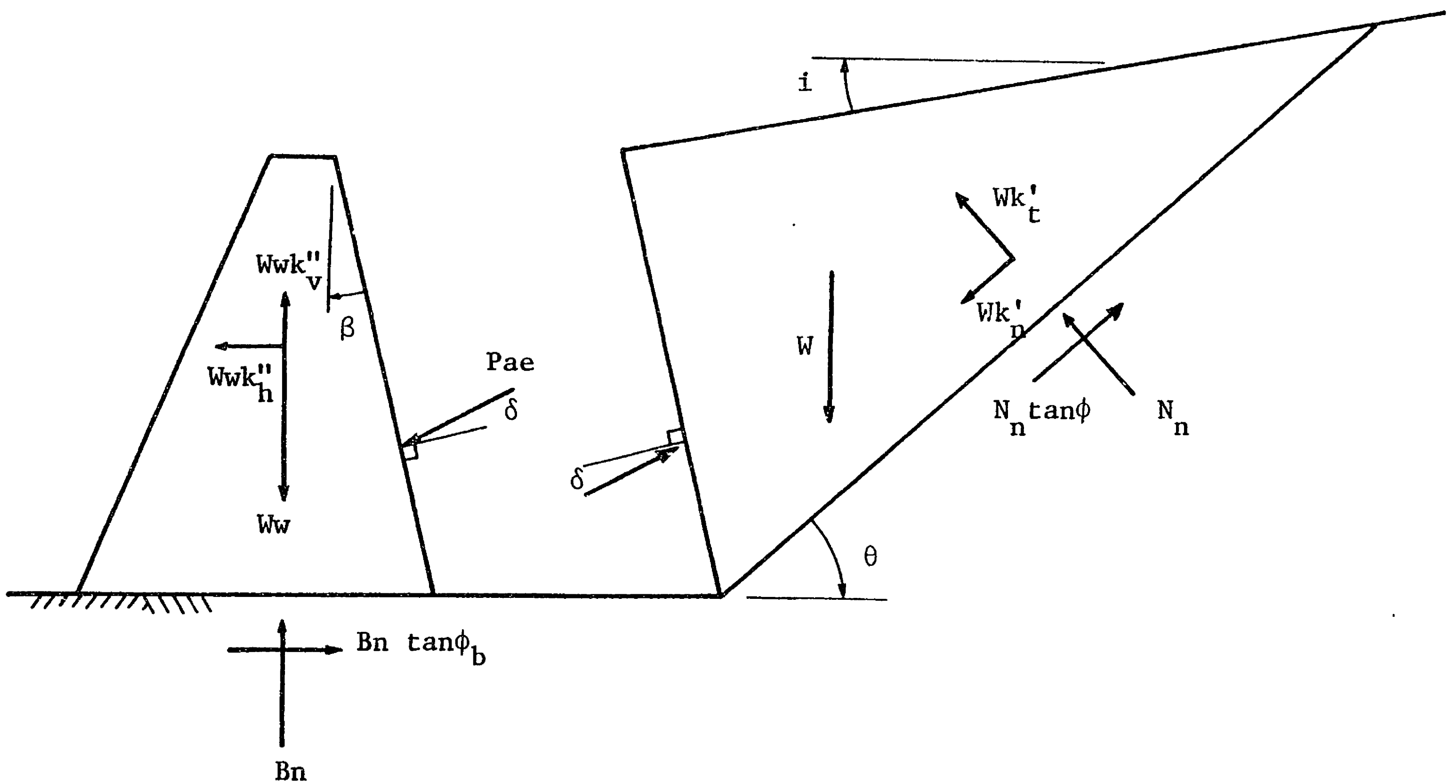


Figure 3.5 Force resolution of wall and soil wedge

$$Bn \tan(\phi b) = Ww\ kh'' + Pae \cos(\beta+\delta)$$

Eliminating Bn, we have:

$$Ww = \frac{[\cos(\beta+\delta)-\sin(\beta+\delta)\tan(\phi b)]\ Pae}{[\tan(\phi b)-kh'']}$$

Substituting for Pae from the Mononobe-Okabe equation (equation 2.1), we have:

$$Ww = 0.5\gamma H^2 \frac{[\cos(\beta+\delta)-\sin(\beta+\delta)\tan(\phi b)]\ Kae}{[\tan(\phi b)-kh'']} \quad .... (3.2)$$

where Kae is the same as in equation 2.1

kh" = N at the limiting condition

This equation is an implicit equation for N, given the weight of the wall and the structural system. In this study, the limiting acceleration is specified and the weight of the wall is calculated instead.

Figure 3.6 is a typical plot of limiting acceleration versus the weight of the wall. The curve is asymptotic to a maximum limiting acceleration corresponding to the situations of α equal to (ϕ-i) or (ϕb) whichever is smaller. This maximum value of limiting acceleration is termed the critical acceleration in the classical design approach.

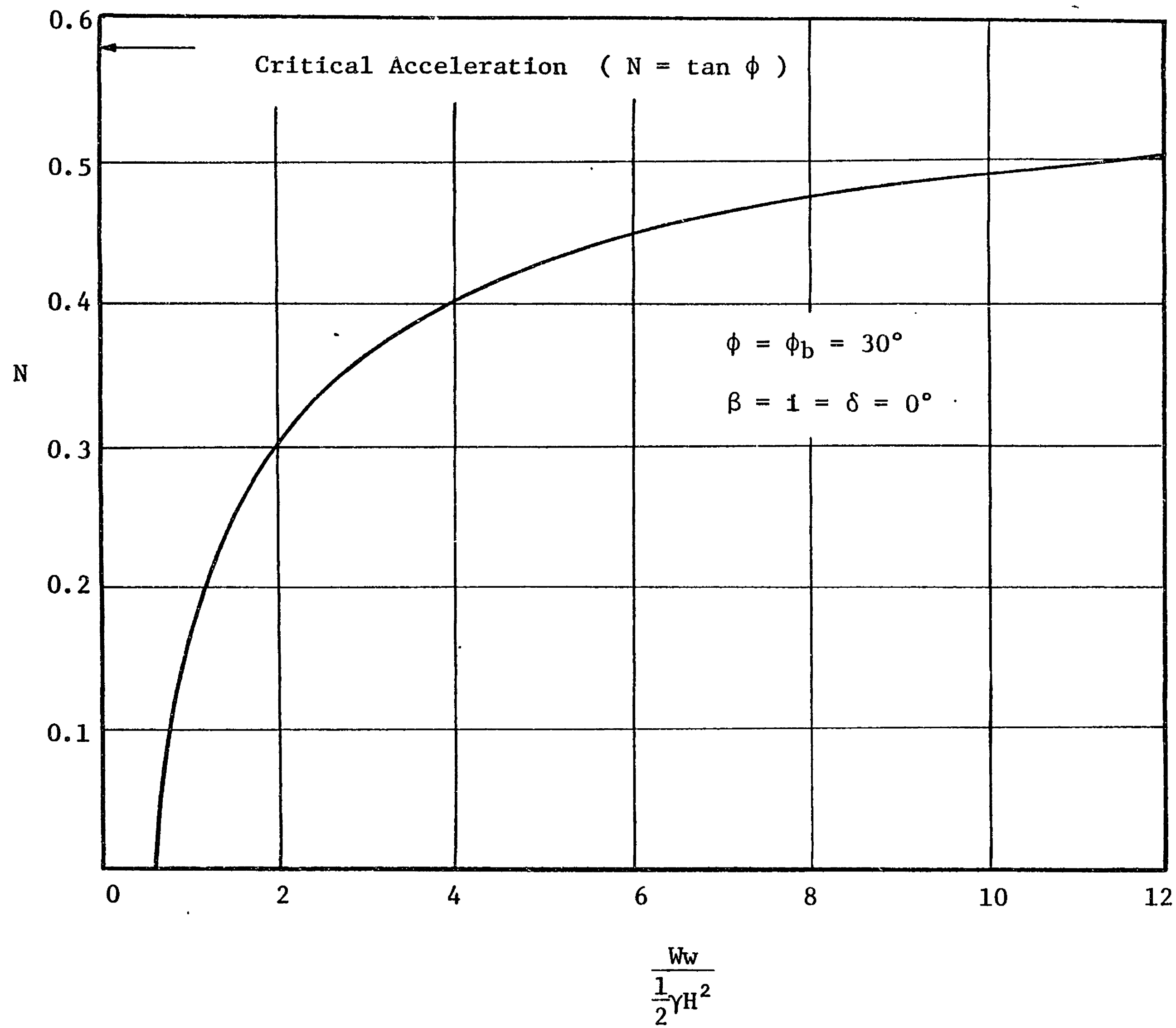


Figure 3.6 Limiting Acceleration and Wall Weight

3.4 Sliding Block Models for Retaining Walls

The basic difference between Newmark's model and Zarrabi's model is in the assumption of the time variation of the dynamic active earth pressure during sliding. Since this does not affect the value of limiting acceleration, equation 3.2 can be applied to both Newmark's and Zarrabi's model.

3.4.1 Newmark's Sliding Block Model

In the simplest form, the wall is modelled as the block and the ground as the plane. Referring to the free body diagram of the wall in Figure 3.5, no relative displacement would result unless the horizontal component of Pae and Wkh" exceeds the maximum shear resistance at the base of the wall. The response acceleration of the wall in the limiting situation is the instantaneous threshold acceleration, (kh")g. Since all but one of the forces are functions of the ground accelerations and the threshold acceleration depends on these forces, the threshold acceleration is also time-dependent. The reason for redefining the limiting acceleration, Ng, becomes apparent.

The passive dynamic resistance of the wall will generally be so large that it is unlikely that it will be exceeded. Hence, a one-way sliding model is appropriate for the retaining wall case. The sliding block model for the retaining wall case is thus established.

For computation of the permanent displacement, the total relative displacement is the sum of the finite relative displacements developed during strong pulses. A computer code has to be developed for the time integration of relative displacement.

In Newmark's model, the dynamic lateral earth pressure is assumed to be constant even after sliding has been initiated. This model is also called the simple sliding block model for this reason. It follows that the vertical acceleration of the soil wedge has no effect on the instantaneous threshold acceleration, (kh")g, which is then not a function of the horizontal ground acceleration, (kh)g.

The vertical ground acceleration, (kv)g, however still affects the instantaneous threshold acceleration by reducing the weight of the wall.

In Figure 3.7, at the limiting condition,

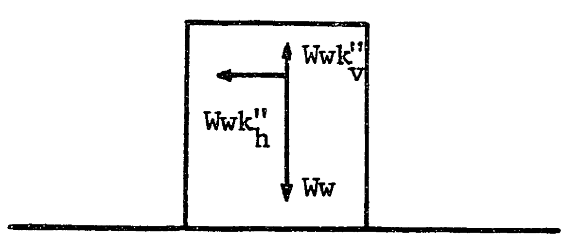


Figure 3.7

$$Ww\ kh'' = [Ww - Ww\ kv'']\ \mu$$

$$kh'' = [\ 1 - kv''\ ]\ \mu$$

where μ = coefficient of friction

At $kv''=0$, $kh''=\mu$. On the other hand, $kh''=N$ by definition. Hence, $\mu=N$ and

$$kh'' = [\ 1 - kv''\ ]\ N \qquad \text{.... (3.3)}$$

In summary, the wall will travel with the ground as long as $kh<(1-kv)N$. After sliding has started, the instantaneous acceleration of the wall is given by equation 3.3. When the velocities are equal upon retardation and also $kh<(1-kv)N$, the ground and the wall will travel as one unit again.

3.4.2 Zarrabi's Sliding Block Model

The constant dynamic lateral earth pressure assumption in Newmark's model is unrealistic for the retaining wall problem. With different ground motions, the soil wedge will have a different vertical acceleration in order to satisfy the compatibility and equilibrium requirements during sliding. Consequently, the dynamic lateral earth pressure and the inclination of the failure rupture plane have to change correspondingly. The assumption of constant dynamic active pressure is obviously not justified.

Zarrabi derived the compatibility equations for the structural system by considering the free body diagrams of the wall, the soil wedge and the ground in Figure 3.5. Calculating Pae in the dynamic equilibrium equations with the Mononobe-Okabe equation, he obtained the following equations for calculating the instantaneous threshold acceleration:

$$kh'' = \frac{(1+B)[A\tan(\phi b)(1-kv)+C]-Bkh}{A(1+B)+1} \quad \ldots\ldots (3.4a)$$

where
$$A = \frac{[\sin(\beta+\delta-\theta)\tan\phi-\cos(\beta+\delta-\theta)]Ww\cos\theta}{[\sin(\beta+\delta)\tan\phi b-\cos(\beta+\delta)]W} \quad \ldots\ldots (3.4b)$$

$$B = \tan\theta \ \tan\beta \quad \ldots\ldots (3.4c)$$

$$C = \cos^2\theta(\tan\theta-\tan\phi)(kv-1+kh\tan\theta) \quad \ldots\ldots (3.4d)$$

$$W = \frac{\gamma H^2\cos(\beta-i)\cos(\theta-\beta)}{2\sin(\theta-i)\cos^2\beta} \quad \ldots\ldots (3.4e)$$

Ww = Weight of the wall

The effect of vertical ground acceleration has been incorporated into the equations already. Because this modification takes into account all the parameters, it is sometimes referred to as the complete model. Since equation 3.4 is nonlinear and implicit in nature, he recommended an iterative scheme to solve for kh" at every time step.

Rearranging the above equations, the ground accelerations and the wall accelerations can be expressed explicitly in terms of the accelerations of the soil wedge:

$$\tan\psi = \frac{kh}{1-kv} = \frac{A(1+B)+1+[S-A\tan\phi b]T}{\tan\theta[A+1+ST]+AB\cot\alpha} \qquad \ldots\ldots (3.5a)$$

$$\text{and } \tan\xi = \frac{kh''}{1-kv''} = \frac{1-\tan\theta\tan\psi}{T} \qquad \ldots\ldots (3.5b)$$

$$\text{where } S = \cos^2\theta\ (\tan\theta - \tan\phi) \qquad \ldots\ldots (3.5c)$$

$$T = \cot\alpha - \tan\theta \qquad \ldots\ldots (3.5d)$$

A,B are the same as in equation 3.4.

If the vaule of α is known, the inclination of the rupture plane, θ, and hence the ground motion input, $\tan\psi$, to produce this soil wedge accelerations can be found from equation 2.2 and 3.5a respectively. The corresponding wall accelerations, $\tan\xi$, can be determined by equation 3.5b. The relationship between the ground accelerations and the wall accelerations has been plotted in Figure 3.8 and Figure 3.9. It can be seen that the assumption of constant dynamic lateral earth pressure in Newmark's model may have an error of 20% in $\tan\xi$ and kh". Figure 3.10 is a schematic plot of the sliding processes for the two models illustrating the consequence. The effect on the total relative displacement will be discussed later.

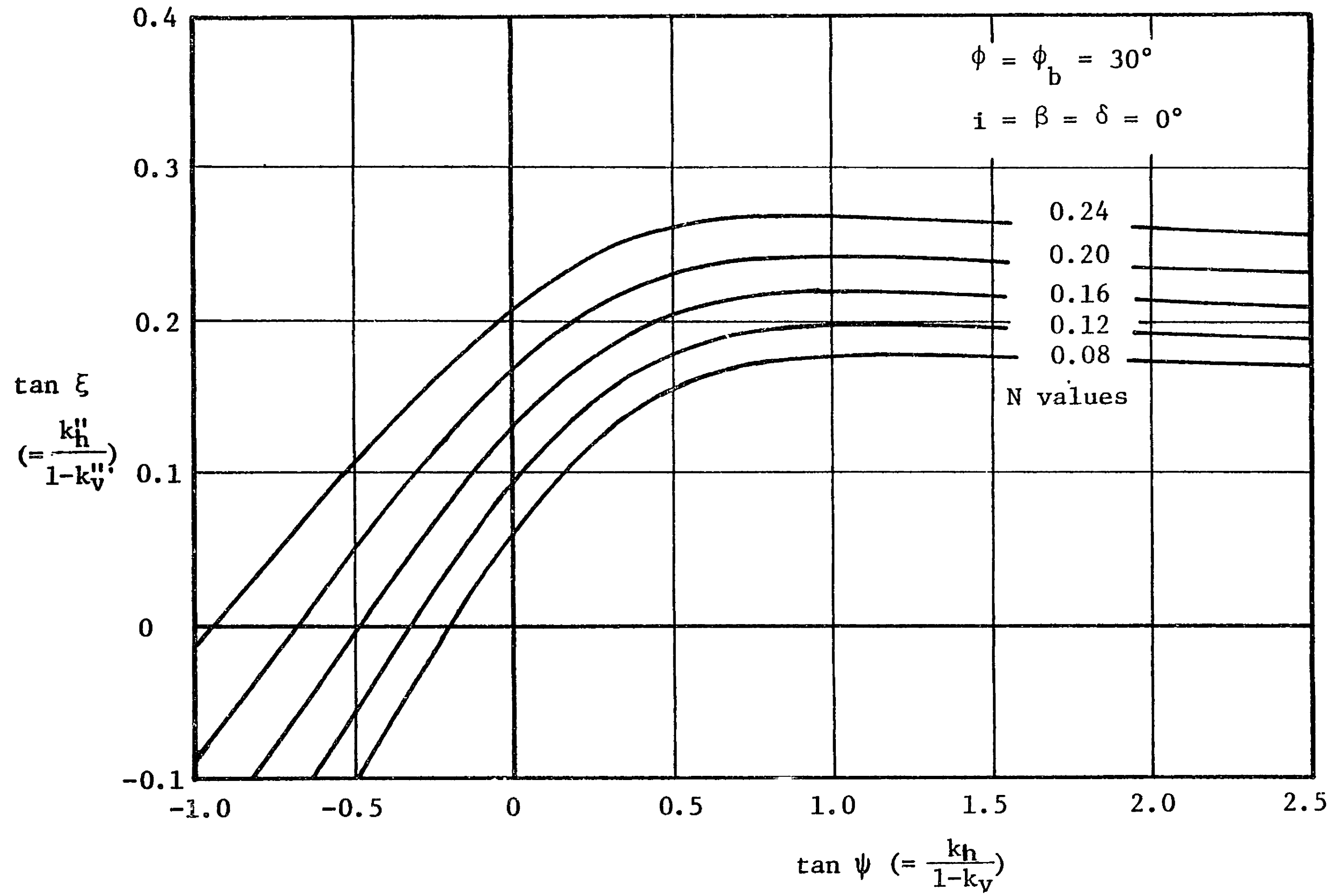


Figure 3.8 Relationship of Ground and Wall Accelerations (Zarrabi's model)

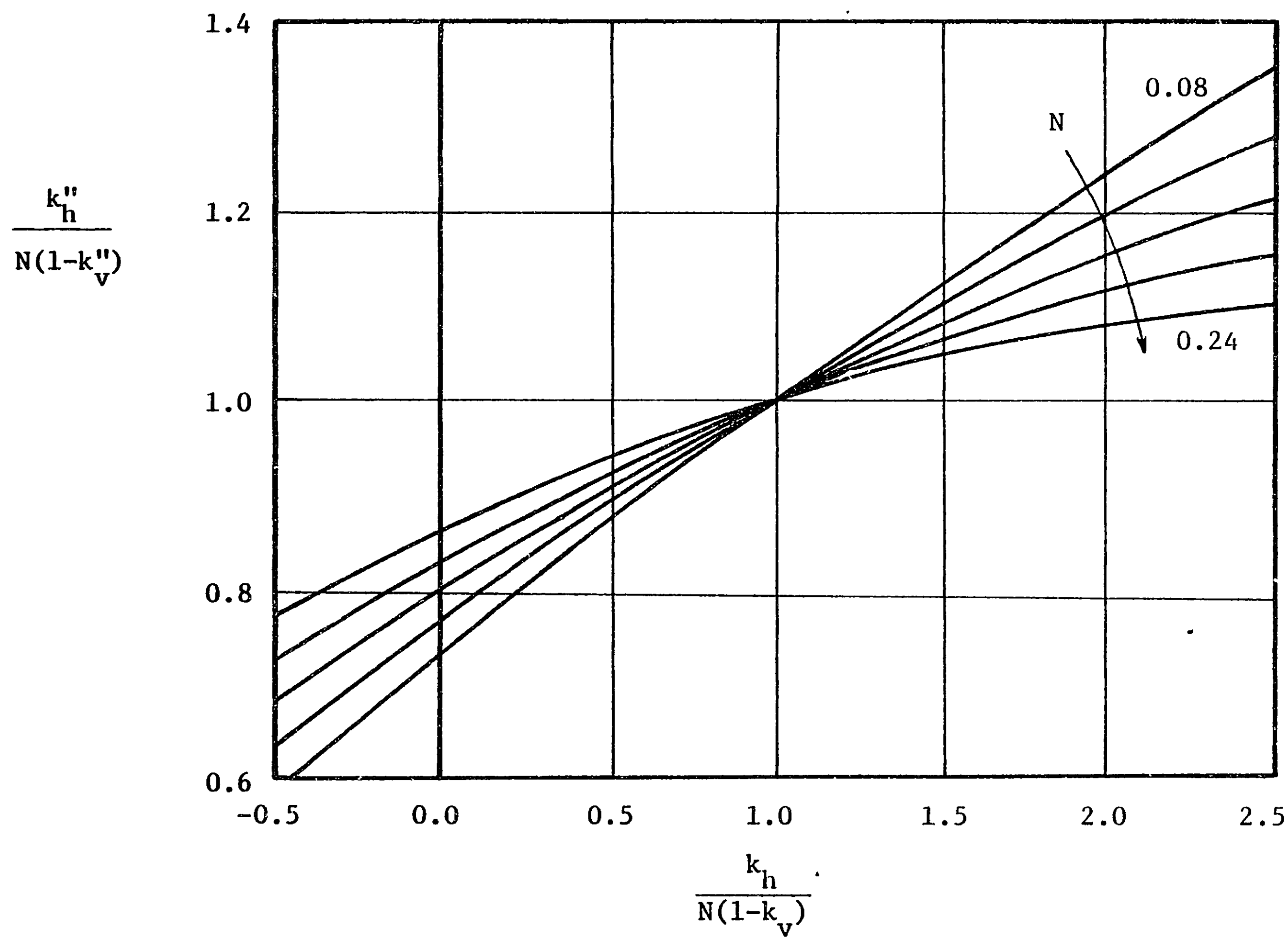


Figure 3.9 Relative error in wall acceleration of Newmark's Model

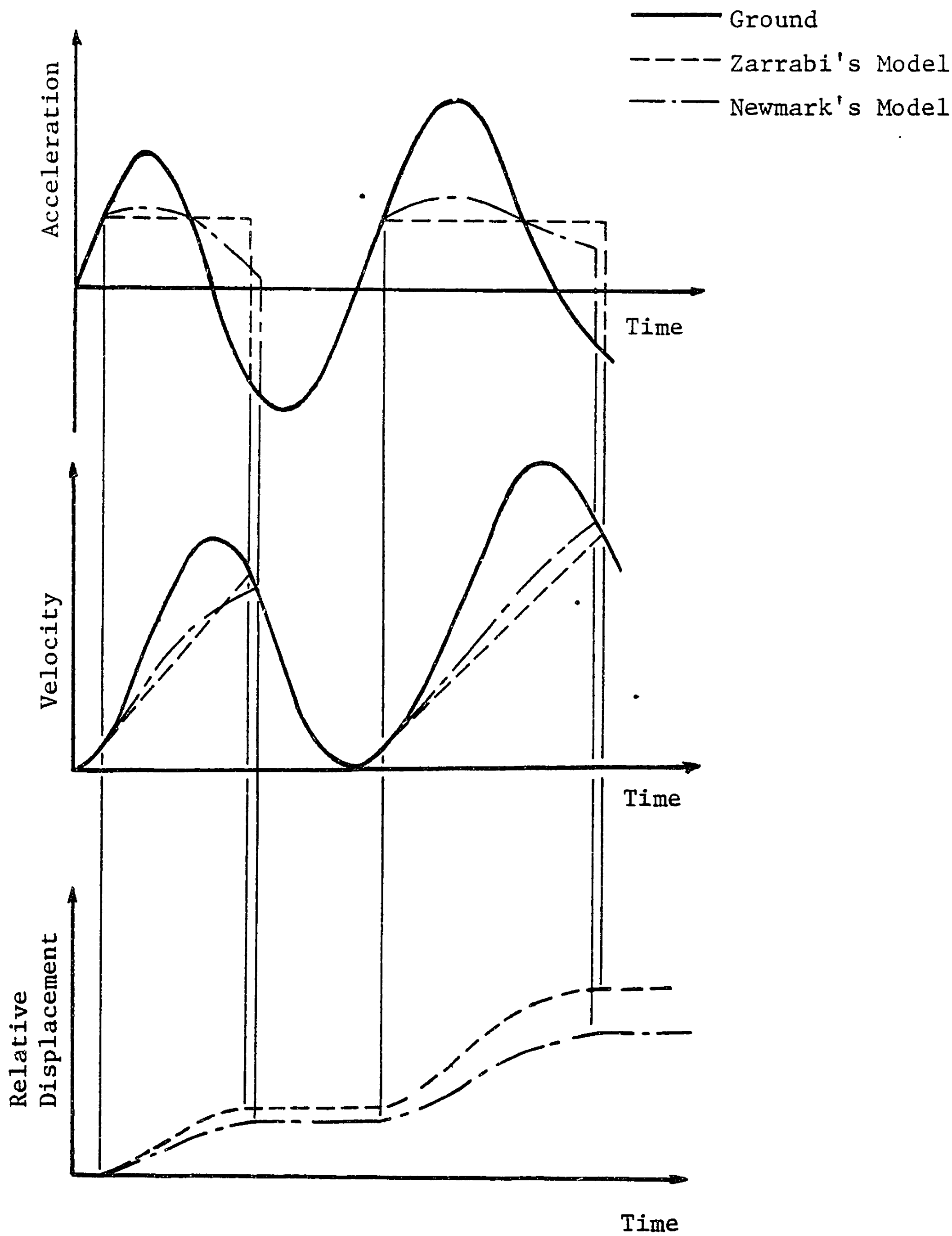


Figure 3.10 Sliding processes of the two models

Chapter IV

The Solution Procedure

4.1 Introduction

In order to compute the relative displacement, the computer codes written by Jordan(1979) for Newmark's model and Zarrabi(1979) for his model have been utilized. Slight modifications have been made to the iterative scheme and normalization process. The general scheme of solution procedure is presented in this chapter and the computer codes are presented in Appendix A.

The ground motion accelerograms are chosen from the digitized, corrected accelerograms of the California Institute of Technology (CIT) Volume II series. The choice of accelerograms will also be discussed. A reference structural system is defined for discussion and comparison purposes.

4.2 The Earthquake Accelerograms

The data base of Franklin and Ch'ang is too extensive because most of the earthquake records then available are used. Even vertical accelerograms were used as horizontal shaking. It is usually the case that low intensity earthquakes give higher normalized relative displacements. This may be due to the more uniform nature of the shaking. When the uniform pulses are scaled to have a higher peak value, there will be more pulses capable of causing slips and a relatively higher relative displacement is computed.

In order to obtain more meaningful and representative results, only those strong motion earthquakes with high intensities are used for analysis in this study. A series of 14 sets of accelerograms of ten earthquakes are chosen from the digitized, corrected accelerograms of CIT Volume II series. The selection criteria are:

1. Magnitude should be greater than 6.

2. Actual peak acceleration should be higher than 0.15g.

With these sets of earthquake accelerograms, it is expected that the computed results will bear better correlation with the field observations. The chosen sets of accelerograms are listed in Appendix B.

4.3 The Normalization Scheme

Various methods have been used to characterize earthquakes. The method adopted here is the one used by Newmark in which the acceleration and the time scales are both normalized so that the absolute maximum horizontal acceleration and velocity are prescribed.

The purpose of scaling the earthquake accelerograms is to permit direct comparison of the permanent displacements computed from records with a wide range of peak accelerations and velocities. These permanent relative displacements are often called the normalized relative displacements.

4.3.1 Normalization of Accelerograms

The way that an earthquake record is normalized is of great concern. The orientation of the quoted maximum acceleration is random; it may act towards or away from the backfill, or even along the length of the wall. The actual peak acceleration that a wall would experience during such earthquake may be somewhat less than this maximum value depending on the orientation of the wall with respect to the shaking. For the 1940 El Centro earthquake, the absolute maximum acceleration is 341.7 cm/s^2 in the direction S00E. Should the wall be facing West (the backfill being due West to the wall), the actual peak acceleration that the wall experiences will be 210.1cm/s², only 61.5% of the absolute maximum value.

Newmark and Franklin and Chang all used one record at a time for their studies. An inherent assumption in doing so is that the absolute maximum acceleration happens to align with the recording instrument. Obviously this assumption is not valid when applied to both accelerograms for the same earthquake recorded at the same station.

When normalizing the accelerograms for analysis, all the earthquake accelerograms (2 horizontal and 1 vertical) of the same earthquake are normalized by the same scaling factor so that the absolute maximum horizontal acceleration is as specified. The inherent assumption is modified to that the peak acceleration aligns with one of the recording directions. For the purpose of this study, this is considered as a close approximation of the actual direction of maximum absolute acceleration and the discrepancy may be small enough to be ignored.

To illustrate the scaling procedure, consider the 1940 El Centro earthquake. This earthquake possesses peak accelerations of 341.7 cm/s² in S00E, 263.1 cm/s² in N00E, 178.6 cm/s² in N90E and 210.1 cm/s² in S90W. When scaled to 0.6g, the corresponding values are 0.6g, 0.462g, 0.314g and 0.369g.

4.3.2 Normalization of Velocities

By changing the time scale, all earthquakes can be scaled to a specified peak velocity. However, this can be achieved more easily by scaling the relative displacements instead. Each relative displacement is multiplied by the square of the ratio of the normalizing velocity Vn to the actual peak velocity corresponding to the normalized accelerograms. For consistency, the direction of normalizing peak velocity should be coresponding to that of the normalizing peak acceleration. In other words, the relative displacements in the four directions should be scaled by the same scaling factor as well. So,

$$Dn = D\ (\ Vn/V\ )^2$$

where Dn = Normalized displacement corresponding to the normalizing peak acceleration and velocity

Vn = Normalizing peak velocity

D = Normalized displacement corresponding to the normalizing peak acceleration only

V = Actual peak velocity in the direction of the the absolute peak acceleration

Proofs have been given by Zarrabi (1979) and by Franklin and Chang (1977), and the reader is referred these references.

4.4 The Reference Structural System

There are eight parameters in Figure 2.1, equation 3.4 and 3.5 describing the whole structural system. These include the material properties such as the soil friction angles, ϕb, ϕ and δ and γ the unit weight of the soil; the geometry of the structure, namely the height, the slope angles of the backfill and the wall; as well as the weight of the wall. However, the coefficient of limiting acceleration, N, can collectively describe all the effects of Ww, γ and H. This reduces the number of parameters to six, yet it is still difficult to generalize the results.

Consequently, the author is forced to adopt a typical structural system as the reference structural system for the purposes of comparison and discussion. The chosen reference structural system is shown in Figure 4.1. The friction angles of the backfill and at the base of the wall are 30°. The wall is assumed to be smooth and so the shear stresses between the wall and the soil are zero. The face of the wall facing the bacfill is vertical while the backfill is horizontal. For this wall designed to a static factor of safety of 1.5, the limiting acceleration would be 0.11g.

Effects of discrepancies in actual parameters will also be considered in the analysis.

4.5 Calculation of Relative Displacements

At any point in time, the instantaneous cut-off acceleration is determined by equation 3.3 for Newmark's

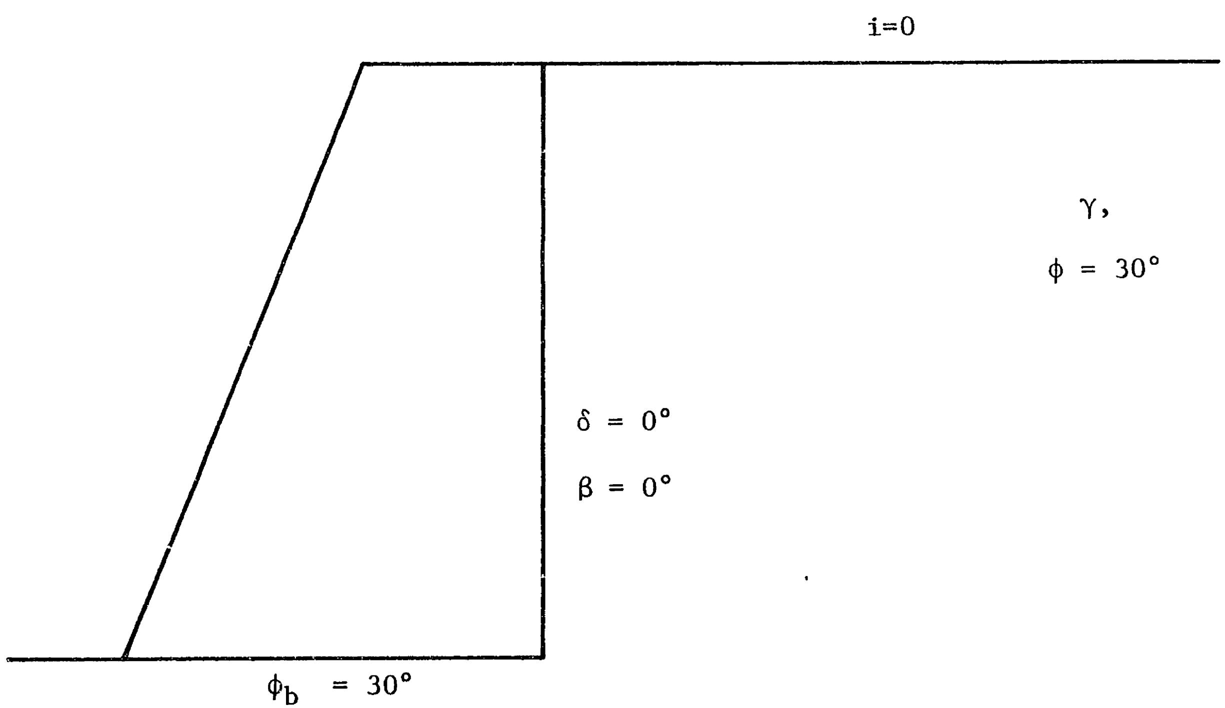


Figure 4.1 Reference Structural System

model and Figure 3.8 for Zarrabi's model. If the ground acceleration is higher than this value, the relative motion is declared to have started. Assuming a linear variation of acceleration during each time step, velocities of the wall and the ground are calculated by integrating the corresponding accelerations numerically. Integrating the velocities once more gives the displacements. This yields the following formulae:

$$V_{i+1} = V_i + 0.5\,(A_i + A_{i+1})\,T \qquad \ldots. \ (4.1)$$

$$D_{i+1} = D_i + V_i T + 1/6\,(2A_i + A_{i+1})\,T \qquad \ldots. \ (4.2)$$

where i = i th time step

D_i = Displacement at t_i

V_i = Velocity at t_i

A_i = Acceleration at t_i

T = Time Step

The difference of displacements is the relative displacement. When the velocities become equal again, sliding is signalled to stop. Schematically, the calulation of relative displacement has been shown in Figure 3.2, 3.3 and 3.10.

CHAPTER V

Results and Prediction Rule

5.1 Introduction

Results for several computer runs using Newmark's simple sliding block model and Zarrabi's modified sliding block model are presented in this chapter. The range of A has been chosen to go from 0.2 to 0.7 and the value of N/A varies from 0.1 to 0.7. The reference structural system described in Section 4.4 is used for Zarrabi's modified model. The computed displacements have been filed in Appendix C.

The effects of orientation and different shaking characteristics are investigated first. It is most convenient to study these two effects with Newmark's model with kv=0. The effect of including vertical acceleration in the analysis is also studied with results from Newmark's model. A correlation function is developed. It is assumed that these effects will be the same for Zarrabi's model with $kv \neq 0$. Another correlation function relating Newmark's model to Zarrabi's model is evaluated using results with $kv=0$. The discrepancies in soil friction angles are also considered. These groupings and formulations are necessary for a systematic formulation of a prediction rule.

A simple equation is developed to predict the relative displacement according to Newmark's model with $kv=0$. Incorporating correlation functions for Zarrabi's model and inclusion of vertical acceleration, a prediction rule for Zarrabi's model with $kv \neq 0$ is formed. The variance associated with this prediction rule is evaluated based on the computed results. A hypothetical lognormal distribution is proposed for the computed results and the goodness of fit is examined.

The statistics terminology and theorems used are summarized in Appendix D.

5.2 Cases of Newmark's Sliding Block Model

The orientation of the wall with respect to the ground shaking has an important role in the determination of permanent relative displacement. This has been specially accounted for by using a revised normalization scheme (see Section 4.3.1). This effect together with the influence of different shaking characteristics are investigated with the results from Newmark's sliding block model with kv=0.

5.2.1 The Effect of Wall Orientation

Results

The computer codes are specially modified to evaluate the permanent relative displacements in each of the four orientations. Each set of these four values portrays a simplified picture of the variation of the normalized relative displacement with respect to the orientation of the wall. The ratio, Eo, of the computed normalized relative displacements to the mean of the same set reflects the variation. It is a normalized random variable with mean of unity. Thus,

$$\overline{Dno} = 1/4 \sum Dno$$

$$Dno = Eo \ \overline{Dno} \qquad \text{.... (5.1)}$$

in which Dno denotes the normalized relative displacement predicted by Newmark's model with kv=0 and $\overline{Dno}$ is the mean of Dno with respect to the orientation of the wall. For example, the normalized relative displacements of the reference wall with A=0.5g, V=600mm/s and N/A=0.5 subjected to the 1965 Washington earthquake are (11.87, 0.99, 19.97, 62.82) in mm. The mean is thus 23.91mm while the set of Eo is (0.496, 0.042, 0.835, 2.627). It is evident that if only the maximum relative displacement is used as prediction, the expected value will be overestimated by more than 100%.

Table 5.1 summarizes the statistics of Eo. The distribution curves at different levels of N/A are shown in Figure 5.1. The conditional distribution of Eo given N/A resembles a normal distribution at low values of N/A (<0.4). At higher values of N/A (>0.5), the conditional distribution does not resemble any simple distribution. Figure 5.2 plots the coefficient of variation of Eo against N/A. It is observed that there is also a change of behavior at N/A between 0.4 to 0.5. The marginal distribution of Eo, however, resembles a lognormal distribution, Figure 5.3.

<u>Discussion</u>

This pattern of distribution for Eo is well expected. At low values of N/A, the number of strong pulses in the four orientations do not differ too much. Consequently, the normalized relative displacements are of the same magnitude and the scatter of the ratio, Eo, is small. On the other hand, the number of strong pulses in these four orientations may be differed by an order of magnitude at higher values of N/A. As a result, the computed normalized relative displacements are no longer of the same order.

With N/A higher than certain level, the wall may not experience any displacement at all depending on its orientation. This level of N/A is a function of the

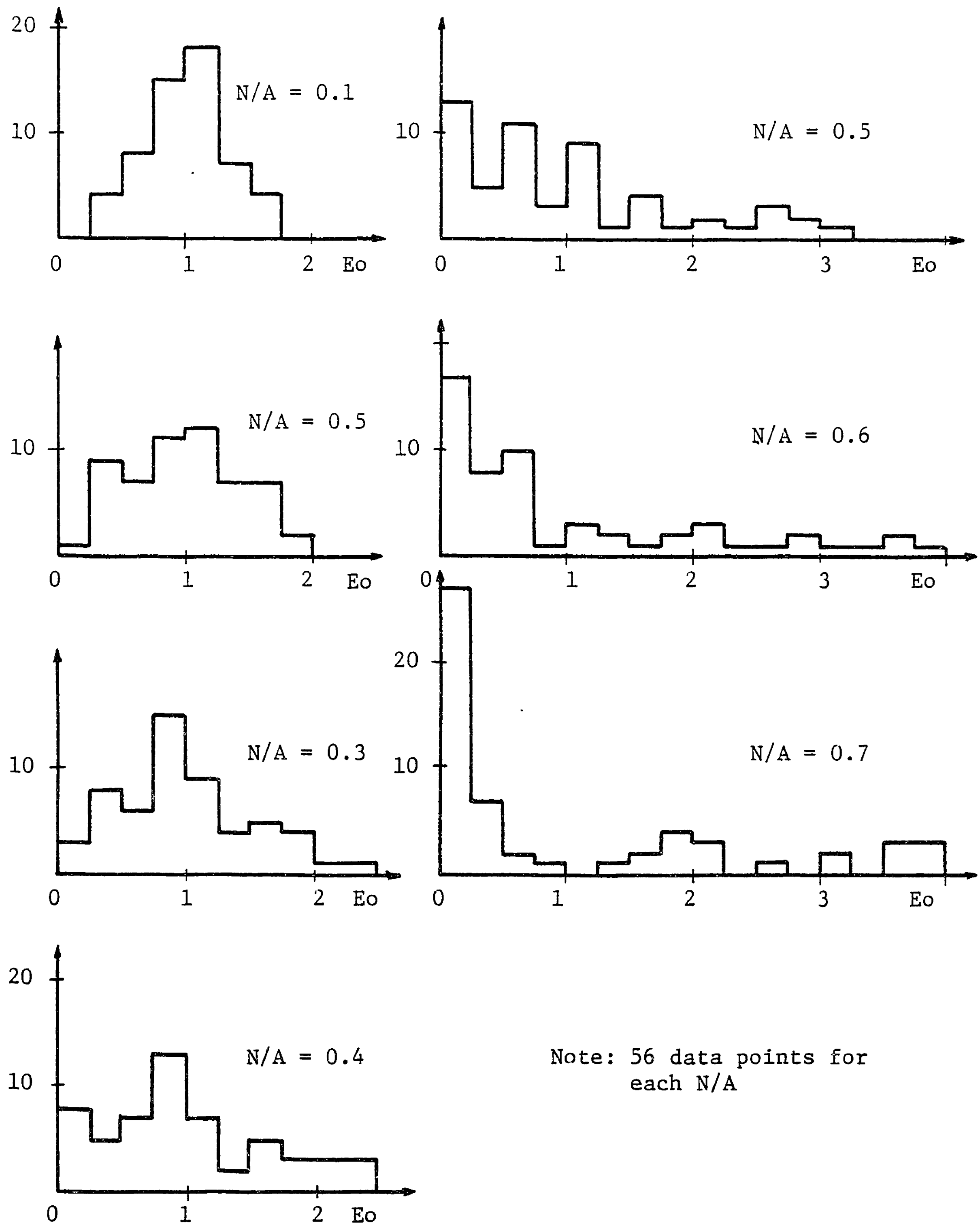


Figure 5.1 Conditional distribution of Eo

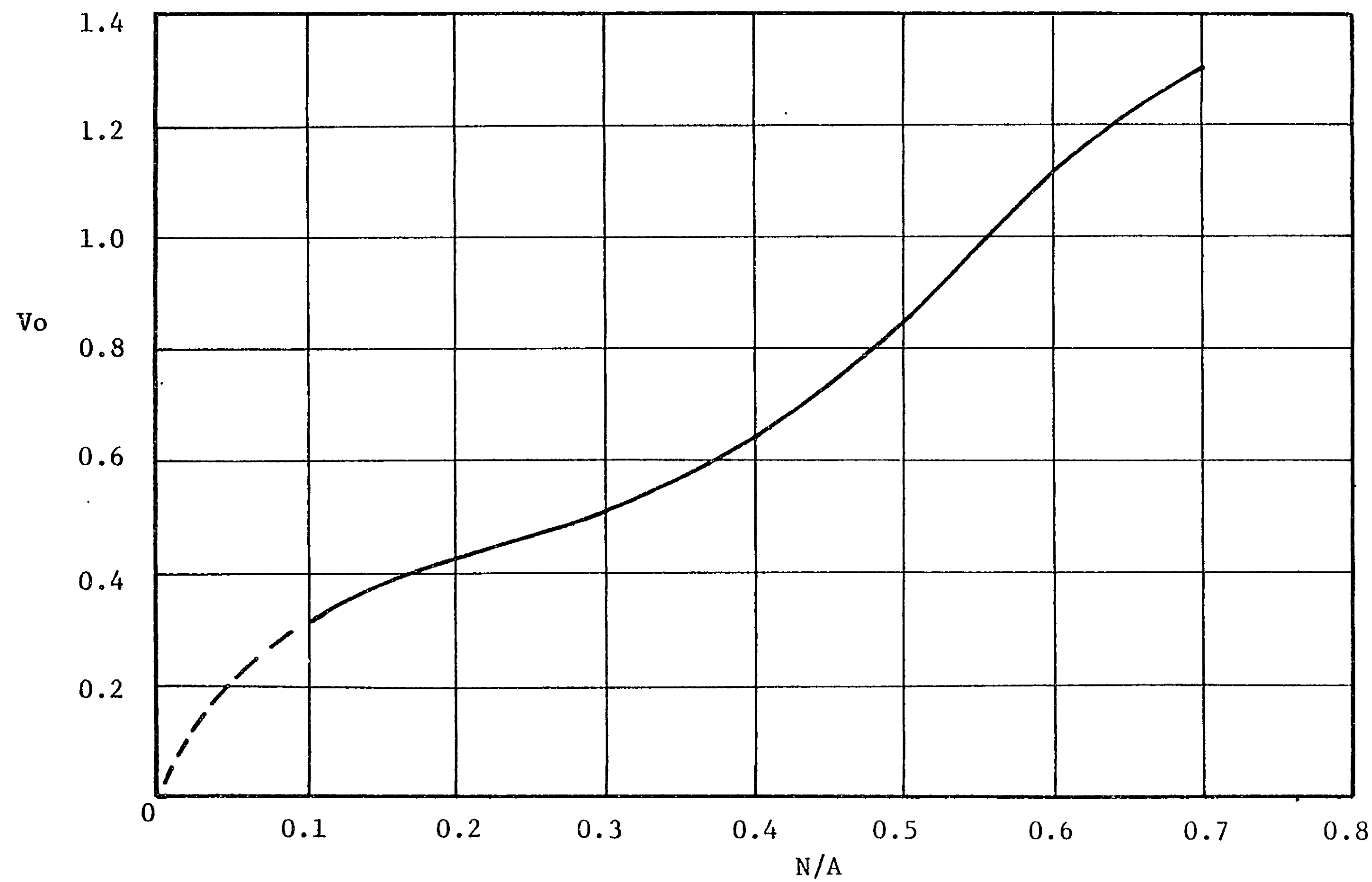


Figure 5.2 Coefficient of variation of Eo (Vo)

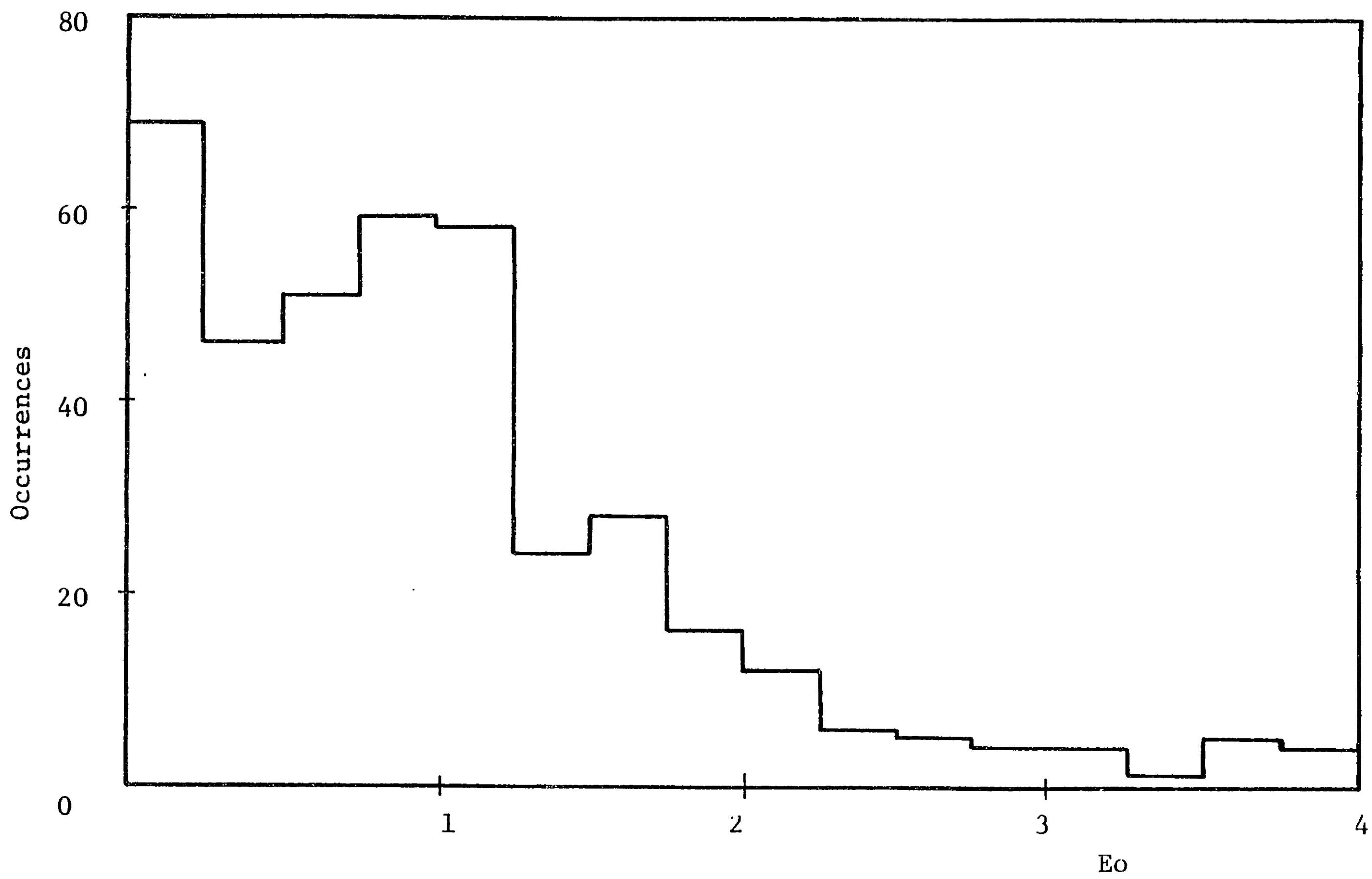


Figure 5.3 Marginal distribution of Eo

relative magnitude of the peak acceleration actually experiences. The change of trend in the coefficient of variation of Eo seems to suggest that this fact becomes significant from N/A between 0.4 and 0.5. In the extreme cases when N/A approaches unity, three of the four normalized relative displacements will be zero since the corresponding actual maximum accelerations are somewhat less than the absolute maximum acceleration Ag due to orientation effect. The set of Eo will be (0,0,0,4). For this set the mean is still unity but the standard deviation is 1.732 which is the upper limit for the standard deviation.

It is clear at this point that the orientation of the wall is one of the most important factor in determining the uncertainty in relative displacement. The main consequence is that even when N/A is less than unity, there is a fair probability for the displacement to be very small and negligible.

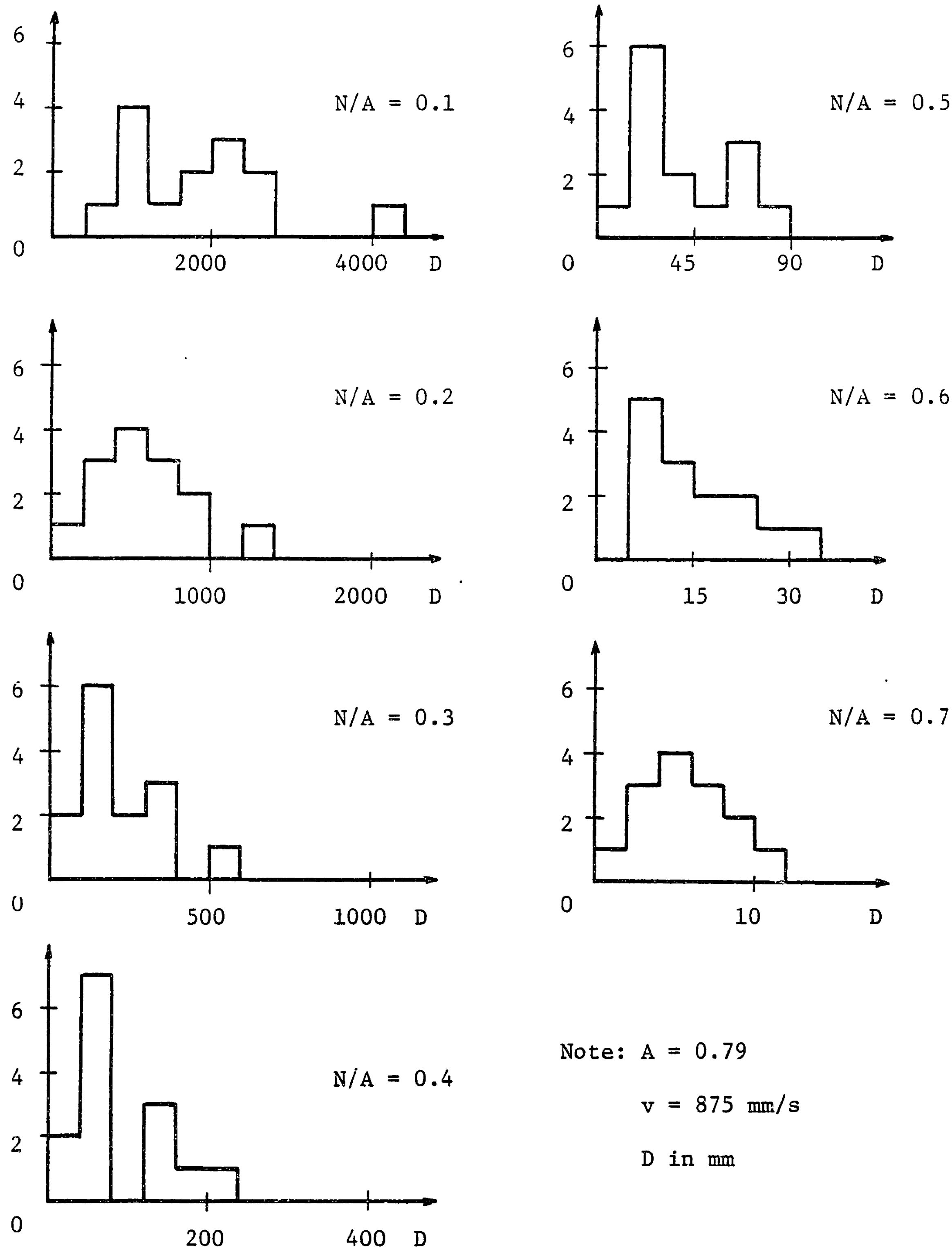
5.2.2 The Effect of Shaking Characteristics

Results

Due to different shaking characteristics of the chosen strong motion accelerograms, the mean of the normalized relative displacements will be different for each earthquake. The set of the mean values for the same structural system form a collection of random data. In this study, the arithmetic average of all the mean values is termed the expected normalized relative displacement, i.e., the normalized relative displacement of a structural system is expected to be of this value considering the probable orientation of the wall and shaking characteristics of different accelerograms. This is of course the arithmetic mean of all the computed slips for all selected earthquakes analyzed in the four orthogonal directions. The expected displacement and standard deviation are summarized in Table 5.2.

Discussion

The distribution of the mean values of normalized relative displacements does not resemble any simple distribution, Figure 5.4. However, Whitman (Private Communication) analyzed the results obtained by Franklin and Chang and suggested that the relative displacements resemble closely to a lognormal distribution. Inasmuch as no further light on the distribution type, only the distribution-free statistical information will be extracted for the present study.



Note: A = 0.79

v = 875 mm/s

D in mm

Figure 5.4 Mean displacement with respect to orientation from Newmark's Model, $k_v = 0$

5.2.3 Simple Estimate for Newmark's model

Formulation

In Newmark's sliding block model with kv=0, AgD/V^2 is constant for any particular N/A due to scaling. Employing a log-linear regression model for the normalized relative displacement,

$$\ln E[\overline{Dno}] = a + \ln\left(\frac{V^2}{Ag}\right) + b(N/A)$$

or,

$$\overline{Dno} = Es\ c\ \frac{V^2}{Ag}\ e^{b\ N/A} \qquad \text{.... (5.2)}$$

in which a and b are the regression parameters. The lack-of-fit term Es measures the departure of $\ln(\overline{Dno})$ from $a+\ln(V^2/Ag)+b(N/A)$. This term is modelled here as an uncertain function of (N/A) with marginal distribution of unity mean. Effectively, Es takes into account the effect of different shaking characteristics.

By plotting the expected normalized relative displacement against N/A in a log-linear plot, the data points lie closely on a straight line, Figure 5.5. It is found that:

$$c = 37$$

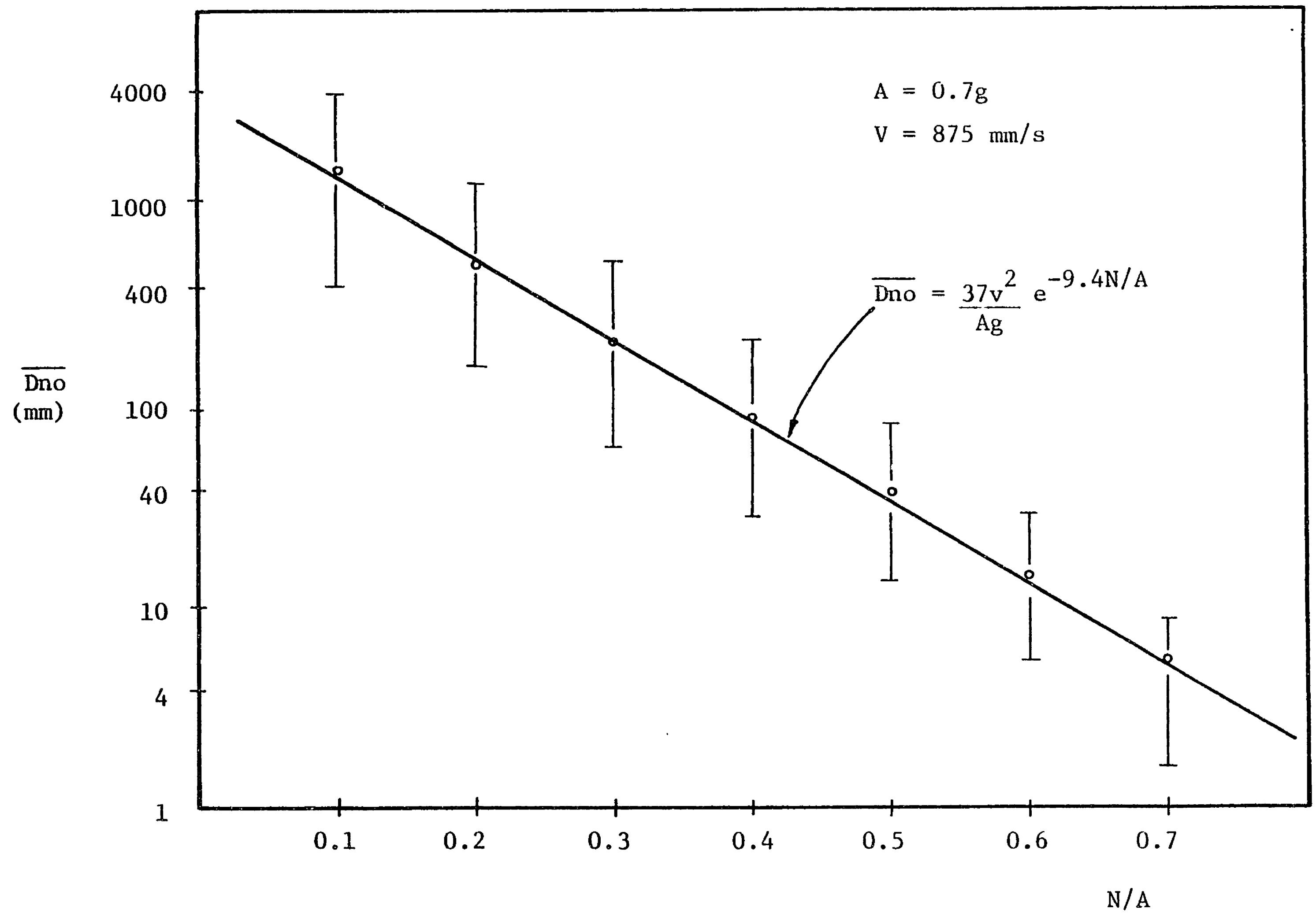


Figure 5.5 Displacement from Newmark's Model with $k_v = 0$ as a function of N/A

$$b = -9.4$$

i.e. $$E[\overline{Dno}] = \frac{37V^2}{Ag} e^{-9.4N/A} \qquad \text{.... (5.3)}$$

and so, $$Dno = Eo\ Es\ E[\overline{Dno}]$$

The corresponding conditional distribution of Es given N/A, however, does not have a mean of one in general. The mean and standard deviation of Es given N/A are presented in Table 5.3.

<u>Accuracy</u>

For example, with A=0.7 and V=875mm/s, the equation predicts a displacement of 4.13m at N=0, 50mm at N=0.329 and 0.34mm at N=A. It can be seen that the displacements predicted for the extreme cases are in the right order of magnitude.

For comparison, the values predicted by equation 5.3 and the corresponding expected normalized relative displacements are listed in Table 5.4. Newmark's estimate (equation 3.1) and Richards and Elms' prediction (equation 2.4) are also included in the table since they are referred to the same model. It is clear that the prediction equation provides very good estimates at higher values of N/A. This is because the fitting is based on a logarithmic scale of displacement; the lower N/A, the higher the displacement and the higher the displacement, the higher the discrepancy.

In the range of interest ($N/A>0.4$), the equation is accurate to ±5%. This equation will be the basic elemnt of relative displacements for the final prediction rule.

Discussion

When compared to Newmark's estimate and Richards and Elms' prediction, equation 5.3 gives a much lower prediction. Moreover, the prediction is extremely sensitive to N/A indicated by a high regression parameter, b, in the index of e.

For example, if N/A increases from 0.5 to 0.6, the predicted displacement will be reduced by 60%. This high sensitivity is believed to be due primarily to the orientation of the wall. Take the 1940 El Centro earthquake for instance. The absolute maximum acceleration is in the South direction. If the backfill is due West of the wall, the actual peak acceleration experienced by the wall is only 61.5%, a fraction of the absolute maximum value. For $N/A=0.7$, there will be NO relative displacement developed. It is then logical for the displacement to be so sensitive to N/A. The orientation of the wall also explains the low prediction. As stated before, there is small or no displacement in some orientations. The prediction should be lower on average when this is taken into account not to mention the conservatism in Newmark's and Richards and Elms' predictions.

5.2.4 The Effect of Including Vertical Ground Acceleration

Results

The effect of including the vertical ground acceleration in the analysis has been measured for Newmark's sliding block. It is quantified in terms of a ratio, Rv, of the normalized relative displacments with to without the vertical acceleration. The statistics of Rv with respect to N/A and Dno are summarized in Table 5.5 and 5.6.

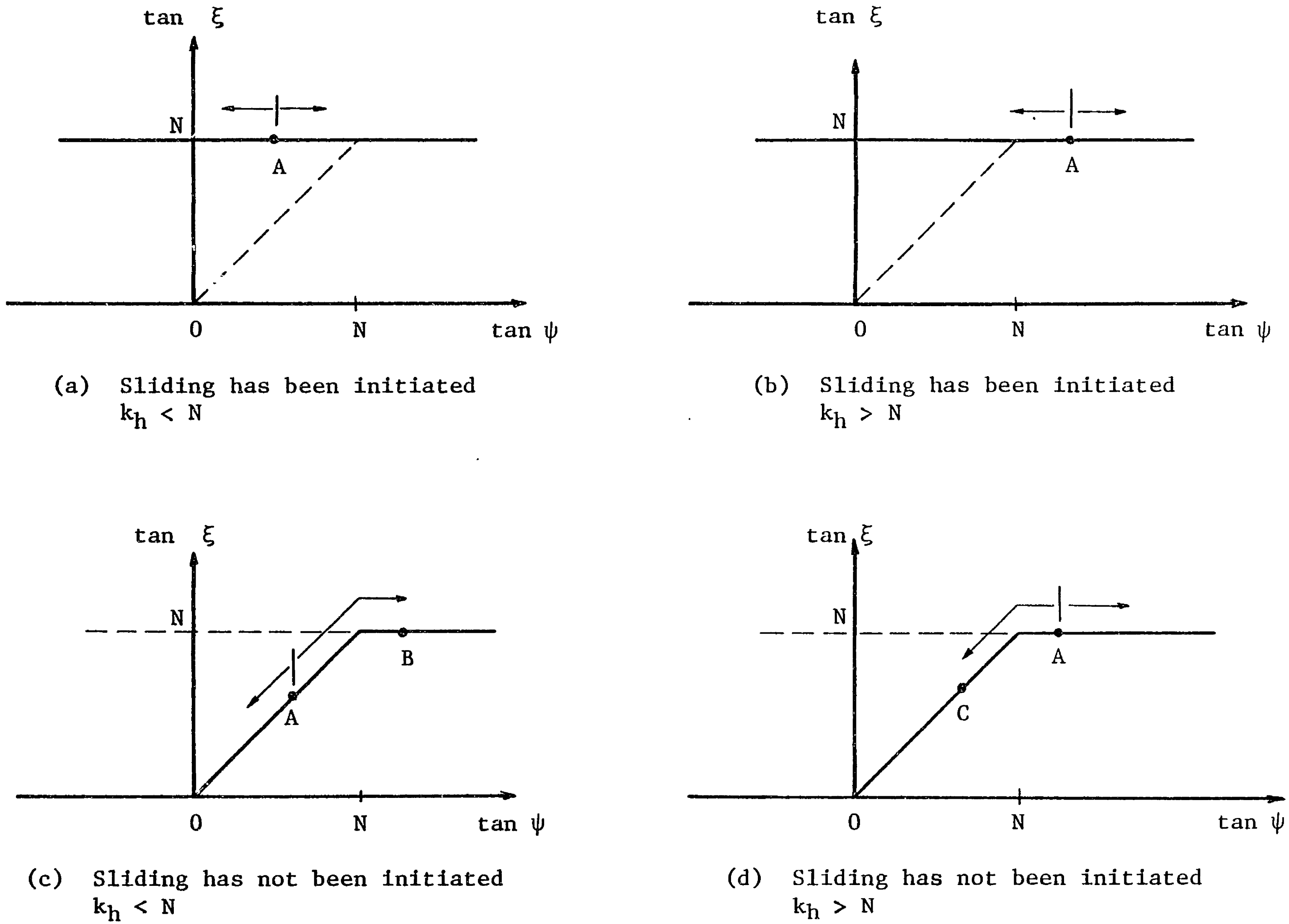
Generally speaking, at low values of N/A (<0.4) or at some large displacements (Dno>30mm) the effect is negligible, i.e., compensating itself. However, the range of interest lies below a normalized relative displacement of about 50mm and N/A being over 0.4. The effect becomes noticeable in this range and the computed values of Rv exhibit more scatter.

Discussion

The main effect of including the vertical ground acceleration into the analysis is similar to having a modified gravitational field. With an acceleration acting downwards, the "weight" of the block is reduced and hence the shear resistance at the interface and the threshold acceleration (kh")g are also reduced. If the acceleration acts upwards, the effect is reversed. This relationship can be easily observed in equation 3.3 and 3.5.

Since the direction of seismic excitation is a random process, it may be intuitively logical to assume that there are as many upward acceleration as downward ones. Hence, the total effect seems to be compensating. This is not the case, however, because the relationship is not additive in nature.

For both models, the pattern of sliding may alter when the vertical ground acceleration is included. Figure 5.6 and 5.7 illustrate the relations for Newmark's and Zarrabi's model respectively. Consider a horizontal ground acceleration (kh)g which corresponds to point A when kv=0. When the vertical acceleration acts downwards (kv=+ve), tanψ is increased. The response moves along the curve to the right. When the vertical ground acceleration acts upwards (kv=-ve), tanψ is reduced and the response moves to the left. If sliding has already been initiated, there is no change in the ratio, tanξ, of kh" to (1-kv") for Newmark's model, see Figure 5.6a and 5.6b. For Zarrabi's model, tanξ is affected, Figure 5.7a and 5.7b. In both models, the wall threshold acceleration would be changed. On the other hand, if sliding has not been initiated, the effect on the sliding pattern is more pronouncingly dependent on the magnitude of kv. A large enough downward ground acceleration may cause



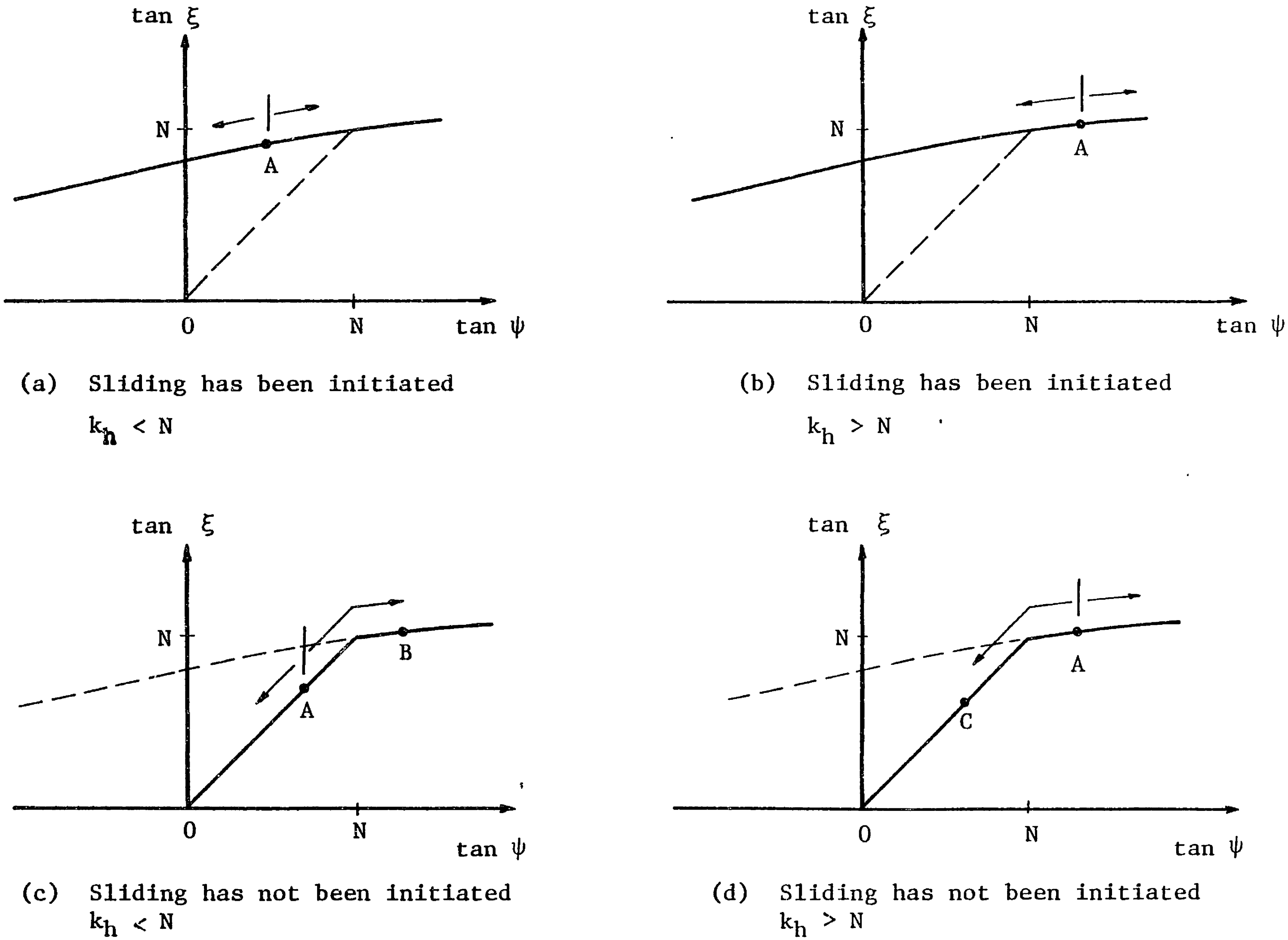
(a) Sliding has been initiated
$k_h < N$

(b) Sliding has been initiated
$k_h > N$

(c) Sliding has not been initiated
$k_h < N$

(d) Sliding has not been initiated
$k_h > N$

Figure 5.6 Effects of Including Vertical Acceleration in Analysis (Newmark's Model)



(a) Sliding has been initiated
$k_h < N$

(b) Sliding has been initiated
$k_h > N$

(c) Sliding has not been initiated
$k_h < N$

(d) Sliding has not been initiated
$k_h > N$

Figure 5.7 Effects of Including Vertical Acceleration in Analysis (Zarrabi's Model) sliding to begin (point B in Figure 5.6c and 5.7c) whereas a large enough upward acceleration may prevent sliding from starting (point C in Figure 5.6d and 5.7d). Figure 5.8 shows the possible change in the sliding pattern schematically.

Also, since the assumption of the variation of acceleration is taken as linear, the shapes of the accelerograms are of inverted triangles. The aspect ratio of inverted triangles suggests a bigger difference in relative velocity for acceleration decrease even for the same change in the cut-off acceleration. It follows from these two arguments that the relative displacement is expected to increase when the vertical acceleration is included. Because the exact details of variation of sliding pattern depend on the phase differences of the shaking, it is not possible to quantify these details other than a collective overview of the computed relative displacements.

Correlation

Assuming that the correlation is multiplicative, the expected relative displacement predicted by Newmark's model can be expressed as:

$$Dn = Ev\ Rv\ (Dno) \quad .... (5.4)$$

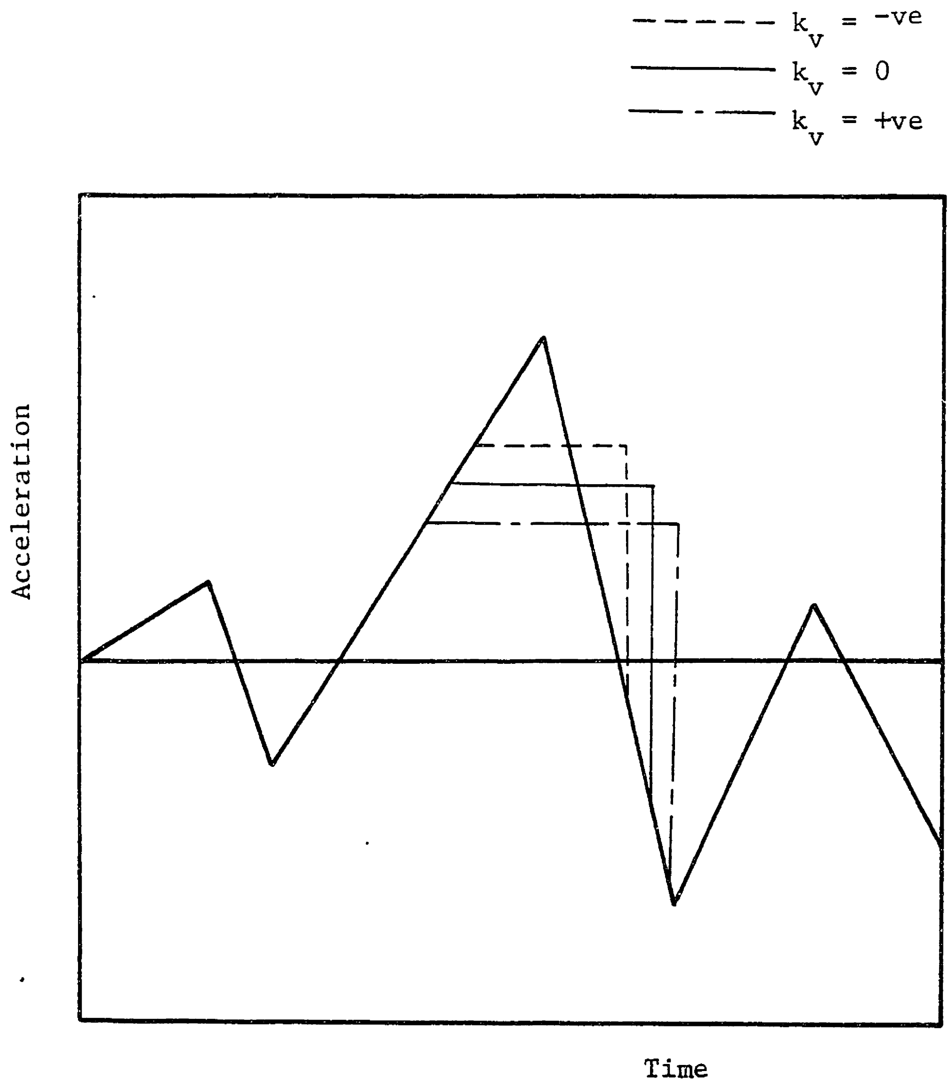


Figure 5.8 Effect of k_v on sliding pattern

in which Dn is the expected relative displacement of Newmark's model with kv=0, Rv is a deterministic correlation function to correct for including vertical acceleration. Another random variable, Ev, models the uncertainties in the correlation.

When the normalized relative displacements are small, the accuracy of the ratio Rv is in doubt. Should all the data be included, the accuracy of the result will be lost due to rounding off errors. In order to cope with this numerical difficulty, those computed values of Rv will be ignored when the normalized relative displacements are less than a certain value. This value has been chosen as 1mm arbitrarily. Effectively, those data points are to be filtered out of the regression calculation. It is noted that due to the filtering out of data with small normalized relative displacements, less than half of the data for N/A=0.7 are left. Consequently, the information at N/A=0.7 should be treated with care.

The ratio Rv is a function of A and N/A. The smaller the intensity, the smaller the change in (1-kv) and so the effect of vertical acceleration diminishes with A. For simplicity, it may be justified to consider Rv as independent of A, at least in curve fitting. Figure 5.9 plots Rv against N/A. The best fit quadratic function to fit the data points is:

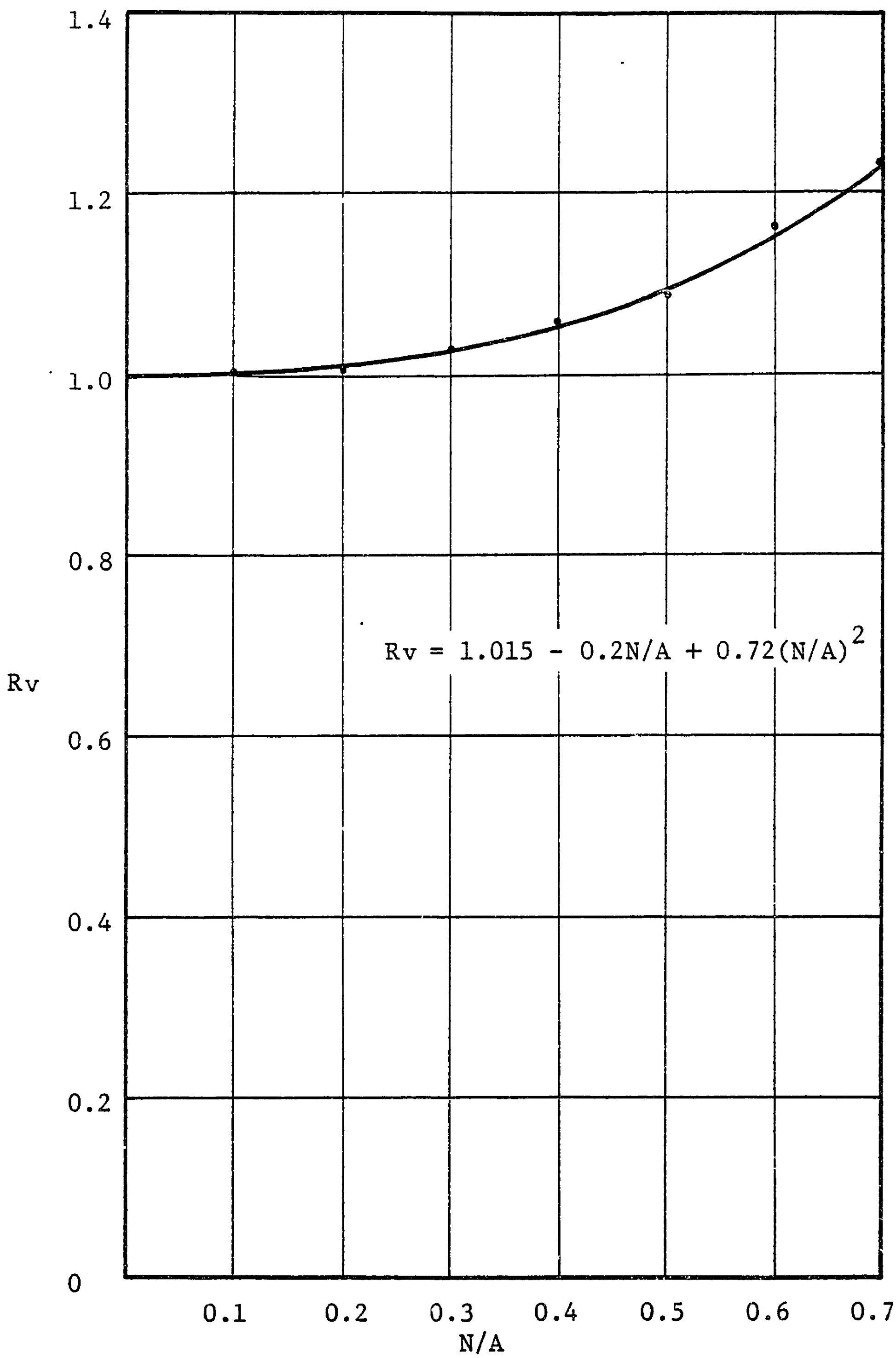


Figure 5.9 Correlation function for including vertical acceleration

$$Rv = 1.015 - 0.2(N/A) + 0.72\ (N/A)^2 \quad \ldots\ (5.5)$$

and $E[Dn] = Rv\ E[Dno]$

$$Dn = Eo\ Es\ Ev\ Rv\ E[\overline{Dno}]$$

The goodness of fit, i.e. how well this quadratic function describes the effect, is measured by Ev. The mean and standard deviation of Ev are tabulated in Table 5.7. The coefficient of variation of Ev is generally small. It can be seen that equation 5.5 gives estimates of Rv within 10% except when N/A=0.7. As mentioned above, the quality of the data may be doubtful at higher values of N/A.

At any time step, the effect on the cut-off acceleration due to including vertical acceleration is similar for Newmark's model as well as for Zarrabi's model. The cut-off acceleration will increase (or decrease) for both models. It then follows that equation 5.5 is also applicable to Zarrabi's model with negligible error. This assumption has been justified with the computed results.

5.3 Cases of Zarrabi's Sliding Block Model

The main difference between Newmark's model and Zarrabi's model is in the time variation of the dynamic lateral earth pressure. The response wall cut-off acceleration would be different for the two models. This section will consider the correlation between the two models. Discrepancies in soil parameters are also studied.

5.3.1 Correlation from Newmark's Model to Zarrabi's Model

Discussion

The relative error in calculating $\tan\xi$ and the instantaneous threshold wall acceleration with Newmark's model can be determined from Figure 3.9. The figure shows that the error can be as large as 20 to 25% if $\tan\psi$ is positive. The velocity of the wall is generally underestimated during sliding, Figure 3.10. However, the velocity of the wall at reunion is not very different for the two models. Hence, most of the individual slips are overestimated by Newmark's model. The actual permanent relative displacement is also expected to be smaller when predicted by Zarrabi's model. This has been confirmed by the computed results.

Correlation

Again, a correlation factor, Rz, is defined as the ratio of displacement predicted by Zarrabi's model to that predicted by Newmark's model. Assume the relationship in correlation is multiplicative, the relative displacement predicted by Zarrabi's model can be written as:

$$Dz = Ez\ Rz\ Dn \qquad \ldots . (5.6)$$

The term Ez models the uncertainty induced by correlation. As was in the case of Rv, the relationship between $\tan\xi$ and $\tan\psi$ is non-linear and the overall effect also depends on the shaking characteristics. Analytical correlation of Rz is not possible. It has been observed from Figure 3.9 that the relationship between $\tan\xi$ and $\tan\psi$ is heavily dependent on N. This suggests that Rz is also strongly dependent on N. Indeed, when the mean and the standard deviation of Rz given N are calculated, the coefficient of variation is very small (CoV=4%). The mean and standard deviation of Rz given N are tabulated in Table 5.8. Figure 5.10 plots the computed Rz against N. Adopting the same filtering criterion as for Rv, the best fit curve for Rz is:

$$Rz = 0.7 + 1.2\, N\, (1-N) \qquad \text{.... (5.7)}$$

for $N < 0.5$

The uncertainty function Ez depends on A and N/A. The marginal mean is unity. The conditional mean and standard deviation of Ez given A and N/A are tabulated in Table 5.9. Intuitively, the variance should increase with increasing A or N/A. At N/A=0.7, however, the variance actually decreases. This is believed to be the consequence of filtering of data. Here, a tradeoff between severe rounding off errors and insufficient data is experienced.

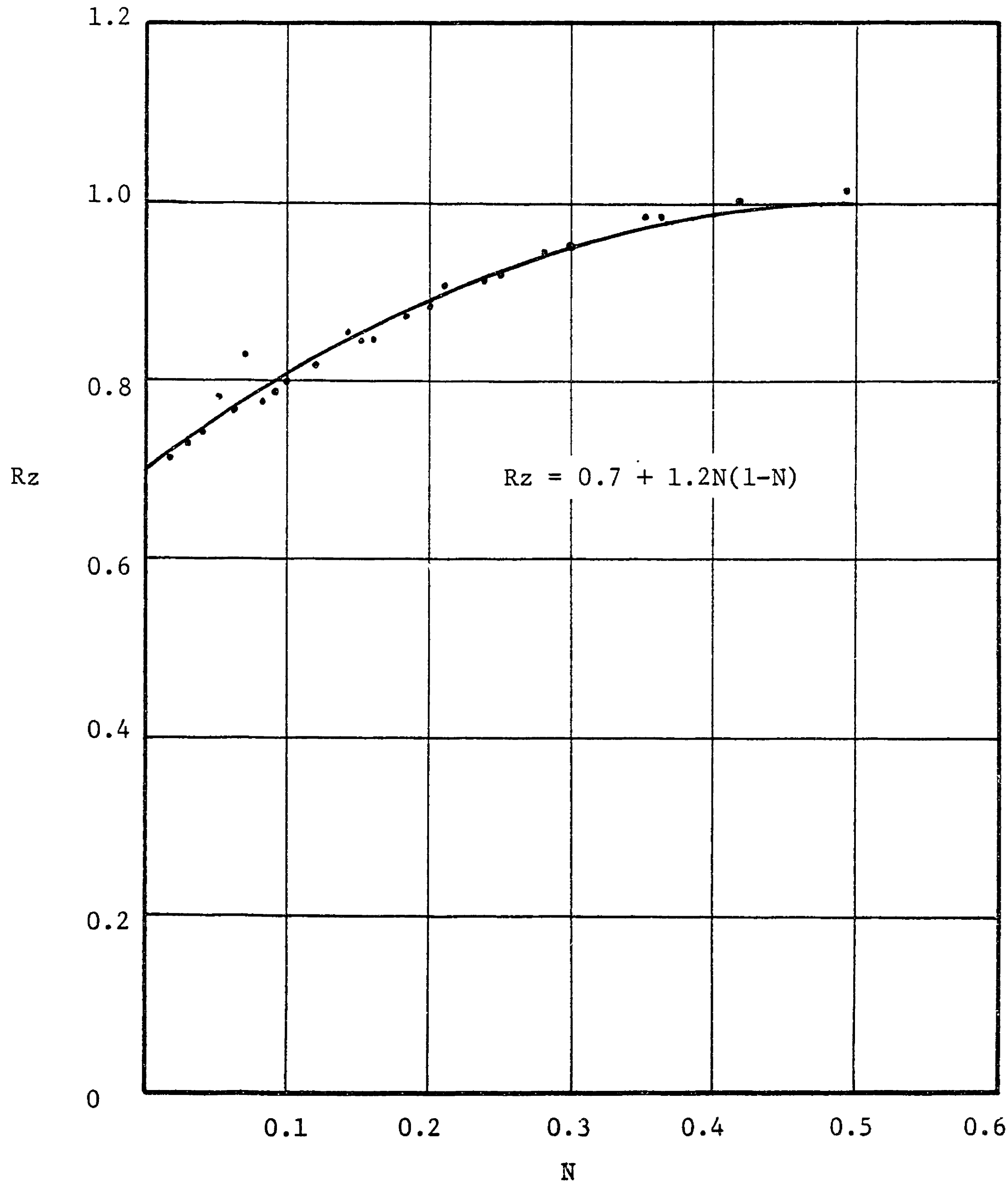


Figure 5.10 Correlation function from Newmark's model to Zarrabi's Model

5.3.2 Discrepancies in Soil Friction Angles

The correlation between Newmark's model and Zarrabi's model has been based on the reference structural system described in Section 4.4. In practice, discrepancies in soil friction angles are unavoidable. With limited data, the general trends are:

1. When δ increases from 0° to 10°, the relative displacement increases by 3 to 4% for the same N/A. (The wall weight has been changed to keep N/A constant.)

2. When ϕ increases from 30° to 35°, the relative displacement decreases by 1 to 2% for the same N/A. (The wall weight has been changed to keep N/A constant.)

3. For the same weight of wall, N increases roughly by 0.03 when δ increases from 0° to 10° and by 0.04 when ϕ increases from 30° to 35°. These together can change the value of N by 20 to 25%.

From points 1 and 2 above, it is obvious that the same prediction rule can be used for most practical ranges of δ and ϕ cited. It follows from point 3 that the main influence of discrepancies in soil friction angles will be in the limiting acceleration coefficient, N.

5.3.3 The Prediction Rule

Formulation

Combining equations 5.1 to 5.7 and dropping the uncertainty and lack-of-fit terms, the relative displacement predicted by Zarrabi's model can be estimated by:

$$E[Dz] = \frac{37V^2}{A\,g} e^{-9.4N/A} Rv\ Rz \qquad \text{.... (5.8)}$$

where $Rv = 1.015 - 0.2(N/A) + 0.72(N/A)^2$

$Rz = 0.7 + 1.2N(1-N)$

Equation 5.8 gives the expected normalized relative displacement predicted by Zarrabi's model including the vertical ground acceleration in the analysis. Discrepancies in soil friction angles are insignificant for prediction so long as the value of N is determined correctly. It will be used as the prediction rule for the proposed design procedure to be presented in next chapter. The subscript z for displacement will be dropped from now on.

Accuracy

It is desirable to check the accuracy of the prediction rule at this stage. Table 5.10 shows this prediction together with Zarrabi's results. From the table, it can be seen that equation 5.8 predicts a much lower displacement than Zarrabi's results. This is believed to be due to the orientation effect of the wall. As mentioned in Section 4.3.1, a wall with high N/A may experience no relative displacement provided the peak acceleration in the direction of the wall is less than N, even when the absolute maximum acceleration of the earthquake is greater than N. Zarrabi did not consider this effect in his study and so his results are 60 to 300% higher.

5.4 Hypothetical Distribution for the Relative Displacement

5.4.1 The Model Parameter, M

The prediction rule formulated in last section enables the expected normalized relative displacement to be evaluated. Incorporating the uncertainty functions due to orientation of the wall, shaking characteristics, including vertical acceleration and correlation, the probabilistic function of relative displacement can be written as:

$$D = E[D]\ Eo\ Es\ Ev\ Ez \qquad \ldots. \ (5.9)$$

where D = relative displacement predicted by Zarrabi's model

E[D] = The expected relative displacement from equation 5.8

Eo,Es,Ev,Ez = Uncertainty Functions for various effects and Correlations

Putting $M=(Eo)(Es)(Ev)(Ez)$,

$$D = E[D]\ M \qquad \text{.... (5.10)}$$

This parameter M relates all the E functions together and is denoted as the model parameter. If all the E's are independent, the mean and variance of M can be expressed as:

$$E[M] = E[Eo]*E[Es]*E[Ev]*E[Ez] \qquad \text{.... (5.11)}$$

$$= 1$$

$$Var[M] = \{E[Eo]^2+Var[Eo]\}*\{E[Es]^2+Var[Es]\} *\{E[Ev]^2+Var[Ev]\}*\{E[Ez]^2+Var[Ez]\} -E[M]^2 \qquad \text{.... (5.12)}$$

$$V_M{}^2 = (1+Vo^2)(1+Vs^2)(1+Vv^2)(1+Vz^2)-1 \qquad \text{.... (5.13)}$$

where Vs = Coefficient of Variation of Es and etc.

The statistics of the E functions have been calculated in the previous sections and hence the mean and variance of M can be evaluated. They are summarized in Table 5.11.

Expressing the model parameter M in logarithmic form, we have:

$$Em = \ln(M) = \ln(Eo)+\ln(Es)+\ln(Ev)+\ln(Ez) \qquad \text{.... (5.14)}$$

Since the E functions are random variables, the ln(E) functions are also random variables. Calling upon the central limit theorem in statistics, the sum of these variables will be approximately normally distributed. In this case, we expect Em to be normally distributed. M is correspondingly described as lognormally distributed. From basic statistics theory, the mean and variance of Em can be written as:

$$\mathrm{Var}[Em] = \ln\left(1+V_M^2\right) \qquad \text{.... (5.15a)}$$

$$E[Em] = \ln\left(E[M]\right) - 0.5\,\mathrm{Var}[Em] \qquad \text{.... (5.15b)}$$

From the calculated information of M, the mean and variance of Em have been calculated, Table 5.12.

At this point, a hypothetical probabilistic description of the relative displacement can be proposed. Based on the central limit theorem, the relative displacement can be approximated as a lognormal distribution characterised by M.

5.4.2 Goodness of Fit

In order to verify this hypothetical distribution, we have to investigate the goodness of fit against the computed results. Four combinations of A and N/A have been chosen for comparison; the pairs of (A, N/A) are (0.2,0.3), (0.5,0.2), (0.6,0.4) and (0.7,0.6). The fitted lognormal distributions are plotted against the computed results in Figure 5.11 to 5.14. As can be seen from the figures, the computed results are very well described by the lognormal distribution. The distribution curves are almost identical. Of course, the lognormal distribution parameters can also be

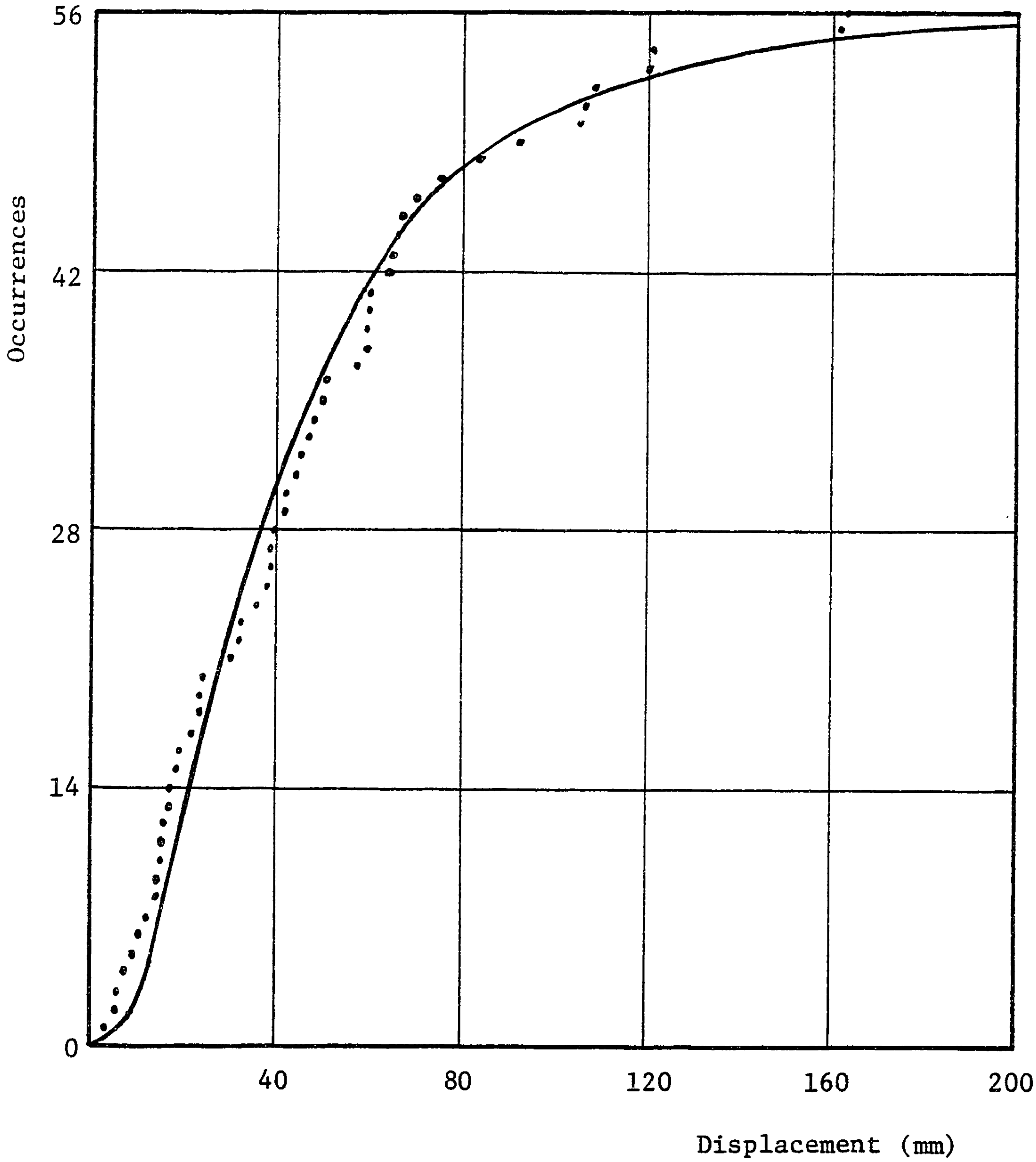


Figure 5.11 Hypothetical Distribution for Displacement
(A = 0.2g, N/A = 0.3)

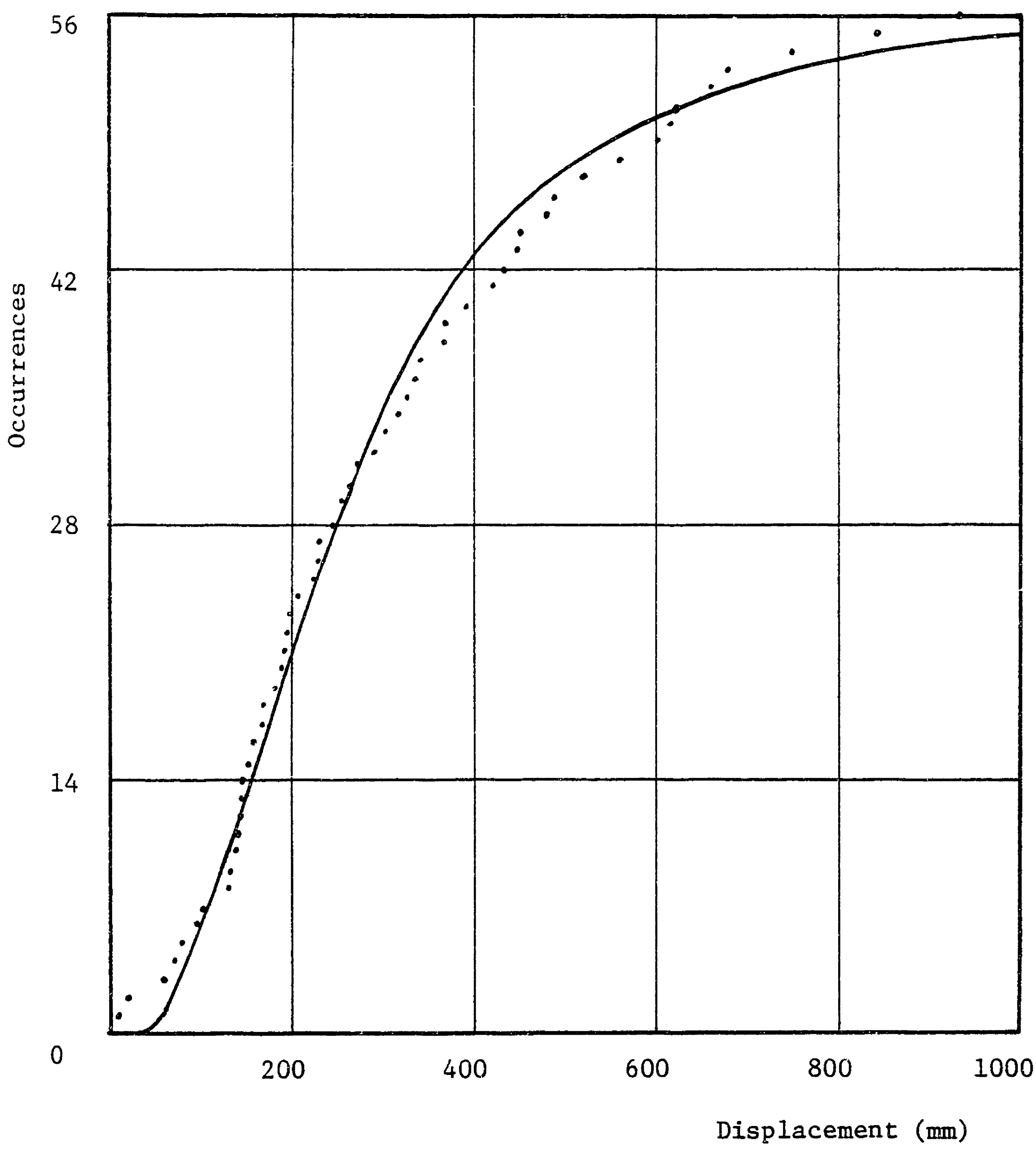


Figure 5.12 Hypothetical distribution for displacement
(A = 0.5g, N/A = 0.2)

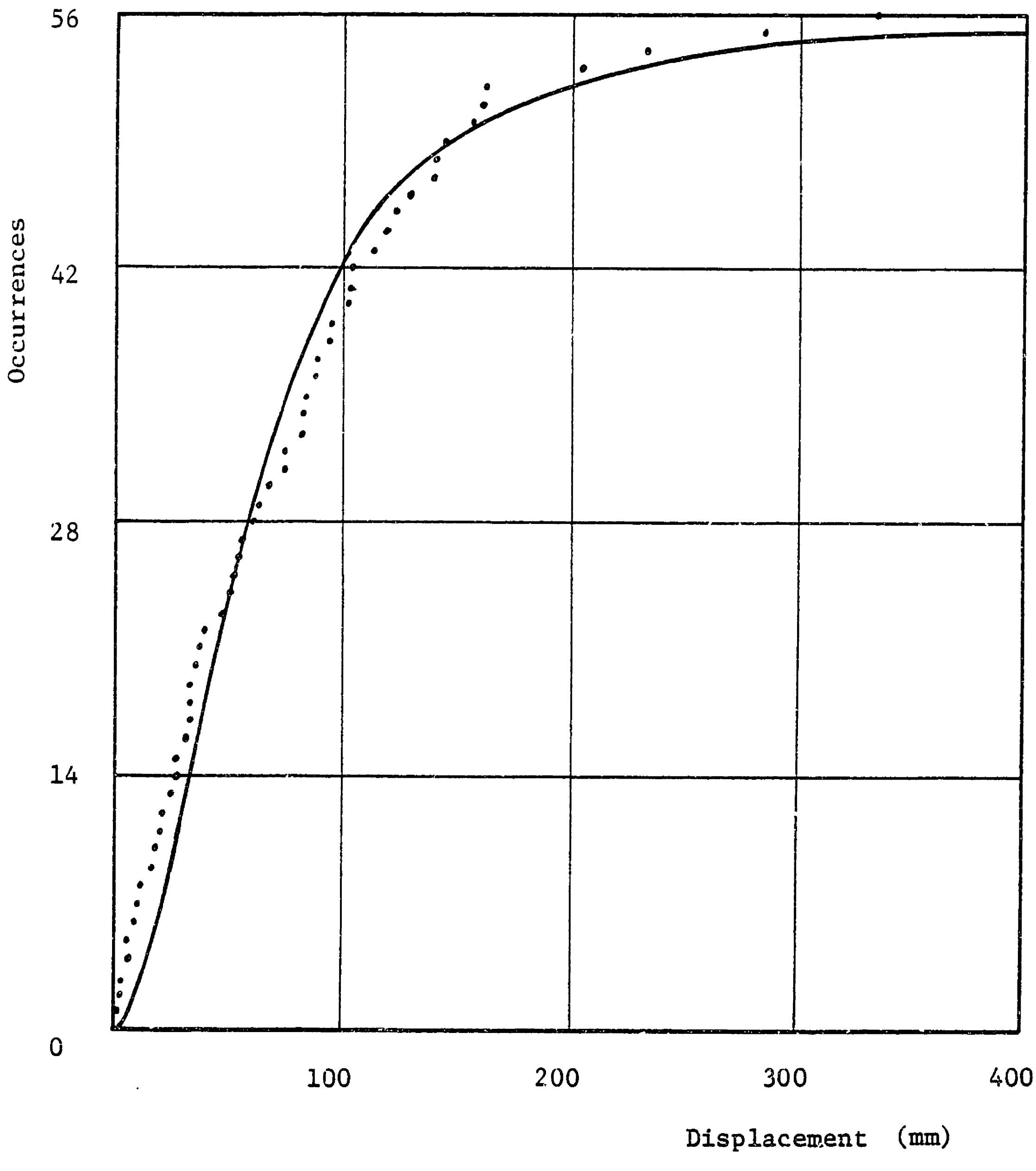


Figure 5.13 Hypothetical distribution for displacement (A = 0.6, N/A = 0.4)

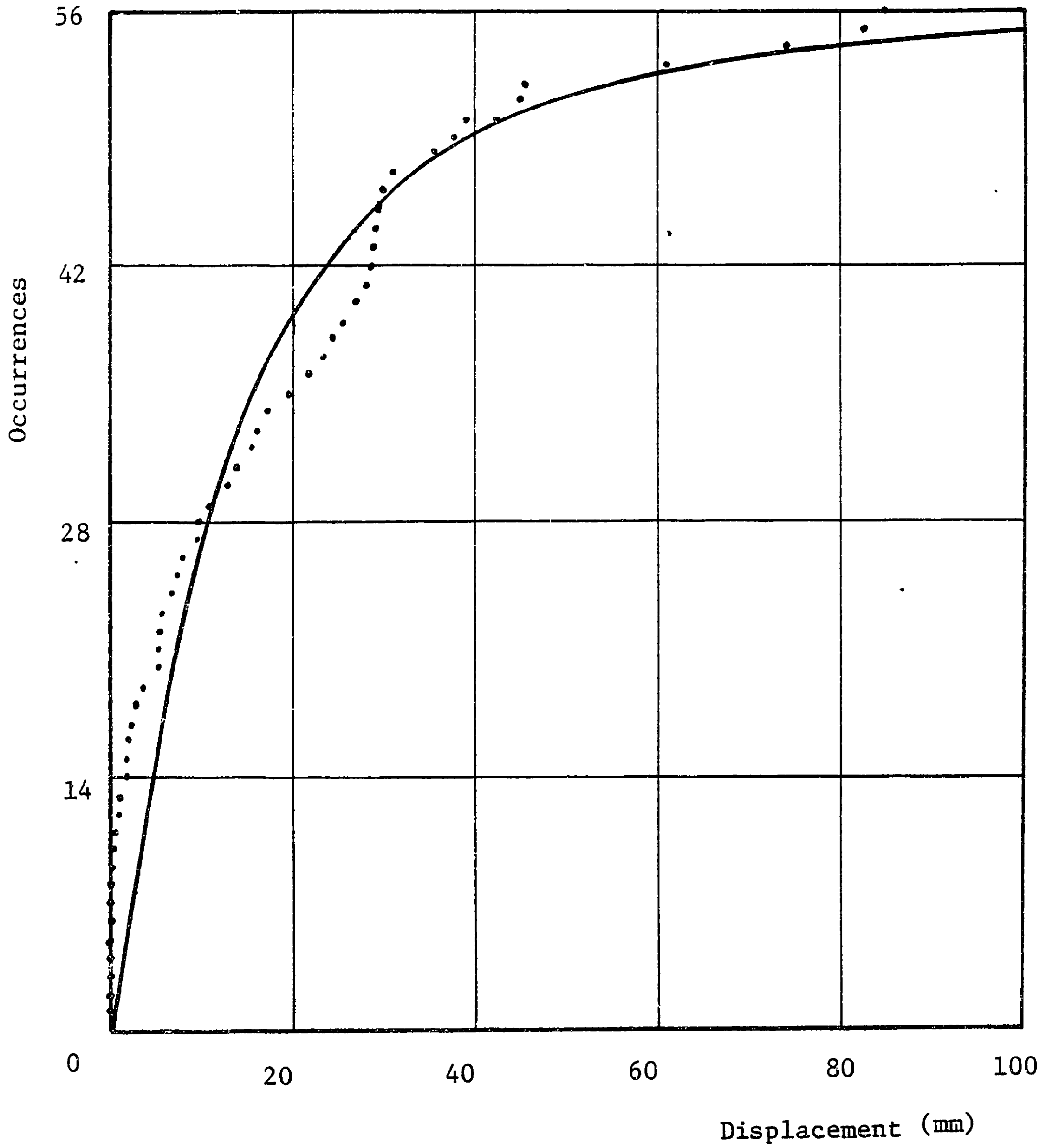


Figure 5.14 Hypothetical distribution for displacement

(A = 0.7, N/A = 0.6)

evaluated from the computed results but the convenience of a better understanding and incorporation of correlation from Newmark's model are lost.

5.4.3 Summary

In summary, a prediction rule for Newmark's model and Zarrabi's model have been established. The factors of orientation of the wall, different shaking characteristics and inclusion of the vertical acceleration have been incorporated. For Zarrabi's model, lognormal distributions are found to describe the normalized relative displacement very well. It then follows that simple calculation can be used to determine the limiting displacement with very high confidence. This can lead to minimum conservatism and economical designs. In next chapter, a design procedure will be formulated from these findings.

Table 5.1 Statistics of Eo

RANGE	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7	All
0.00 -- 0.25	0	1	3	8	13	17	27	69
0.25 -- 0.50	4	9	8	5	5	8	7	46
0.50 -- 0.75	8	7	6	7	11	10	2	51
0.75 -- 1.00	15	11	15	13	3	1	1	59
1.00 -- 1.25	18	12	9	7	9	3	0	58
1.25 -- 1.50	7	7	4	2	1	2	1	24
1.50 -- 1.75	4	7	5	5	4	1	2	28
1.75 -- 2.00	0	2	4	3	1	2	4	16
2.00 -- 2.25	0	0	1	3	2	3	3	12
2.25 -- 2.50	0	0	1	3	1	1	0	6
2.50 -- 2.75	0	0	0	0	3	1	1	5
2.75 -- 3.00	0	0	0	0	2	2	0	4
3.00 -- 3.25	0	0	0	0	1	1	2	4
3.25 -- 3.50	0	0	0	0	0	1	0	1
3.50 -- 3.75	0	0	0	0	0	2	3	5
3.75 -- 4.00	0	0	0	0	0	1	3	4
CeV	0.314	0.424	0.514	0.636	0.858	1.115	1.303	

Table 5.2

Displacement from Newmark's Model
A=0.7g, V=875mm/s, kv=0

N/A	Displacement (mm) Mean	S.D.
0.1	1770.38	943.77
0.2	584.78	313.64
0.3	227.79	133.31
0.4	95.18	55.65
0.5	39.35	21.95
0.6	15.35	7.74
0.7	5.55	2.27

Table 5.3

Statistics of Es

N/A	Mean	S.D.
0.1	1.098	0.533
0.2	0.929	0.536
0.3	0.926	0.585
0.4	0.991	0.585
0.5	1.048	0.558
0.6	1.047	0.504
0.7	0.969	0.409

Table 5.4

Predicted and Computed Results
Newmark's Model A=0.7g, V=875mm/s, kv=0

N/A	Displacement (mm) equation 5.3	Computed	% error	equation 2.4	equation 3.1
0.1	1612.00	1770.38	-8.95	97032.9	5018.9
0.2	629.69	584.78	+7.68	6064.6	1115.3
0.3	245.97	227.79	+7.98	1197.9	433.7
0.4	96.08	95.18	+0.95	379.0	209.1
0.5	37.53	39.35	-4.62	155.3	111.5
0.6	14.66	15.35	-4.48	74.9	62.0
0.7	5.73	5.55	+3.19	40.4	34.1

* equation 2.4 is proposed by Richards and Elms
equation 3.1 is proposed by Newmark
equation 5.3 is proposed by this study
Computed results refer to the expected displacement

Table 5.5

Statistics of Rv
with respect to N/A

RANGE (Rv)	N/A 0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.000-0.575	0	0	0	0	0	3	10
0.575-0.625	0	0	0	0	1	1	4
0.625-0.675	0	0	0	0	2	5	3
0.675-0.725	0	0	0	0	3	5	5
0.725-0.775	0	0	0	0	4	7	8
0.775-0.825	0	0	0	3	7	6	5
0.825-0.875	0	0	1	7	17	12	11
0.875-0.925	0	1	5	17	27	16	8
0.925-0.975	4	30	47	53	41	19	4
0.975-1.025	324	239	156	82	39	23	5
1.025-1.075	8	56	87	70	47	35	10
1.075-1.125	0	9	21	44	27	26	12
1.125-1.175	0	1	10	19	22	13	11
1.175-1.225	0	0	6	15	15	10	6
1.225-1.275	0	0	1	8	10	10	10
1.275-1.325	0	0	1	5	12	7	5
1.325-1.375	0	0	1	3	6	8	7
1.375-1.425	0	0	0	2	2	2	1
1.425-1.475	0	0	0	0	4	4	3
1.475-1.525	0	0	0	2	1	2	3
1.525-	0	0	0	5	16	29	25
Total	336	336	336	335	303	243	156
Mean	1.0011	1.0052	1.0206	1.0530	1.0896	1.1611	1.2285
S.D.	0.0107	0.0289	0.0582	0.1343	0.3012	0.4447	0.7155

Table 5.6

Statistics of Rv
with respect to Displacement

Range of Displacement (mm)	Points	Mean	S.D.
1.0 -- 2.0	86	1.254	0.784
2.0 -- 4.0	111	1.295	0.604
4.0 -- 8.0	147	1.191	0.494
8.0 -- 16.0	205	1.089	0.277
16.0 -- 32.0	230	1.039	0.167
32.0 -- 64.0	248	1.037	0.124
64.0 -- 128.0	249	1.021	0.078
128.0 -- 256.0	234	1.011	0.055
256.0 -- 512.0	215	1.006	0.039
512.0 -- 1024.0	178	1.001	0.021
1024.0 -- 2048.0	101	1.000	0.013
2048.0 -- 4096.0	40	1.003	0.009
4096.0 -- 8192.0	1	0.984	-----

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Table 5.7

Statistics of Ev

(A) Mean

A	N/A 0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.2	0.998	0.998	0.987	0.968	0.933	0.916	0.837
0.3	0.999	0.999	0.992	0.979	0.949	0.939	0.894
0.4	0.999	1.000	0.997	0.992	0.971	0.970	0.910
0.5	0.999	1.002	1.003	1.007	0.998	1.013	1.031
0.6	1.000	1.004	1.009	1.024	1.036	1.063	1.078
0.7	1.000	1.006	1.016	1.044	1.079	1.118	1.149

(B) Standard Deviation

A	N/A 0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.2	0.004	0.012	0.022	0.046	0.069	0.134	0.103
0.3	0.006	0.018	0.034	0.069	0.119	0.211	0.242
0.4	0.009	0.024	0.046	0.095	0.178	0.291	0.340
0.5	0.011	0.030	0.058	0.124	0.251	0.378	0.588
0.6	0.013	0.036	0.070	0.156	0.343	0.472	0.709
0.7	0.016	0.042	0.083	0.195	0.451	0.570	0.840

(C) Number of data points

A	N/A 0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.2	56	56	56	55	48	37	18
0.3	56	56	56	56	51	38	24
0.4	56	56	56	56	51	42	25
0.5	56	56	56	56	51	42	28
0.6	56	56	56	56	51	42	30
0.7	56	56	56	56	51	42	31

Table 5.8

Statistics of Rz

N	Mean	S.D.	Vz (%)
0.02	0.7099	0.009	1.27
0.03	0.7324	0.014	1.98
0.04	0.7406	0.021	2.87
0.05	0.7791	0.026	3.34
0.06	0.7669	0.033	4.27
0.07	0.8257	0.038	4.59
0.08	0.7720	0.017	2.23
0.09	0.7808	0.013	1.72
0.10	0.7964	0.023	2.94
0.12	0.8160	0.023	2.87
0.14	0.8545	0.032	3.71
0.15	0.8411	0.020	2.40
0.16	0.8462	0.011	1.33
0.18	0.8725	0.024	2.77
0.20	0.8811	0.012	1.39
0.21	0.9038	0.027	2.98
0.24	0.9144	0.013	1.46
0.25	0.9191	0.009	1.02
0.28	0.9456	0.014	1.47
0.30	0.9527	0.008	0.85
0.35	0.9804	0.007	0.72
0.36	0.9830	0.005	0.51
0.42	1.0035	0.003	0.33
0.49	1.0128	0.002	0.17

Table 5.9

Statistics of Ez

(A) Mean

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	0.981	0.973	0.968	0.962	0.960	0.960	0.961
0.3	0.997	0.984	0.978	0.972	0.970	0.972	0.975
0.4	1.013	0.996	0.989	0.982	0.982	0.985	0.990
0.5	1.029	1.007	1.000	0.993	0.994	0.998	1.003
0.6	1.045	1.018	1.010	1.002	1.003	1.007	1.010
0.7	1.061	1.028	1.018	1.010	1.010	1.012	1.013

(B) Standard Deviation

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	0.012	0.009	0.012	0.007	0.006	0.004	0.002
0.3	0.020	0.014	0.017	0.011	0.008	0.006	0.004
0.4	0.027	0.019	0.021	0.013	0.010	0.006	0.005
0.5	0.034	0.022	0.024	0.014	0.010	0.006	0.003
0.6	0.042	0.025	0.026	0.015	0.009	0.005	0.003
0.7	0.049	0.028	0.027	0.014	0.008	0.003	0.002

(C) Number of data points

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	56	56	56	55	48	37	18
0.3	56	56	56	56	51	38	24
0.4	56	56	56	56	51	42	25
0.5	56	56	56	56	51	42	28
0.6	56	56	56	56	51	42	30
0.7	56	56	56	56	51	42	31

Table 5.10

Comparison between Prediction and Zarrabi's Results

A=0.5g, V=600mm/s

	Displacement (mm)	
N/A	equation 5.8	Zarrabi's Result
0.2	336.20	536.7
0.4	59.25	139.6
0.5	25.03	71.9
0.6	10.61	36.1

Table 5.11

Statistics of M

(A) Mean

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	1.075	0.900	0.883	0.921	0.936	0.918	0.777
0.3	1.092	0.912	0.897	0.940	0.963	0.953	0.842
0.4	1.110	0.924	0.912	0.963	0.997	0.997	0.870
0.5	1.129	0.936	0.927	0.989	1.037	1.054	0.998
0.6	1.147	0.948	0.942	1.015	1.087	1.116	1.050
0.7	1.164	0.959	0.957	1.043	1.140	1.181	1.123

(B) Variance

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	0.413	0.465	0.602	0.765	1.089	1.538	1.347
0.3	0.427	0.477	0.622	0.801	1.173	1.731	1.712
0.4	0.442	0.491	0.645	0.849	1.297	2.003	1.989
0.5	0.457	0.505	0.669	0.905	1.474	2.392	3.205
0.6	0.473	0.518	0.693	0.970	1.741	2.879	3.931
0.7	0.489	0.531	0.717	1.047	2.104	3.467	4.902

Table 5.12

Statistics of Em

(A) Mean

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	-0.081	-0.332	-0.410	-0.403	-0.469	-0.605	-0.839
0.3	-0.065	-0.319	-0.395	-0.384	-0.447	-0.581	-0.787
0.4	-0.049	-0.306	-0.379	-0.362	-0.421	-0.555	-0.784
0.5	-0.032	-0.293	-0.363	-0.339	-0.396	-0.521	-0.722
0.6	-0.017	-0.281	-0.348	-0.317	-0.370	-0.489	-0.710
0.7	-0.002	-0.270	-0.334	-0.296	-0.350	-0.457	-0.677

(B) Variance

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	0.306	0.454	0.572	0.642	0.807	1.038	1.173
0.3	0.306	0.454	0.573	0.645	0.818	1.067	1.229
0.4	0.306	0.454	0.574	0.650	0.835	1.067	1.289
0.5	0.307	0.455	0.575	0.656	0.863	1.148	1.440
0.6	0.307	0.455	0.577	0.663	0.906	1.197	1.518
0.7	0.308	0.456	0.579	0.675	0.963	1.248	1.586

CHAPTER VI

An Improved Seismic Design Procedure

6.1 The Aim of the Proposed Design Procedure

In this chapter, an improved version of seismic design procedure for gravity retaining walls, based on the limiting displacement approach, is proposed. The primary aim of this procedure is to address two basic questions of design within the context of the limiting displacement approach:

1. What is the most likely displacement of the retaining wall under the design load?

2. What is the confidence level that the actual displacement will be less than a certain limiting value? In other words, what is the limiting displacement for a specified confidence level for a given design?

Referring to these two questions, the main goal of the procedure is to formulate a pair of simple equations for design. The first one should be a reliable and representative prediction rule from which the expected displacement can be evaluated. The second one should integrate most design parameters whereby the limiting acceleration can be determined rationally. The confidence level is chosen as 95% on the limiting displacement criterion and is to be incorporated in the equation.

6.2 The Approach of the Proposed Design Procedure

Following the study on seismic behavior of gravity retaining walls presented in previous chapters, many of the shortcomings in modelling of seismic behavior of retaining walls have been eliminated. The emphasis on sliding-only mode of failure remains, but this is justified for most practical purposes according to Nadim(1980). The conclusions from the study form the basis for the proposed procedure.

The prediction rule (equation 5.8) formulated in Chapter 5 is the result of extensive analysis using the most rigorous sliding block model with a carefully chosen set of strong motion accelerograms. Not only the vertical ground acceleration and the time variation of the dynamic active earth pressure are taken into account, but the most neglected effect of the orientation of the wall is also accounted for. This is believed to give a more reliable and representative estimate of the field displacement than both Newmark's and Richards and Elms' prediction rules. The first design equation is established readily.

The conditional distribution of the relative displacement given A and N/A has been examined in Chapter 5. It has been found that a lognormal distribution describes the displacement distribution reasonably well. This finding provides the rationale for determining the limiting displacement for design. Basically, the relative displacement is assumed to be lognormally distributed. The approach of this procedure is to evaluate the factor of safety on displacement ($D_L/E[D]$) required for 95% confidence.

In next section, the variance of the expected displacement is to be evaluated through a study of the variances of the input parameters and the computed displacements. The factor of safety to be used is determined from the statistics of the computed results and typical parameters.

6.3 Formulation of the Variance in Displacement

The actual relative displacement calculation is a function of several factors:

1. The specified conditions in the analysis of the deterministic model;

   * The orientation of the wall;
   * The earthquake shaking characteristics;
   * The inclusion of vertical ground acceleration;
   * The correlation to Zarrabi's model;

2. The intensity of shaking(A) and the resistance(N);

3. The soil friction angles;

4. The physical geometry of the system.

The probabilistic function of relative displacement has been derived as:

$$D = E[D]\ M$$
$$= \frac{37V^2}{Ag} e^{-9.4(N/A)}\ Rv\ Rz\ M \qquad \text{.... (6.1)}$$

The displacement is an integrated function of the loading and resistance which were taken as deterministic in the analysis. The uncertainties in the model have been collectively modelled in the model parameter, M.

Obviously, N and A are independent of each other. For convenience, it will be assumed that N, A and M are independent of each other. It follows that, by the first order second moment approximation, the variance of displacement can be written as:

$$Var[D] = \left.\frac{\partial D}{\partial A}\right|^2 *Var[A] + \left.\frac{\partial D}{\partial N}\right|^2 *Var[N] + \left.\frac{\partial D}{\partial M}\right|^2 *Var[M] \quad .... (6.2)$$

where D = actual displacement given in equation 5.8

$$\frac{\partial D}{\partial A} = \frac{E[D]}{A}\left[9.4\frac{N}{A} + 1 + \frac{N/A - 7.2(N/A)^2}{5\ Rv}\right]$$

$$\frac{\partial D}{\partial N} = \frac{E[D]}{A}\left[\frac{1.2A(1-2N)}{Rz} + \frac{7.2(N/A)-1}{5\ Rv} - 9.4\right]$$

$$\frac{\partial D}{\partial M} = E[D]$$

To make the formulation complete, it is necessary to investigate and evaluate the variance contributions of these parameters and from the soil parameters. The variance of the geometry of the wall is assumed to be negligible since the geometry is controllable.

6.3.1 Variances in the Model

The uncertainties attributable to the input conditions and in the analysis with the deterministic model has been collectively represented in the model parameter, M. It models the variation in the computed displacement given A and N/A. Obviously, the variations in the soil parameters should be reflected in M. Surprisingly, the computed results are not sensitive to the variations in the soil parameters (see Section 5.3.2) as long as the limiting acceleration is determined properly. It follows that the influence of the soil parameters is in the limiting acceleration only and the model parameter M can be taken to be independent of the soil parameters.

As a result, the conditional mean and variance of M given A and N/A, tabulated in Table 5.11, need not be modified even when the uncertainties in the soil parameters are taken into account.

6.3.2 Variance in the Shaking Intensity

The intensity of shaking depends on the geology of the site and epicentral distance. The local building codes may provide information on the expected ground acceleration. However, there are always some uncertainties in the value and the variance of the intensity should be taken into account based on local experience. For the proposed design method, a standard deviation of (0.05)g is assumed for the shaking intensity.

6.3.3 Variance in the Limiting Acceleration

The limiting acceleration depends on the soil parameters and the geometry of the structural system.

Excluding the variation in the geometry and taking first order second moment approximation, the variance of N can be written as:

$$Var[N] = \frac{\partial N}{\partial \phi}^2 *Var[\phi] + \frac{\partial N}{\partial \phi b}^2 *Var[\phi b] + \frac{\partial N}{\partial \delta}^2 *Var[\delta] \qquad .... (6.3)$$

Equation 3.2 expresses the wall weight as an analytical function of the soil parameters, limiting acceleration and other factors. For a given weight of the wall, the limiting acceleration is implicitly related to the soil parameters. By differentiating the expression, the derivatives of N with respect to the soil parameters are:

$$\frac{\partial N}{\partial \phi_b} = \frac{\sec^2\phi_b}{G}\left[\frac{\cot(\beta+\delta) - N}{(\cot(\beta+\delta)-\tan\phi_b)\ (\tan\phi_b - N)}\right] \qquad .... (6.4a)$$

$$\frac{\partial N}{\partial \phi} = \frac{1}{G}\left[2\ \tan(\phi-\alpha-\beta) + \frac{\cot(\phi+\delta)+\cot(\phi-\alpha-i)}{1 + H}\right] \qquad .... (6.4b)$$

$$\frac{\partial N}{\partial \delta} = \frac{1}{G}\left[\frac{\cot(\phi+\delta)-H\tan(\alpha+\beta+\delta)}{1 + H} + \frac{\tan(\beta+\delta)+\tan\phi_b}{1-\tan(\beta+\delta)\tan\phi_b}\right] \qquad .... (6.4c)$$

$$G = \frac{1}{1+N^2}\left[2\tan(\phi-\alpha-\beta) + N + \frac{\cot(\phi-\alpha-i)+H\tan(\alpha+\beta+\delta)}{1 + H}\right] + \frac{1}{\tan\phi_b - N} \qquad .... (6.4d)$$

$$H = \sqrt{\frac{\cos(i-\beta)\cos(\alpha+\beta+\delta)}{\sin(\phi+\delta)\sin(\phi-\alpha-i)}} \qquad .... (6.4e)$$

The variance of N can then be determined given the means and variances of the soil friction angles.

In order to simplify variance calculations, the upper bound of the variance in N is evaluated. Adopting typical ranges of N and soil friction angles, namely N=0.2 to 0.35, ϕ=28 to 35 degrees, ϕb=28 to 35 degrees and δ=0 to 20 degrees, the maximum values of the derivatives are:

$$\frac{\partial N}{\partial \phi b} < 0.017 \text{ per degree}$$

$$\frac{\partial N}{\partial \phi} < 0.008 \text{ per degree} \quad .... (6.5)$$

$$\frac{\partial N}{\partial \delta} < 0.0045 \text{ per degree}$$

For measurements in the laboratory, typical coefficients of variation for ϕ, ϕb are 10 to 15%, say 3 degrees for the standard deviation. As for the wall friction angle, higher uncertainty justifies a conservative standard deviation of 15 degrees. So,

$$Var[N] < 0.017^2 * Var[\phi b] + 0.008^2 * Var[\phi] + 0.0045^2 * Var[\delta]$$

and, $Var[N] < 0.008$ per degree squared .... (6.6)

This upper bound for the variance associated with N will be used in the calculation of the variance in the displacement. A slight conservatism is considered tolerable for the sake of simplicity.

6.3.4 Overall Variance in Displacement

It has been established that N, A and M may be considered as independent of each other. Hence, the first order second moment approximation applies. From equation 6.2, the coefficient of variation of displacement can be written in the form of:

$$V_D^2 = DA*Var[A] + DN*Var[N] + DM*Var[M] \quad .... (6.7)$$

$$\text{where } DA = \left\{\frac{1}{E[D]} \frac{\partial D}{\partial A}\right\}^2$$

$$DN = \left\{\frac{1}{E[D]} \frac{\partial D}{\partial N}\right\}^2$$

$$DM = 1$$

Substituting for the variances, we have:

$$V_D^2 = DA*0.0025 + DN*0.008 + Var[M] \quad .... (6.8)$$

The derivatives of D with respect to A and N are evaluated for the ranges of A and N/A. The normalized derivatives, DA and DN, are summarized in Table 6.1. Putting these normalized derivatives and the variances of A, N and M into the equation, the coefficient of variation of displacement is found. Table 6.2 summarizes the coefficient of variation for the displacement. As can be seen, the value of the coefficient of variation is very high for lower N and A. This behavior is the result of using constant (upper bound) values for Var[N] and Var[A]. At low N and A, the derivatives are large and so the discrepancies are amplified.

6.4 The Factor of Safety

Incorporating the uncertainties in A and N, M cannot completely represent the total uncertainties in the displacement. It is convenient to define a new modified model parameter, Q, which is also a random variable, such that:

$$D = E[D]\ Q$$

Following the logic of Section 5.4.2, this modified model parameter is assumed to have the same property as M, namely lognormally distributed and the mean values are the same as M. The coefficient of variation of Q, however, is equal to the coefficient of variation of the displacement which has been tabulated in Table 6.2. Hence, expressing the displacement function in exponential form, it follows that:

$$D = E[D]\ e^{q}$$

$$\mathrm{Var}[q] = \ln\,(1 + V_Q^{\,2}) \qquad \ldots.\ (6.9)$$

$$= \ln\,(1 + V_D^{\,2})$$

$$E[q] = \ln(E[M]) - 0.5\,Var[q]$$

Table 6.3 presents the calculated mean and variance of q. Since Q is lognormally distributed, q is normally distributed. For 95% confidence level, the limiting displacement should be 1.645 $\sigma[q]$ away from the mean in a logarithmic scale. Hence,

$$D_L = E[D]\, e^{E[q]+1.645\sigma[q]} \qquad \text{.... (6.10)}$$

The factor of safety on displacement is then:

$$FS = D_L/E[D]$$

$$= e^{E[q]+1.645\sigma[q]} \qquad \text{.... (6.11)}$$

Table 6.4 summarizes the factor of safety required for 95% confidence. With this table of factor of safety and the prediction rule, a systematic and rational design procedure can be achieved.

To illustrate the procedure, a simple example is given here. Assume that a wall is to be designed for an earthquake of 0.4g and velocity 500mm/s. The limiting displacement is 60mm. The following table shows the trials in determining N..

Trial No.	N	N/A	Rz	Rv	E[D]	FS	D
1	0.2	0.5	0.868	1.095	20.95	3.707	77.66
2	0.24	0.6	0.919	1.154	8.89	3.749	33.31
3	0.21	0.525	0.889	1.108	16.71	3.718	62.21
4	0.212	0.53	0.900	1.111	16.19	3.720	60.21

So, the design limiting acceleration is about 0.212g for this wall.

Since the correlation functions Rv and Rz are functions of N, the limiting acceleration calculation will be implicit and a trial and error approach has to be used. The constant referring to the table of factor of safety makes the calculation tedious. For simplicity and ease of calculation, an equivalent factor of safety is constructed such that:

$$F = FS\ Rv\ Rz \qquad \text{.... (6.12)}$$

and $D_L = F\ E[Dno]$

Table 6.5 presents the values of this equivalent factor of safety for the various combinations of A and N/A. Figure 6.1 plots F against N showing a steadily increasing trend. This shows that the higher the limiting acceleration, the higher the uncertainties or the variance in the displacement. This is consistent with the conclusions when the wall orientation and the vertical ground acceleration are taken into account.

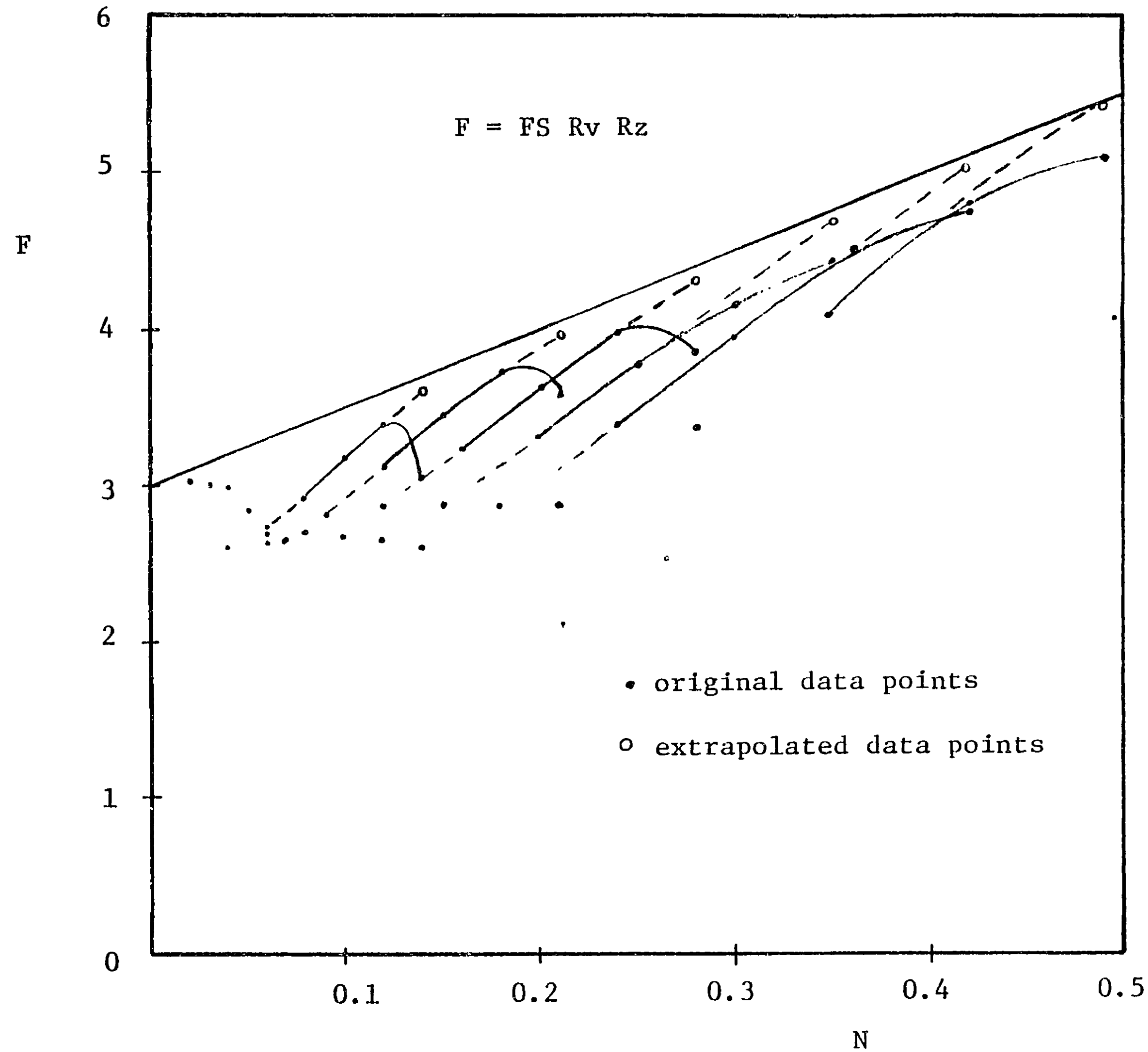

Figure 6.1 Equivalent Factor of Safety

In order to compensate for the filtering out of data, extrapolation of data points of N/A=0.7 is made in the figure according to the trend.

It can be seen that the required equivalent factor of safety is not well behaved at low N. This is believed to be the result of using upper bounds of Var[N] and Var[A] as mentioned earlier. Nevertheless, a retaining wall satisfying the normal static factor of safety requirement typically possesses a N value of 0.1 or higher. There should be no need to accurately model the behavior at the lower range of N. An upper bound envelop is drawn to enclose the data in the figure. The upper bound is found as F=3+5N.

Using this upper bound for the factor of safety, the design equation becomes:

$$D_L = (3+5N) \frac{37V^2}{A\,g} e^{-9.4N/A} \qquad \text{.... (6.13)}$$

Rearranging,
$$N = \frac{A}{9.4} \ln \frac{37(3+5N)\,V^2}{D_L A g} \qquad \text{.... (6.14)}$$

Equation 6.14 can be used to approximate the required limiting acceleration iteratively. The iteration for the limiting acceleration is greatly simplified and can be easily programmed on a small programmable calculator. For the example given previously, the iteration process is shown below:

Assumed N	F	N/A	N
0.5	5.5	0.572	0.229
0.228	4.14	0.542	0.217
0.216	4.08	0.540	0.216

Or, if a different initial value is assumed:

Assumed N	F	N/A	N
0.0	3.0	0.507	0.203
0.203	4.015	0.538	0.215
0.216	4.08	0.540	0.216

From the iteration calculations, it is observed that the convergence rate is very high. Typically, it takes no more than three iterations no matter what initial assumed value is. As for the calculated value of limiting acceleration, a 2% error (0.216 vs 0.212) on the safe side has resulted. The greatly improved efficiency and simplicity in calculation outweighs this slight conservative shortcoming. The expected displacement is to be evaluated with equation 5.8.

It is also noted that the limiting acceleration is not very sensitive to the equivalent factor of safety. For F to change from 5.5 to 4.1 or from 3.0 to 4.1, the calculated N value changes by roughly 7 percent only. This is due to the high coefficient of -9.4 in the index of e. Consequently, a constant value of 5 for F may be used for quick and preliminary design. For detailed designs, the more rigorous form should be used.

In summary, equation 6.14 is recommended to be used for calculating the limiting acceleration. The factor of safety has been incorporated into the equation so that the confidence level in design is at least 95%.

6.5 Steps of the Proposed Design Procedure

The necessary pair of equations for design, namely one for calculating the expected displacement and one for evaluating the limiting acceleration, have been established. They are:

$$E[D] = \frac{37V^2}{Ag} Rv\ Rz \qquad \text{.... [5.8]}$$

where $Rv=1.015-0.2(N/A)+0.72(N/A)^2$

$Rz=0.7+1.2N(1-N)$

$$N = \frac{A}{9.4} \ln \frac{37(3+5N)\ V^2}{D_L\ Ag} \qquad \text{.... [6.14]}$$

With the these two design equations, the following steps for seismic desgin of gravity retaining walls are proposed:

1. Determine the peak acceleration and velocity. Evaluate the relative displacement that can be tolerated.

2. Use equation 6.14 iteratively to calculate the limiting acceleration N for design.

3. Detail the wall using Ng as the input acceleration with equation 3.2.

4. The expected relative displacement for the design earthquake is evaluated by equation 5.8.

5. The actual factor of safety on displacement can be backfigured from the limiting displacement and the expected displacement.

The procedure has been illustrated in last section. The iteration process is simple and normally three iterations are required.

6.6 Comparisons with Richards and Elms' Design Procedure

The basic approach of the proposed design procedure is the same as Richards and Elms' design procedure. For comparisons, the example in Section 2.3.2 is reconsidered. For A=0.4g, V=400mm/s and limiting displacemnt of 50mm, equation 6.14 yields 0.204g as the limiting acceleration. The required weight of the reference wall, for example, is

0.640 (γH^2). This is even 1% lower than the required weight computed with Richards and Elms' procedure before a factor of safety is applied. The expected displacement is found to be 12.30mm and the actual factor of safety on displacement is 4.06. Table 6.6 compares the prediction and calculated parameters between both procedures. It is observed that both methods result in a factor of safety about 4 to 5 on the displacement in the practical range. The main difference is in the prediction rule.

By assuming the actual peak acceleration acting towards the backfill as the absolute maximum, using Newmark's model and an upper bound envelop, Richards and Elms' prediction appears to be excessively conservative and the prediction is not representative of the field displacement at all. The further application of factor of safety gives no idea of the confidence level in design.

According to the study conducted, the confidence level on limiting displacement is in the 90% range with their prediction already. There should be no need to apply another factor of safety on the weight of the wall.

6.7 Evaluation and Comments

The proposed design procedure offers several desirable features for design purpose. The merits and shortcomings of the procedure are discussed below:

6.7.1 The Merits

1. The limiting displacement approach is most appropriate for seismic design of retaining walls. Retaining walls can be built ecomoically while the performance is still satisfactory.

2. The proposed procedure is formulated from extensive study. This ensures minimum conservatism and maximum economics under allowable performance criterion.

3. The factor of safety has been derived as a linear function of N. This requires only slight amount of calculation over conventional design practice yet the trend of the variance in the displacement which increases with N is also modelled. This is considered as the most optimal approach for rational and simple design.

4. More information on field performance is available. Not only is a confidence level of 95% is built in, but the EXPECTED displacement can also be evaluated explicitly. This provides a better understanding of the design process.

6.7.2 The Limitations and Warnings

1. Zarrabi's model has been developed recently. Even though the formulation is sound, there has been limited verification of the accuracy of the model. Hence, the proposed procedure should be used with caution.

2. Tilting displacement has not been considered. This is acceptable provided that (N/A)t is higher than 1.15(N/A)s. More research is needed before this limitation can be eliminated. Meanwhile, this requirement should be satisfied in each individual case before this procedure is employed.

3. Zarrabi's model has been formulated for the case of gravity retaining walls with non-liquefying backfill. The proposed procedure should NOT be applied to force governed retaining walls.

4. The sensitivity of the relative displacement to the variation of the base friction angle has not been studied.

Table 6.1

Normalized derivatives of Displacement

(A) DA (with respect to A)

A	N/A Ø.1	Ø.2	Ø.3	Ø.4	Ø.5	Ø.6	Ø.7
Ø.2	94.63	2Ø4.84	351.89	532.87	745.99	99Ø.62	1267.12
Ø.3	42.Ø6	91.Ø4	156.4Ø	236.83	331.55	44Ø.28	563.17
Ø.4	23.66	51.21	87.97	133.22	186.5Ø	247.66	316.78
Ø.5	15.14	32.78	56.3Ø	85.26	119.36	158.5Ø	2Ø2.74
Ø.6	1Ø.52	22.76	39.1Ø	59.21	82.89	11Ø.Ø7	14Ø.79
Ø.7	7.73	16.72	28.73	43.5Ø	6Ø.9Ø	8Ø.87	1Ø3.44

(B) DN (with respect to N)

A	N/A Ø.1	Ø.2	Ø.3	Ø.4	Ø.5	Ø.6	Ø.7
Ø.2	2Ø84.3	2Ø26.6	197Ø.8	1919.3	1873.9	1835.8	18Ø5.2
Ø.3	896.2	874.5	853.1	833.Ø	815.4	8ØØ.5	788.8
Ø.4	488.2	478.8	468.9	459.4	451.Ø	443.9	438.4
Ø.5	3Ø3.Ø	298.9	294.1	289.3	284.8	281.1	278.3
Ø.6	2Ø4.2	2Ø2.9	2ØØ.7	198.2	195.8	193.8	192.3
Ø.7	145.8	146.Ø	145.2	144.Ø	142.8	141.7	141.Ø

Table 6.2

Coefficient of Variation of Relative Displacement

$V_D{}^2$

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	14.993	21.213	22.097	20.558	20.463	22.194	31.414
0.3	6.456	9.265	9.739	9.114	9.196	10.168	13.317
0.4	3.576	5.211	5.549	5.233	5.405	6.210	8.313
0.5	2.292	3.397	3.677	3.511	3.768	4.530	5.965
0.6	1.622	2.446	2.698	2.624	2.977	3.776	5.965
0.7	1.235	1.892	2.131	2.123	2.615	3.441	4.984

Table 6.3

Statistics of q

(A) Mean

				N/A			
A	0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.2	-1.314	-1.655	-1.694	-1.617	-1.599	-1.658	-1.992
0.3	-0.916	-1.257	-1.296	-1.219	-1.199	-1.255	-1.503
0.4	-0.656	-0.992	-1.032	-0.952	-0.932	-0.991	-1.255
0.5	-0.475	-0.806	-0.847	-0.765	-0.745	-0.802	-0.973
0.6	-0.345	-0.672	-0.713	-0.629	-0.607	-0.672	-0.869
0.7	-0.250	-0.573	-0.615	-0.528	-0.511	-0.579	-0.778

(B) Variance

				N/A			
A	0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.2	2.772	3.101	3.140	3.071	3.066	3.144	3.479
0.3	2.009	2.329	2.374	2.314	2.322	2.413	2.661
0.4	1.521	1.826	1.879	1.830	1.857	1.975	2.321
0.5	1.191	1.481	1.543	1.507	1.562	1.710	1.941
0.6	0.964	1.237	1.308	1.288	1.381	1.564	1.837
0.7	0.804	1.062	1.142	1.139	1.285	1.491	1.789

Table 6.4

Factor of Safety on Displacement

(Confidence level = 95%)

				N/A			
A	0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.2	4.158	3.460	3.391	3.544	3.603	3.523	2.934
0.3	4.118	3.503	3.452	3.610	3.698	3.672	3.256
0.4	3.946	3.424	3.399	3.572	3.707	3.749	3.327
0.5	3.746	3.305	3.308	3.506	3.710	3.854	3.740
0.6	3.562	3.183	3.215	3.448	3.764	3.996	3.897
0.7	3.405	3.073	3.134	3.413	3.870	4.178	4.146

Table 6.5

Equivalent Factor of Safety on Displacement

F = FS Rv Rz

A	0.1	0.2	0.3	N/A 0.4	0.5	0.6	0.7
0.2	3.015	2.591	2.655	2.934	3.188	3.361	3.042
0.3	3.033	2.699	2.810	3.134	3.454	3.717	3.594
0.4	2.951	2.710	2.865	3.231	3.620	3.976	3.847
0.5	2.842	2.681	2.878	3.284	3.758	4.235	4.468
0.6	2.740	2.641	2.876	3.327	3.924	4.503	4.748
0.7	2.656	2.605	2.874	3.377	4.124	4.785	5.089

Table 6.6

Comparisons between the Proposed Design Procedure
and Richards and Elms' Design Procedure

For : A = 0.4g

V = 400mm/s

D = 50mm

Parameter	R. and E. Procedure	Proposed Procedure
Calculated N	0.206	-----
Calculated Ww	0.645	-----
Design Ww	0.968	0.640
Actual N	0.298	0.204
E[D]	11.5	12.30

** According to equation 5.8, Richards and Elms' design will have a displacement of 1.4mm only, i.e., a factor of safety of 36 on the limiting displacement criterion.

Chapter VII

Conclusions and Recommendations

7.1 Conclusion on Sliding Behavior

1. It is evident that the normalization of accelerograms will affect the quoted prediction dramatically. By assuming the absolute maximum acceleration to act towards the backfill as opposed to a random direction, the predicted relative displacement will typically be doubled. This means that the effect of orientation of the wall should not be ignored.

2. Shaking characteristics of an earthquake also plays an important role in determining the relative displacement. the coefficient of variation in displacement attributed to shaking characteristics is 0.5 for the chosen group of accelerograms.

3. Inclusion of vertical acceleration in the analysis increases the computed relative displacement. The effect increases with N/A and decreases with the computed relative displacement. For practical calculation, the correlation can be approximated by:

$$Rv = 1.015 - 0.2(N/A) + 0.72\ (N/A)^2 \qquad \text{for } N/A<0.7$$

4. In order to correlate the results from Newmark's model to Zarrabi's model, the correlation can be approximated by:

$$Rz = 0.7 + 1.2\ N\ (1-N) \qquad \text{for } N < 0.5$$

Future studies can concentrate on Newmark's model and the results can be corrected with this function.

5. The average relative displacement predicted by Zarrabi's model taking into account of the effects of orientation of the wall, shaking characteristics and inclusion of vertical acceleration can be estimated as:

$$D = \frac{37V^2}{Ag} e^{-9.4N/A}\ Rv\ Rz$$

6. A multiplicative model has been used to describe the relative displacement distribution. The goodness of fit in the most cases are reasonably well.

7.2 Recommendation for Seismic Design of Retaining Walls

A simple yet practical and rational procedure to the design of gravity retaining walls against earthquake has been described herein. The procedure is based on the limiting displacement approach proposed by Richards and Elms but modified to allow for the time variation of the dynamic active earth pressure, the orientation of the wall and shaking characteristics as well as incorporating the vertical acceleration. The procedure is, however, restricted in application to dry non-liquefying backfill. The level of confidence on the limiting displacement criterion is chosen to be above 95%. The expected displacement can be evaluated explicitly.

It should be noted that the prediction rule is derived from the results of a range of earthquake records using Zarrabi's model. The prediction rule should be updated and refined as more results for Zarrabi's model are available. Correlation from results of Newmark's model may also be utilized.

Whereas the procedure described above provides a rational approach to the seismic design of gravity retaining walls and offers a significant improvement over Richards and Elms's design procedure, the lack of field and experimental validation requires that it should be used with caution and good judgement.

7.3 Recommendations for Future Study

1. The proposed design procedure has been based on Zarrabi's sliding block model for calculating relative displacement developed during earthquakes. Though the formulation is sound, the accuracy of the model has been confirmed by only limited model tests. There is a need for experimental validation of the prediction.

2. Tilting displacement has been ignored in the study. This is justified for high (N/A)t. Further study for the cases of low (N/A)t is recommended.

3. Only limited reports have been made about retaining wall failures. The lack of data for actual motions of a wall makes it difficult to prove the accuracy of the model. It is recommended that every opportunity must be seized to compare prediction with field observations after future earthquakes.

4. If future model tests and field observations show that Zarrabi's model to be inappropriate, a better model capable of modelling the soil stress-strain relationship should be considered. A non-linear finite elemnt model is recommended for this purpose. In any case, the limiting displacement approach is recommended.

5. The limiting acceleration is very sensitive to the dynamic soil friction angles; therefore, the dynamic properties of soil should be investigated in detail.

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Appendix A

Computer Code and User's Manual

A.1 Description

This computer code calculates the normalized permanent relative displacement of a gravity retaining wall during seismic loading. It is a modified version of the computer code developed by Zarrabi (1979). It adopts a sliding-block-on-inclined-plane model with variable shear strength between the block and the plane (and hence variable threshold acceleration). The variation of shear strength simulates the change of inclination of the rupture surface during sliding. The vertical ground acceleration is also taken into account. Each earthquake will be normalized to specified peak accelerations and peak velocities. All components are scaled by the same scaling factor so that the absolute maximun horizontal accelerations are those specified. The equilibrium and compatibility equations used are summarized in Section 3.4.2 in this thesis.

A.2 Limitation

The code is limited to handle 5000 data points for each component in the accelerograms. In some extreme cases, when the maximun horizontal acceleration (kh) and maximum vertical acceleration (kv) occur simultaneously, the program may experience numerical difficulty. For example, when kv=1, there is no theoretical solution for dynamic equilibrium. An error message will be output for tracing the particular time step in the accelerogram.

A.3 File Managemnet

A.3.1 Input Files

Unit	Description
FOR001	Horizontal Acceleration Record 1
FOR002	Horizontal Acceleration Record 2
FOR003	Vertical Acceleration Record
FOR005	System Parameters

A.3.2 Output File

Unit	Description
FOR006	Output Normalized Permanent Relative Displacement

A.4 Input Data

A.4.1 Unit 1

```
1st card   (20A4)
     col. 1-80  Title of Earthquake and
                Accelerogram
2nd card   (I5,F10.2)
     col. 1- 5  Number of acceleration values in
                the Accelerogram
          6-10  Time Step in Accelerogram
3rd and consecutive cards  (8F9.0)
     col. 1-72  8 acceleration values per card
```

A.4.2 Unit 2

Same as Unit 1

A.4.3 Unit 3

```
1st card   (20A4)
     col. 1-80  Title of Earthquake
2nd card   (20A4)
     col. 1-80  Title of Accelerogram
3rd card   (2I5)
     col. 1- 5  Number of acceleration values in
                the Accelerogram
          6-10  Sense of Accelerogram
                   1 for downward positive
                  -1 for upward positive
4th and consecutive cards  (8F9.0)
     col. 1-72  8 acceleration values per card
```

A.4.4 Unit 5

```
1st card   (7I5)
     col.   1-5  Number of Normalizing peak
                 acceleration to be studied
     col.  6-10  Number of (N/A) ratios to be
                 analyzed
     col. 11-15  Number of horizontal
                 accelerograms to be studied.
     col. 16-20  Number of vertical accelerogram
```

col. 21-25 Number of Structural systems to be studied

col. 26-30 Direction of Backfill to be studied
1 backfill in forward direction
2 backfill in backward direction
3 analyze both cases

col. 31-35 Option for vertical acceleration inclusion
1 include vertical acceleration
2 exclude vertical acceleration
3 analyze both cases

** If there is no vertical accelerogram supplied, the program will reset to option 2.

2nd card (2F10.2)
col. 1-10 Normalizing peak acceleration value
11-20 Normalizing peak velocity value
** Repeat this card for the number of cases specified in first card

3rd card (5F10.4)
col. 1-50 5 Values of (N/A)
** Repeat this card for the number of cases specified in first card

4th card (5F10.2)
col. 1-10 Soil Friction Angle (in degree)
11-20 Wall Friction Angle (in degree)
21-30 Slope inclination of backfill (in degree)
33-40 Wall base Friction Angle (in degree)
41-50 Inclination of Wall (in degree)
** Repeat this card for the number of cases specified in first card

A.5 Output

The output will print the titles of earthquake and the accelerograms. For each value of normalized peak acceleration and (N/A), there will be one line of output giving the calculated normalized relative displacements for the types of analysis specified. The output will be in a tabulated forms.

A.6 Error Message

A negative displacement indicates instability in analysis. This is an ERROR message. The integer part indicates the time interval that causes this instability. (See also A.2)

--- COMPUTER CODE LISTING ---

```
C**********************************************************************
C                                                                     *
C                PROGRAM FOR SEISMIC ANALYSIS OF                      *
C                      GRAVITY RETAINING WALLS                        *
C                                                                     *
C                     BY  C.P.WONG                                    *
C                                                                     *
C**********************************************************************
C
      DIMENSION AS(5000),ASV(5000),PEAK(2),LABEL(2),LABELA(2),
     1          PHI1(5),DELTA1(5),SLOPE1(5),PHIB1(5),BETA1(5),
     2          A(7),V(7),DX(4),LTITLE(60),OVERNA(7),TR(8)
      DATA LABEL,LABELA/4H FOR,4HBACK,4H<> 0,4H== 0/
      LOGICAL   SLIDE,IFAIL
      COMMON /SLID/AB1,AP1,AB,AP,DT,GROUND,IFAIL,SLIDE,VB1,VP1,
     1      VB,VP,VER,X
      COMMON /TAB/ACTN,PHI,SLOPE,DELTA,BETA,PHIB
      COMMON AG(99),AW(99)
C
C   ***  READ IN SYSTEM PARAMETERS SUCH AS A,V,N/A AND ANGLES
C
      PEAK(1)=0.
      READ (5,100) NAK,NOVERA,NHOR,NVER,NSOIL,NFB,NV
      READ (5,110) ((A(I),V(I)),I=1,NAK)
      READ (5,120) (OVERNA(I),I=1,NOVERA)
      READ (5,130) (PHI1(I),DELTA1(I),SLOPE1(I),PHIB1(I),BETA1(I),
     1             I=1,NSOIL)
C
C   ***  READ IN GROUND VERTICAL ACCELERATIONS  (IF SUPPLIED)
C
      VERT=0.0
      IF (NVER.EQ.1)  THEN
              READ (3,140) (LTITLE(I),I=1,40)
              READ (3,100) NTV,NSENSE
              READ (3,160) (ASV(I),I=1,NTV)
              IF (NSENSE.GT.0)  VERT=1.0
              IF (NSENSE.LT.0)  VERT=-1.0
              M=1
      ELSE
              M=41
              NV=2
              NTV=0
      END IF
C
C   ***  DETERMINE THE PEAK VALUE OF ACCELERATION IN RECORD 2
C        (IF SUPPLIED)
C
      IF (NHOR.EQ.2) THEN
              READ (2,140) (LTITLE(I),I=41,60)
```

```
               READ (2,150) NTH
               DO 10 I=1,NTH,8
                  READ (2,160) (TR(J),J=1,8)
                  DO 10 J=1,8
                       TPEAK=ABS(TR(J))
                       IF (TPEAK.GT.PEAK(1))  PEAK(1)=TPEAK
   10          CONTINUE
               REWIND (2)
       END IF
C
C   ***  SET LOOPING INDICES ACCORDING TO OPTIONS
C              FORWARD AND/OR BACKWARD
C              KV <> 0 AND/OR KV == 0
C
       NA=NFB/2
       NB=NA+1
       NC=NV/2
       ND=NC+1
       IF (NFB.EQ.NB)  NA=NB
       IF (NV .EQ.ND)  NC=ND
C
C   ***  START LOOPING
C
       DO 70 J1=1,NHOR
C
C   *** READ IN GROUND HORIZONTAL ACCELERATIONS
C
       READ (J1,140) (LTITLE(I),I=41,60)
       READ (J1,150) NTH,DT
       READ (J1,160) (AS(I),I=1,NTH)
C
C   ***  FILL UP ASV(I) IF ASV(I) IS SHORTER THAN AS(I)
C
       NT=NTH
       IF (NTV.LT.NT)  THEN
                NTA=NTV+1
                DO 20 I=NTA,NT
                ASV(I)=0.0
   20   CONTINUE
       END IF
C
C   ***  DETERMINE THE PEAK VALUE OF ACCELERATION IN RECORD 1 AND 2
C
       IF (J1.EQ.1)  THEN
               DO 30 I=1,NTH
               TPEAK=ABS(AS(I))
               IF (PEAK(1).LT.TPEAK)  PEAK(1)=TPEAK
   30          CONTINUE
               PEAK(2)=-PEAK(1)
       END IF
```

```
      DO 70 J2=1,NSOIL
      WRITE (6,200) PHI1(J2),DELTA1(J2),SLOPE1(J2),BETA1(J2),PHIB1(J2)
      WRITE (6,210) (LTITLE(I),I=M,60)
      IF (NFB.NE.3)  THEN
             WRITE (6,211) LABEL(NA)
             IF (NV.EQ.3)  THEN
                    WRITE (6,212) LABELA
             ELSE
                    WRITE (6,213) LABELA(NV)
             END IF
      ELSE IF (NV.EQ.3)  THEN
             WRITE (6,214)
      ELSE
             WRITE (6,215) LABELA(NC),LABELA(NC)
      END IF
      WRITE (6,220)
      BETA=BETA1(J2)*0.01753293
      PHI=PHI1(J2)*0.01753293
      DELTA=DELTA1(J2)*0.017453293
      SLOPE=SLOPE1(J2)*0.017453293
      PHIB=PHIB1(J2)*0.017453293
      DO 70 J3=1,NAK
      DO 70 J4=1,NOVERA
      ACTN=A(J3)*OVERNA(J4)
      CALL TABLE
      L=0
      DO 60 J5=NA,NB
C
C   ***  DETERMINE THE NORMALIZING FACTORS FOR CORRESPONDING A
C
      TEMP1=A(J3)*9806.6/PEAK(J5)
      TEMP2=VERT*ABS(TEMP1)
      DO 60 J6=NC,ND
C
C   ***  INITIALIZE VARIABLES
C
      IF (J6.EQ.2) TEMP2=0.0
      L=L+1
      X=0.0
      VB1=0.0
      VP1=0.0
      AB1=0.0
      AP1=0.0
      VPMAX=0.0
      IFAIL=.FALSE.
      SLIDE=.FALSE.
C
C   ***  START STEP BY STEP CALCULATION
C
      DO 40 I=1,NT
      AP=AS(I)*TEMP1
      VP=VP1+0.5*DT*(AP+AP1)
```

```
      TEMPVP=ABS(VP)
      IF (TEMPVP.GT.VPMAX)  VPMAX=TEMPVP
      VER=ASV(I)*TEMP2
      GROUND=AP/(9806.6-VER)
C
C  ***  CHECK FOR SLIDING FOR THIS TIME INTERVAL
C           (1)  SLIDE IN PREVIOUS TIME INTERVAL
C           (2)  GROUND > ACTUAL N
C
      IF (SLIDE.EQ..TRUE..OR.GROUND.GT.ACTN)  CALL SLIDING
      IF (IFAIL.EQ..TRUE.) GOTO 50
      IF (SLIDE.EQ..FALSE.)  THEN
              AB=AP
              VB=VP
      END IF
C
C  ***  SHIFT PRESENT STATUS ONE TIME STEP BACKWARDS
C
      VP1=VP
      AP1=AP
      VB1=VB
      AB1=AB
   40 CONTINUE
C
C  ***  NORMALIZE THE RELATIVE DISPLACEMENT
C
      DX(L)=X*(V(J3)/VPMAX)**2
      GO TO 60
   50 DX(L)=-FLOAT(I)
   60 CONTINUE
C
C  ***  OUTPUT RESULTS
C
      WRITE (6,230) A(J3),V(J3),OVERNA(J4),(DX(I),I=1,L)
   70 CONTINUE
  100 FORMAT(7I5)
  110 FORMAT(2F10.2)
  120 FORMAT(5F10.4)
  130 FORMAT(5F10.2)
  140 FORMAT(20A4)
  150 FORMAT(I5,F10.2)
  160 FORMAT(8F9.0)
  200 FORMAT(1H1,4HPHI=,F5.1,3X,6HDELTA=,F5.1,3X,6HSLOPE=,
      1       F5.1,3X,5HBETA=,F5.1,3X,5HPHIB=,F5.1,/)
  210 FORMAT(5X,20A4,/,2(10X,20A4,/),///)
  211 FORMAT(28X,'DISPLACEMENT (MM)',/,28X,A4,'WARD')
  212 FORMAT(8X,'A',6X,'V',5X,'N/A',4X,2('KV ',A4,3X))
  213 FORMAT(8X,'A',6X,'V',5X,'N/A',4X,'KV ',A4)
  214 FORMAT(38X,'DISPLACEMENT (MM)',/,
      1       28X,'FORWARD',13X,'BACKWARD',/,
      2        8X,'A',6X,'V',5X,'N/A',4X,2('KV <> 0',3X,'KV == 0',3X))
```

```
215   FORMAT(28X,'DISPLACEMENT (MM)',/,
      1      28X,'FORWARD',3X,'BACKWARD',/,
      2       8X,'A',6X,'V',5X,'N/A',4X,2('KV ',A4,3X))
220   FORMAT(1H0,5X,61(1H*))
230   FORMAT(7X,F3.1,3X,F5.1,3X,F3.1,4F10.2)
      STOP
      END
```

```
C*********************************************************************
      SUBROUTINE TABLE
C*********************************************************************
      COMMON /TAB/ACTN,PHI,SLOPE,DELTA,BETA,PHIB
      COMMON AG(99),AW(99)
      LOGICAL IFAIL
C
C    ***  CALCULATE WALL WEIGHT FACTOR FOR THIS VALUE OF N
C
      TPHI=TAN(PHI)
      TANPB=TAN(PHIB)
      TA=TANPB*SIN(DELTA+BETA)-COS(DELTA+BETA)
      ALPHA=ATAN(ACTN)
      C2=COS(ALPHA+DELTA+BETA)
      C1=(COS(PHI-ALPHA-BETA)/COS(BETA))**2/(COS(ALPHA)*C2)
      C2=SIN(PHI+DELTA)*SIN(PHI-ALPHA-SLOPE)/COS(SLOPE-BETA)/C2
      WW=C1*TA/(1.0+SQRT(C2))**2/(ACTN-TANPB)
C
C    ***  FORM TABLE OF INPUT EXCITATION AND RESONDING LIMITING
C          ACCELERATION
C
      IFAIL=.TRUE.
      ALP=-0.16
      DO 10 I=1,99
      ALP=ALP+0.0066
      COTA=1.0/TAN(ALP)
      P=TAN(PHI-SLOPE-ALP)
      Q=1.0/TAN(PHI-ALP-BETA)
      R=TAN(DELTA+BETA+ALP)
      TEM=(-P+SQRT(P*(P+Q)*(1.0+Q*R)))/(1.0+R*(P+Q))
      THETA=PHI-ALP+ATAN(TEM)
      TANT=TAN(THETA)
      C1=SIN(THETA-SLOPE)*COS(BETA)**2
      W=COS(BETA-SLOPE)*COS(THETA-BETA)/C1
      C1=TPHI*SIN(DELTA+BETA-THETA)-COS(DELTA+BETA-THETA)
      A=C1*WW*COS(THETA)/(TA*W)
      B=TANT*TAN(BETA)
      S=COS(THETA)**2*(TANT-TPHI)
      T=COTA-TANT
      C1=A*(1.0+B)+1.0+(S-A*TANPB)*T
      C2=TANT*(A+1.0+S*T)+A*B*COTA
      AG(I)=C1/C2
      AW(I)=(1.0-TANT*AG(I))/T
C
C    ***  SAFE GUARD FOR UNSTABLE AG AT TOO LOW AN ASSUMED ALPHA
C
      IF (IFAIL.EQ..FALSE.)  GOTO 10
      IF (AG(I).LT.0.0)  THEN
              IFAIL=.FALSE.
      ELSE
              AG(I)=-1000.0
      END IF
   10 CONTINUE
      RETURN
      END
```

```
C*********************************************************************
      SUBROUTINE SLIDING
C*********************************************************************
      COMMON /SLID/AB1,AP1,AB,AP,DT,GROUND,IFAIL,SLIDE,VB1,VP1,
     1      VB,VP,VER,X
      COMMON AG(99),AW(99)
      LOGICAL SLIDE,IFAIL
C
C   ***  INTERPOLATE THE EXCITATION FROM THE TABLE
C
      DO 10 I=1,99
      IF (GROUND.LT.AG(I))  GOTO 30
   10 CONTINUE
C
C   ***  UNSTABLE CASE :  1)  GROUND > AG(MAX)
C                         2)  GROUND < AG(MIN)
C
   20 IFAIL=.TRUE.
      RETURN
   30 IF (I.EQ.1)  GOTO 20
C
C   ***  CALCULATE RESPONDING LIMITING ACCELERATION
C
      AB=AW(I)-(AG(I)-GROUND)*(AW(I)-AW(I-1))/(AG(I)-AG(I-1))
      AB=AB*(9806.6-VER)
      VB=VB1+0.5*(AB+AB1)*DT
C
C   ***  DETERMINE ADDITIONAL RELATIVE DISPLACEMENT IN THIS
C        TIME INTERVAL
C
      IF (SLIDE.EQ..FALSE.)  THEN
              SLIDE=.TRUE.
              X=X+(AP-AB)*DT**2/6.0
      ELSE IF (VP.GT.VB)  THEN
              X=X+(VP1-VB1)*DT+(AP+AP1+AP1-AB-AB1-AB1)*DT**2/6.0
           ELSE
              SLIDE=.FALSE.
              D1=(VP1-VB1)*DT/(VB+VP1-VB1-VP)
              X=X+D1*(VP1-VB1)
     1          +D1*D1*0.5*(AP1-AB1+D1*(AP-AP1-AB+AB1)/3.0/DT)
      END IF
      RETURN
      END
```

Appendix B

Strong Motion Earthquakes Chosen for Analysis

No.	Earthquakes	File No.	Date	M	I
1	El Centro Earthquake, Imperial Valley	A001	5/18/40	6.7	8
2	Kern County Earthquake, Taft Lincoln School	A004	7/21/52	7.7	7
3	Eureka Earthquake, Eureka Federal Building	A008	12/21/54	6.5	7
4	Eureka Earthquake, Ferndale City Hall	A009	12/21/54	6.5	7
5	Long Beach Earthquake, Vernon CMD Building	B021	3/10/33	6.3	6
6	Lower California Earthquake, Imperial Valley	B024	12/30/34	6.5	6
7	Western Washington Earthquake at				
	Olympia, Washington, Highway Test Lab.	B029	4/13/49	7.1	8
8	Puget Sound, Washington Earthquake at				
	Olympia, Washington, Highway Test Lab.	B032	4/29/65	6.5	7
	San Fernando Earthquake at				
9	8244, Orion Blvd., 1st floor	C048			
10	Old Ridge Route, Castaic	D056	2/ 9/71	6.6	7
11	Griffith Park Observatory	O198			
	Imperial Valley Earthquake				
12	Station 7				
13	Station 10		10/15/79	6.4	-
14	Bonds Corner				

* M stands for Magnitude
I stands for Intensity
File No. refers to CIT files
Computed results are filed as numbered

Appendix C

Computed Relative Displacements

The computed relative displacements are summarized in this Appendix. Section C1 presents the computed relative displacements using Newmark's model while the results using Zarrabi's model on the reference structural system are tabulated in Section C2.

Section C1

Computed Relative Displacements

using Newmark's Model

Table C.1.1.A

El Centro Earthquake, Imperial Valley
CIT File No. -- A001

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S00E	N00E	S90W	S90E
	0.1	380.90	529.47	409.72	335.06
	0.2	131.14	203.62	94.89	86.18
Ag=0.2g	0.3	52.32	65.45	27.47	18.87
	0.4	24.96	23.08	8.36	3.06
V=250mm/s	0.5	13.13	5.92	1.29	0.02
	0.6	7.20	0.54	0.02	0.00
	0.7	3.65	0.03	0.00	0.00
	0.1	571.34	794.20	614.56	502.59
	0.2	196.71	305.43	142.34	129.27
Ag=0.3g	0.3	78.48	98.17	41.20	28.32
	0.4	37.44	34.62	12.54	4.60
V=375mm/s	0.5	19.69	8.87	1.95	0.03
	0.6	10.80	0.80	0.02	0.00
	0.7	5.47	0.05	0.00	0.00
	0.1	761.79	1058.93	819.41	670.13
	0.2	262.28	407.24	189.80	172.37
Ag=0.4g	0.3	104.64	130.90	54.93	37.76
	0.4	49.92	46.16	16.71	6.12
V=500mm/s	0.5	26.26	11.83	2.59	0.03
	0.6	14.41	1.07	0.03	0.00
	0.7	7.29	0.07	0.00	0.00
	0.1	877.59	1219.89	943.97	771.98
	0.2	302.15	469.14	218.64	198.57
Ag=0.5g	0.3	120.55	150.80	63.28	43.51
	0.4	57.51	53.18	19.25	7.06
V=600mm/s	0.5	30.25	13.63	2.98	0.03
	0.6	16.60	1.23	0.03	0.00
	0.7	8.40	0.08	0.00	0.00
	0.1	1142.69	1588.40	1229.13	1005.19
	0.2	393.42	610.86	284.71	258.55
Ag=0.6g	0.3	156.96	196.35	82.40	56.64
	0.4	74.88	69.24	25.08	9.18
V=750mm/s	0.5	39.39	17.75	3.88	0.05
	0.6	21.61	1.61	0.05	0.00
	0.7	10.94	0.10	0.00	0.00
	0.1	1333.14	1853.13	1433.99	1172.71
	0.2	458.98	712.68	332.14	301.63
Ag=0.7g	0.3	183.11	229.07	96.14	66.08
	0.4	87.35	80.78	29.25	10.72
V=875mm/s	0.5	45.95	20.70	4.53	0.07
	0.6	25.21	1.87	0.05	0.00
	0.7	12.76	0.12	0.00	0.00

Table C.1.1.B

El Centro Earthquake, Imperial Valley
CIT File No. -- A001

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S00E	N00E	S90W	S90E
Ag=0.2g	0.1	381.29	528.95	408.72	336.02
V=250mm/s	0.2	132.26	202.89	94.32	86.41
	0.3	53.26	65.42	26.91	19.69
	0.4	25.29	23.09	7.97	3.68
	0.5	13.35	5.60	1.15	0.03
	0.6	7.47	0.52	0.00	0.00
	0.7	3.92	0.04	0.00	0.00
Ag=0.3g	0.1	572.24	793.04	612.35	504.82
V=375mm/s	0.2	199.36	303.80	141.12	129.82
	0.3	80.60	98.13	39.97	30.09
	0.4	38.19	34.65	11.69	6.02
	0.5	20.20	8.19	1.62	0.08
	0.6	11.41	0.78	0.00	0.00
	0.7	6.09	0.06	0.00	0.00
Ag=0.4g	0.1	763.46	1056.88	815.50	674.16
V=500mm/s	0.2	267.11	404.36	187.72	173.38
	0.3	108.43	130.88	52.79	41.15
	0.4	51.36	46.22	15.21	8.71
	0.5	27.18	10.65	2.03	0.29
	0.6	15.51	1.04	0.00	0.00
	0.7	8.40	0.09	0.00	0.00
Ag=0.5g	0.1	880.12	1216.95	938.34	777.85
V=600mm/s	0.2	309.23	465.02	216.07	200.09
	0.3	126.02	150.84	60.24	48.60
	0.4	59.72	53.28	17.11	10.84
	0.5	31.61	11.98	2.21	0.59
	0.6	18.21	1.20	0.00	0.00
	0.7	10.00	0.11	0.00	0.00
Ag=0.6g	0.1	1146.29	1583.82	1220.36	1014.45
V=750mm/s	0.2	404.64	604.46	281.15	261.04
	0.3	165.56	196.50	77.69	64.87
	0.4	78.64	69.43	21.92	15.19
	0.5	41.55	15.23	2.72	1.13
	0.6	24.15	1.56	0.00	0.00
	0.7	13.44	0.16	0.00	0.00
Ag=0.7g	0.1	1338.59	1846.94	1422.12	1185.51
V=875mm/s	0.2	474.44	704.09	327.85	305.17
	0.3	194.92	229.37	89.80	77.56
	0.4	92.81	81.08	25.14	18.99
	0.5	48.96	17.38	3.01	1.77
	0.6	28.72	1.82	0.00	0.07
	0.7	16.17	0.21	0.00	0.00

Table C.1.2.A

Kern County Earthquake, Taft Lincoln School. Newmark's Model
CIT File No. -- A004 kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	S69E	N69W
Ag=0.2g V=250mm/s	0.1	635.15	491.36	529.48	649.85
	0.2	213.26	175.10	181.05	224.34
	0.3	78.90	76.47	83.30	84.90
	0.4	26.93	29.85	38.93	41.72
	0.5	9.59	9.85	16.53	22.21
	0.6	3.30	1.66	5.77	11.23
	0.7	0.97	0.25	2.57	4.23
Ag=0.3g V=375mm/s	0.1	952.73	737.05	794.22	974.78
	0.2	319.89	262.65	271.57	336.51
	0.3	118.35	114.71	124.94	127.35
	0.4	40.39	44.76	58.39	62.58
	0.5	14.37	14.77	24.80	33.31
	0.6	4.94	2.49	8.65	16.84
	0.7	1.45	0.37	3.86	6.35
Ag=0.4g V=500mm/s	0.1	1270.31	982.73	1058.95	1299.70
	0.2	426.53	350.21	362.09	448.68
	0.3	157.80	152.94	166.59	169.81
	0.4	53.86	59.69	77.85	83.44
	0.5	19.17	19.70	33.07	44.41
	0.6	6.58	3.32	11.54	22.46
	0.7	1.94	0.48	5.15	8.46
Ag=0.5g V=600mm/s	0.1	1463.39	1132.10	1219.91	1497.26
	0.2	491.36	403.44	417.13	516.88
	0.3	181.78	176.18	191.91	195.62
	0.4	62.05	68.76	89.68	96.12
	0.5	22.08	22.69	38.10	51.16
	0.6	7.59	3.83	13.29	25.87
	0.7	2.23	0.56	5.93	9.75
Ag=0.6g V=750mm/s	0.1	1905.46	1474.08	1588.43	1949.55
	0.2	639.79	525.31	543.14	673.02
	0.3	236.70	229.40	249.88	254.71
	0.4	80.78	89.52	116.78	125.16
	0.5	28.76	29.55	49.60	66.61
	0.6	9.87	4.98	17.31	33.69
	0.7	2.91	0.73	7.72	12.70
Ag=0.7g V=875mm/s	0.1	2223.04	1719.77	1853.17	2274.48
	0.2	746.41	612.87	633.66	785.20
	0.3	276.14	267.64	291.54	297.16
	0.4	94.24	104.46	136.24	146.03
	0.5	33.54	34.47	57.87	77.72
	0.6	11.53	5.81	20.19	39.30
	0.7	3.39	0.85	9.01	14.81

Table C.1.2.B

Kern County Earthquake, Taft Lincoln School. Newmark's Model
CIT File No. -- A004 kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	S69E	N69W
Ag=0.2g V=250mm/s	0.1	634.42	493.12	525.80	654.26
	0.2	211.07	177.49	176.25	229.32
	0.3	77.52	78.93	79.44	89.48
	0.4	25.98	31.38	36.35	44.09
	0.5	8.32	11.30	14.87	23.80
	0.6	2.52	2.83	5.10	12.86
	0.7	0.75	0.51	2.14	5.64
Ag=0.3g V=375mm/s	0.1	951.22	741.06	786.00	984.89
	0.2	315.02	268.12	260.92	347.89
	0.3	115.35	120.40	116.60	137.86
	0.4	38.38	49.13	52.78	68.03
	0.5	11.58	18.28	21.19	37.05
	0.6	3.33	5.24	7.20	20.54
	0.7	0.99	1.00	2.89	9.57
Ag=0.4g V=500mm/s	0.1	1267.74	989.99	1044.42	1317.93
	0.2	417.99	360.10	343.46	469.20
	0.3	152.62	163.28	152.14	188.80
	0.4	50.48	68.39	68.27	93.31
	0.5	14.29	26.18	26.84	51.37
	0.6	4.01	8.37	9.05	29.09
	0.7	1.17	1.86	3.47	14.31
Ag=0.5g V=600mm/s	0.1	1459.91	1143.42	1199.08	1523.76
	0.2	479.32	418.00	390.72	546.90
	0.3	174.57	191.35	171.54	223.37
	0.4	57.42	82.70	76.30	110.72
	0.5	15.22	32.54	29.37	61.90
	0.6	4.25	11.52	9.84	35.54
	0.7	1.20	3.15	3.56	18.31
Ag=0.6g V=750mm/s	0.1	1901.29	1492.75	1556.08	1991.29
	0.2	621.07	549.08	502.49	720.88
	0.3	226.20	253.57	218.69	298.84
	0.4	73.90	112.90	96.39	148.59
	0.5	18.31	45.60	36.72	84.28
	0.6	5.11	17.74	12.07	48.98
	0.7	1.37	5.67	4.10	26.30
Ag=0.7g V=875mm/s	0.1	2218.65	1746.26	1809.50	2331.68
	0.2	722.01	646.42	579.55	851.48
	0.3	262.82	301.37	249.86	358.21
	0.4	85.32	138.02	109.15	178.73
	0.5	19.87	57.39	41.32	102.91
	0.6	5.53	23.98	13.25	60.34
	0.7	1.38	8.74	4.19	33.62

Table C.1.3.A

Eureka Earthquake, Eureka Federal Building
CIT File No. -- A008

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N11W	S11E	N79E	S79W
Ag=0.2g V=250mm/s	0.1	207.36	135.45	281.04	322.54
	0.2	58.58	31.47	138.82	117.81
	0.3	22.27	7.29	67.46	57.27
	0.4	8.74	0.70	35.04	30.44
	0.5	2.57	0.00	18.88	16.44
	0.6	0.18	0.00	8.80	7.83
	0.7	0.00	0.00	3.04	2.69
Ag=0.3g V=375mm/s	0.1	311.04	203.17	421.56	483.81
	0.2	87.87	47.22	208.23	176.72
	0.3	33.40	10.94	101.20	85.90
	0.4	13.11	1.06	52.56	45.66
	0.5	3.85	0.01	28.32	24.65
	0.6	0.28	0.00	13.20	11.74
	0.7	0.00	0.00	4.55	4.04
Ag=0.4g V=500mm/s	0.1	414.72	270.89	562.09	645.08
	0.2	117.17	62.95	277.64	235.63
	0.3	44.54	14.58	134.93	114.54
	0.4	17.47	1.41	70.08	60.87
	0.5	5.14	0.01	37.76	32.87
	0.6	0.37	0.00	17.60	15.65
	0.7	0.00	0.00	6.07	5.39
Ag=0.5g V=600mm/s	0.1	477.76	312.07	647.52	743.14
	0.2	134.98	72.52	319.84	271.45
	0.3	51.31	16.80	155.44	131.95
	0.4	20.13	1.62	80.73	70.12
	0.5	5.92	0.01	43.50	37.87
	0.6	0.43	0.00	20.28	18.03
	0.7	0.00	0.00	6.99	6.21
Ag=0.6g V=750mm/s	0.1	622.09	406.34	843.13	967.62
	0.2	175.75	94.42	416.46	353.45
	0.3	66.82	21.88	202.39	171.81
	0.4	26.20	2.12	105.12	91.31
	0.5	7.71	0.01	56.64	49.31
	0.6	0.55	0.00	26.40	23.48
	0.7	0.00	0.00	9.11	8.08
Ag=0.7g V=875mm/s	0.1	725.76	474.06	983.65	1128.90
	0.2	205.03	110.16	485.86	412.35
	0.3	77.94	25.53	236.13	200.44
	0.4	30.59	2.47	122.64	106.53
	0.5	8.99	0.01	66.07	57.52
	0.6	0.65	0.00	30.81	27.39
	0.7	0.00	0.00	10.63	9.43

Table C.1.3.B

Eureka Earthquake, Eureka Federal Building
CIT File No. -- A008

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N11W	S11E	N79E	S79W
Ag=0.2g V=250mm/s	0.1	206.02	136.75	281.49	321.73
	0.2	57.59	32.67	139.41	117.04
	0.3	21.64	7.42	67.44	56.84
	0.4	8.39	0.72	34.70	30.05
	0.5	2.41	0.00	18.55	16.23
	0.6	0.14	0.00	8.55	7.63
	0.7	0.00	0.00	2.88	2.57
Ag=0.3g V=375mm/s	0.1	308.01	206.11	422.59	481.99
	0.2	85.64	49.91	209.56	174.98
	0.3	32.01	11.22	101.14	84.93
	0.4	12.34	1.11	51.80	44.80
	0.5	3.50	0.00	27.59	24.21
	0.6	0.18	0.00	12.64	11.31
	0.7	0.00	0.00	4.21	3.76
Ag=0.4g V=500mm/s	0.1	409.35	276.14	563.91	641.84
	0.2	113.22	67.75	280.02	232.55
	0.3	42.07	15.10	134.84	112.82
	0.4	16.13	1.52	68.75	59.37
	0.5	4.51	0.00	36.47	32.11
	0.6	0.19	0.00	16.61	14.93
	0.7	0.00	0.00	5.47	4.90
Ag=0.5g V=600mm/s	0.1	470.03	319.63	650.16	738.48
	0.2	129.30	79.46	323.28	267.01
	0.3	47.78	17.56	155.32	129.49
	0.4	18.21	1.80	78.85	68.01
	0.5	5.02	0.00	41.65	36.80
	0.6	0.18	0.00	18.86	17.03
	0.7	0.00	0.00	6.16	5.52
Ag=0.6g V=750mm/s	0.1	610.08	418.18	847.27	960.36
	0.2	166.90	105.29	421.86	346.53
	0.3	61.33	23.08	202.24	167.98
	0.4	23.25	2.42	102.23	88.12
	0.5	6.32	0.00	53.77	47.67
	0.6	0.18	0.00	24.20	21.97
	0.7	0.00	0.00	7.85	7.02
Ag=0.7g V=875mm/s	0.1	709.49	490.21	989.30	1119.03
	0.2	193.04	124.99	493.25	402.96
	0.3	70.53	27.21	235.95	195.27
	0.4	26.60	2.92	118.78	102.31
	0.5	7.12	0.00	62.18	55.32
	0.6	0.15	0.00	27.82	25.39
	0.7	0.00	0.00	9.01	8.01

Table C.1.4.A

Eureka Earthquake, Ferndale City Hall
CIT File No. -- A009

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N44E	S44W	N46W	S46E
	0.1	673.46	555.86	367.70	261.11
	0.2	328.45	194.55	165.28	78.08
Ag=0.2g	0.3	165.19	85.07	78.11	31.12
	0.4	76.75	40.96	43.86	13.17
V=250mm/s	0.5	32.82	16.39	22.15	4.51
	0.6	7.22	3.98	13.13	1.62
	0.7	1.40	0.30	7.18	0.31
	0.1	1010.20	833.78	551.56	391.67
	0.2	492.66	291.82	247.92	117.12
Ag=0.3g	0.3	247.78	127.63	117.16	46.68
	0.4	115.13	61.44	65.79	19.76
V=375mm/s	0.5	49.21	24.59	33.22	6.77
	0.6	10.83	5.97	19.69	2.44
	0.7	2.09	0.46	10.78	0.46
	0.1	1346.93	1111.71	735.41	522.22
	0.2	656.90	389.09	330.56	156.16
Ag=0.4g	0.3	330.38	170.16	156.22	62.24
	0.4	153.51	81.92	87.73	26.35
V=500mm/s	0.5	65.62	32.78	44.30	9.03
	0.6	14.44	7.95	26.26	3.25
	0.7	2.78	0.62	14.37	0.62
	0.1	1551.66	1280.69	847.19	601.60
	0.2	756.75	448.23	380.81	179.90
Ag=0.5g	0.3	380.60	196.02	179.97	71.70
	0.4	176.84	94.37	101.06	30.36
V=600mm/s	0.5	75.58	37.77	51.03	10.40
	0.6	16.64	9.15	30.25	3.74
	0.7	3.20	0.71	16.55	0.71
	0.1	2020.39	1667.57	1103.11	783.34
	0.2	985.34	583.63	495.84	234.24
Ag=0.6g	0.3	495.57	255.24	234.33	93.36
	0.4	230.26	122.88	131.60	39.53
V=750mm/s	0.5	98.42	49.17	66.45	13.55
	0.6	21.67	11.91	39.39	4.88
	0.7	4.18	0.92	21.55	0.93
	0.1	2357.12	1945.50	1286.97	913.89
	0.2	1149.56	680.92	578.48	273.28
Ag=0.7g	0.3	578.14	297.77	273.38	108.91
	0.4	268.63	143.35	153.52	46.11
V=875mm/s	0.5	114.85	57.37	77.52	15.80
	0.6	25.28	13.93	45.95	5.68
	0.7	4.89	1.08	25.14	1.08

Table C.1.4.B

Eureka Earthquake, Ferndale City Hall
CIT File No. -- A009

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N44E	S44W	N46W	S46E
Ag=0.2g V=250mm/s	0.1	671.57	558.44	365.18	262.68
	0.2	325.77	196.29	163.07	79.87
	0.3	163.45	86.65	76.98	31.82
	0.4	75.62	42.75	42.70	13.59
	0.5	31.74	18.07	21.31	4.72
	0.6	6.78	5.17	12.44	1.66
	0.7	1.26	0.41	6.54	0.33
Ag=0.3g V=375mm/s	0.1	1005.95	839.64	545.90	395.21
	0.2	486.66	295.77	242.97	121.19
	0.3	243.92	131.18	114.65	48.28
	0.4	112.62	65.55	63.19	20.72
	0.5	46.80	28.43	31.35	7.27
	0.6	9.90	8.74	18.14	2.52
	0.7	1.79	0.71	9.34	0.52
Ag=0.4g V=500mm/s	0.1	1339.39	1122.17	725.38	528.53
	0.2	646.24	396.16	321.80	163.47
	0.3	323.58	176.54	151.80	65.13
	0.4	149.04	89.29	83.10	28.06
	0.5	61.35	39.69	40.98	9.95
	0.6	12.94	13.01	23.51	3.41
	0.7	2.27	1.08	11.83	0.72
Ag=0.5g V=600mm/s	0.1	1540.86	1295.81	832.78	610.70
	0.2	741.45	458.50	368.26	190.52
	0.3	370.91	205.25	173.64	75.96
	0.4	170.43	105.15	94.40	32.85
	0.5	69.48	47.83	46.28	11.77
	0.6	14.64	16.62	26.31	3.99
	0.7	2.46	1.43	12.92	0.86
Ag=0.6g V=750mm/s	0.1	2003.61	1691.25	1080.65	797.57
	0.2	961.55	599.88	476.34	251.02
	0.3	480.59	269.75	224.50	100.22
	0.4	220.29	140.00	121.20	43.46
	0.5	88.91	65.09	59.05	15.75
	0.6	18.71	23.86	33.26	5.27
	0.7	3.01	2.21	16.00	1.16
Ag=0.7g V=875mm/s	0.1	2334.39	1977.82	1256.50	933.30
	0.2	1117.31	703.29	552.06	296.38
	0.3	557.98	317.63	260.07	118.54
	0.4	255.11	166.96	139.39	51.52
	0.5	101.94	79.30	67.49	18.90
	0.6	21.67	30.50	37.65	6.25
	0.7	3.31	3.73	17.81	1.41

Table C.1.5.A

Long Beach Earthquake, Vernon CMD Building. Newmark's Model
CIT File No. -- B021 kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S08W	N08E	N82W	S82E
	0.1	256.77	306.06	192.12	194.87
	0.2	50.15	76.82	67.55	38.47
Ag=0.2g	0.3	20.64	21.05	22.21	9.77
	0.4	11.32	7.05	10.12	4.82
V=250mm/s	0.5	6.05	2.99	4.20	2.83
	0.6	2.83	0.98	1.16	1.45
	0.7	0.86	0.23	0.03	0.69
	0.1	385.15	459.08	288.18	292.31
	0.2	75.24	115.24	101.32	57.71
Ag=0.3g	0.3	30.95	31.58	33.31	14.65
	0.4	16.99	10.59	15.18	7.24
V=375mm/s	0.5	9.07	4.47	6.30	4.25
	0.6	4.26	1.49	1.74	2.17
	0.7	1.30	0.33	0.04	1.04
	0.1	513.54	612.11	384.24	389.75
	0.2	100.31	153.64	135.09	76.94
Ag=0.4g	0.3	41.27	42.11	44.42	19.54
	0.4	22.65	14.12	20.24	9.65
V=500mm/s	0.5	12.10	5.96	8.40	5.66
	0.6	5.68	1.99	2.33	2.89
	0.7	1.72	0.44	0.06	1.38
	0.1	591.59	705.16	442.65	448.99
	0.2	115.56	176.99	155.62	88.63
Ag=0.5g	0.3	47.55	48.51	51.17	22.51
	0.4	26.09	16.26	23.32	11.12
V=600mm/s	0.5	13.94	6.88	9.68	6.52
	0.6	6.54	2.29	2.68	3.33
	0.7	1.99	0.51	0.06	1.60
	0.1	770.31	918.18	576.36	584.62
	0.2	150.46	230.46	202.63	115.41
Ag=0.6g	0.3	61.89	63.18	66.63	29.31
	0.4	33.97	21.19	30.36	14.47
V=750mm/s	0.5	18.15	8.95	12.60	8.49
	0.6	8.53	2.99	3.49	4.34
	0.7	2.58	0.67	0.08	2.08
	0.1	898.68	1071.21	672.42	682.06
	0.2	175.53	268.88	236.41	134.65
Ag=0.7g	0.3	72.21	73.69	77.73	34.19
	0.4	39.63	24.70	35.41	16.88
V=875mm/s	0.5	21.15	10.44	14.70	9.91
	0.6	9.93	3.46	4.07	5.06
	0.7	3.02	0.77	0.10	2.42

Table C.1.5.B

Long Beach Earthquake, Vernon CMD Building. Newmark's Model
CIT File No. -- B021 kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S08W	N08E	N82W	S82E
	0.1	257.26	306.34	194.51	194.44
	0.2	50.64	76.12	69.29	38.83
Ag=0.2g	0.3	20.94	21.47	24.20	10.15
	0.4	11.62	7.24	10.73	5.22
V=250mm/s	0.5	6.28	3.36	4.55	3.21
	0.6	3.01	1.27	1.24	1.77
	0.7	0.93	0.19	0.03	0.87
	0.1	386.27	459.72	293.60	291.33
	0.2	76.33	113.69	105.25	58.55
Ag=0.3g	0.3	31.63	32.58	37.87	15.52
	0.4	17.67	11.04	16.60	8.14
V=375mm/s	0.5	9.62	5.45	7.12	5.11
	0.6	4.64	2.15	2.00	2.92
	0.7	1.46	0.33	0.05	1.45
	0.1	515.58	613.13	393.96	388.02
	0.2	102.28	151.04	142.11	78.51
Ag=0.4g	0.3	42.52	44.06	52.64	21.12
	0.4	23.90	15.37	22.85	11.27
V=500mm/s	0.5	13.10	7.86	9.93	7.23
	0.6	6.37	3.43	2.96	4.27
	0.7	2.02	0.81	0.10	2.15
	0.1	594.55	706.67	457.04	446.53
	0.2	118.41	173.74	165.77	90.99
Ag=0.5g	0.3	49.36	51.59	63.18	24.84
	0.4	27.92	18.39	27.21	13.46
V=600mm/s	0.5	15.40	9.81	12.02	8.81
	0.6	7.56	4.73	3.77	5.35
	0.7	2.43	1.39	0.23	2.77
	0.1	774.93	920.77	599.95	580.81
	0.2	154.96	225.95	218.56	119.23
Ag=0.6g	0.3	64.78	68.38	85.65	33.06
	0.4	36.91	24.95	36.66	18.17
V=750mm/s	0.5	20.50	13.80	16.45	12.11
	0.6	10.16	7.23	5.43	7.57
	0.7	3.29	2.85	0.53	4.13
	0.1	905.03	1075.04	706.63	665.77
	0.2	181.74	263.33	258.18	140.01
Ag=0.7g	0.3	76.19	81.31	103.95	39.50
	0.4	43.73	30.38	44.29	21.98
V=875mm/s	0.5	24.46	17.35	20.19	14.90
	0.6	12.26	9.69	6.98	9.56
	0.7	4.03	4.62	1.13	5.47

Table C.1.6.A

Lower California Earthquake,
Imperial Valley
CIT File No. -- B024

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S00W	N00E	S90W	N90E
Ag=0.2g V=250mm/s	0.1	1210.66	1047.54	1082.84	1247.30
	0.2	357.96	360.01	389.20	463.16
	0.3	147.84	143.81	136.28	223.97
	0.4	52.80	50.01	44.80	110.39
	0.5	17.68	16.48	13.78	51.25
	0.6	5.13	6.30	3.78	19.65
	0.7	0.85	1.56	0.96	6.41
Ag=0.3g V=375mm/s	0.1	1815.95	1571.31	1624.26	1870.95
	0.2	536.96	540.04	583.80	694.75
	0.3	221.76	215.71	204.42	335.96
	0.4	79.23	74.98	67.19	165.59
	0.5	26.53	24.72	20.67	76.88
	0.6	7.71	9.44	5.66	29.47
	0.7	1.27	2.30	1.44	9.62
Ag=0.4g V=500mm/s	0.1	2421.28	2095.04	2165.68	2494.60
	0.2	715.93	720.06	778.40	926.33
	0.3	295.68	287.62	272.56	447.94
	0.4	105.65	99.99	89.59	220.78
	0.5	35.37	32.96	27.56	102.51
	0.6	10.29	12.59	7.55	39.29
	0.7	1.70	3.08	1.92	12.83
Ag=0.5g V=600mm/s	0.1	2789.32	2413.50	2494.86	2873.78
	0.2	824.75	829.53	896.72	1067.13
	0.3	340.63	331.33	313.99	516.03
	0.4	121.70	115.19	103.21	254.34
	0.5	40.74	37.99	31.75	118.09
	0.6	11.85	14.50	8.70	45.26
	0.7	1.98	3.57	2.22	14.78
Ag=0.6g V=750mm/s	0.1	3631.94	3142.58	3248.52	3741.90
	0.2	1073.89	1080.11	1167.60	1389.49
	0.3	443.52	431.42	408.84	671.91
	0.4	158.49	150.00	134.38	331.17
	0.5	53.05	49.44	41.34	153.76
	0.6	15.46	18.89	11.33	58.94
	0.7	2.58	4.63	2.89	19.24
Ag=0.7g V=875mm/s	0.1	4237.27	3666.35	3789.94	4365.54
	0.2	1252.89	1260.10	1362.21	1621.08
	0.3	517.40	503.33	476.97	783.90
	0.4	184.87	175.00	156.78	386.37
	0.5	61.93	57.65	48.22	179.39
	0.6	18.00	22.07	13.22	68.77
	0.7	3.01	5.41	3.37	22.45

Table C.1.6.B

Lower California Earthquake,
Imperial Valley
CIT File No. -- B024

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S00W	N00E	S90W	N90E
Ag=0.2g	0.1	1209.46	1050.01	1087.75	1241.47
	0.2	355.52	362.77	395.16	458.33
	0.3	147.49	146.25	144.28	219.92
V=250mm/s	0.4	54.11	52.20	48.65	107.66
	0.5	17.79	17.65	16.63	50.46
	0.6	5.27	6.83	5.06	20.03
	0.7	0.74	1.56	1.64	6.91
Ag=0.3g	0.1	1813.30	1577.04	1635.71	1857.88
	0.2	531.69	547.29	597.28	684.02
	0.3	221.23	221.23	222.69	326.94
V=375mm/s	0.4	82.41	80.07	76.14	159.61
	0.5	26.81	27.48	27.29	75.16
	0.6	7.99	10.65	8.80	30.35
	0.7	0.99	2.41	3.01	10.75
Ag=0.4g	0.1	2416.58	2105.41	2186.41	2471.42
	0.2	707.12	733.93	802.48	907.44
	0.3	295.29	297.59	305.37	432.20
V=500mm/s	0.4	111.76	109.18	105.89	210.48
	0.5	35.97	38.20	39.79	99.54
	0.6	10.79	14.82	13.47	40.89
	0.7	1.20	3.25	4.79	14.85
Ag=0.5g	0.1	2782.57	2428.60	2525.06	2840.47
	0.2	812.80	850.50	931.56	1040.17
	0.3	340.60	345.90	361.61	493.71
V=600mm/s	0.4	130.90	128.85	127.17	239.97
	0.5	41.98	46.33	49.90	113.95
	0.6	12.59	17.83	17.71	47.61
	0.7	1.24	3.82	6.49	17.72
Ag=0.6g	0.1	3621.50	3166.42	3296.10	3689.95
	0.2	1056.06	1114.03	1222.28	1347.72
	0.3	444.54	454.62	483.77	637.53
V=750mm/s	0.4	173.34	171.96	172.88	309.47
	0.5	55.67	63.59	70.49	147.50
	0.6	16.62	24.30	26.40	62.66
	0.7	1.45	5.13	9.85	23.88
Ag=0.7g	0.1	4223.19	3699.07	3855.11	4295.00
	0.2	1229.79	1307.57	1437.21	1564.96
	0.3	520.16	535.55	579.62	737.74
V=875mm/s	0.4	205.84	205.70	210.57	357.83
	0.5	66.10	78.23	88.92	171.15
	0.6	19.66	29.64	35.09	73.90
	0.7	1.49	6.30	13.37	28.81

Table C.1.7.A

Western Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B029

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N04W	S04E	N86E	S86W
Ag=0.2g V=250mm/s	0.1	715.74	565.07	874.91	1031.66
	0.2	188.83	103.56	228.21	331.76
	0.3	54.29	20.74	60.18	125.67
	0.4	12.90	2.41	16.10	45.94
	0.5	1.74	0.00	3.37	20.51
	0.6	0.00	0.00	0.22	9.78
	0.7	0.00	0.00	0.00	4.82
Ag=0.3g V=375mm/s	0.1	1073.61	847.61	1312.37	1547.50
	0.2	283.25	155.36	342.32	497.63
	0.3	81.43	31.11	90.28	188.50
	0.4	19.34	3.63	24.15	68.91
	0.5	2.61	0.00	5.06	30.76
	0.6	0.00	0.00	0.33	14.66
	0.7	0.00	0.00	0.00	7.22
Ag=0.4g V=500mm/s	0.1	1431.47	1130.14	1749.83	2063.33
	0.2	377.66	207.14	456.42	663.51
	0.3	108.58	41.48	120.37	251.34
	0.4	25.79	4.84	32.19	91.88
	0.5	3.48	0.01	6.75	41.01
	0.6	0.00	0.00	0.44	19.55
	0.7	0.00	0.00	0.00	9.63
Ag=0.5g V=600mm/s	0.1	1649.06	1301.92	2015.80	2376.96
	0.2	435.07	238.62	525.80	764.36
	0.3	125.08	47.79	138.67	289.54
	0.4	29.71	5.57	37.08	105.85
	0.5	4.01	0.01	7.78	47.24
	0.6	0.00	0.00	0.51	22.52
	0.7	0.00	0.00	0.00	11.10
Ag=0.6g V=750mm/s	0.1	2147.21	1695.21	2624.74	3094.99
	0.2	566.50	310.71	684.63	995.27
	0.3	162.86	62.22	180.56	377.01
	0.4	38.69	7.26	48.28	137.82
	0.5	5.22	0.01	10.13	61.51
	0.6	0.00	0.00	0.66	29.32
	0.7	0.00	0.00	0.00	14.45
Ag=0.7g V=875mm/s	0.1	2505.09	1977.75	3062.20	3610.83
	0.2	660.92	362.49	798.74	1161.15
	0.3	190.01	72.60	210.65	439.84
	0.4	45.13	8.47	56.34	160.79
	0.5	6.08	0.01	11.80	71.77
	0.6	0.00	0.00	0.76	34.22
	0.7	0.00	0.00	0.00	16.86

Table C.1.7.B

Western Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B029

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N04W	S04E	N86E	S86W
Ag=0.2g V=250mm/s	0.1	714.42	566.51	876.49	1031.60
	0.2	186.55	104.25	228.83	331.68
	0.3	53.57	20.78	61.04	125.22
	0.4	12.64	2.49	16.59	44.79
	0.5	1.64	0.01	3.62	19.22
	0.6	0.00	0.00	0.20	8.84
	0.7	0.00	0.00	0.00	4.00
Ag=0.3g V=375mm/s	0.1	1070.67	851.24	1315.94	1547.44
	0.2	278.19	157.17	343.76	497.51
	0.3	79.87	31.24	92.25	187.55
	0.4	18.79	3.81	25.30	66.37
	0.5	2.38	0.02	5.67	27.90
	0.6	0.00	0.00	0.29	12.58
	0.7	0.00	0.00	0.00	5.40
Ag=0.4g V=500mm/s	0.1	1426.29	1137.02	1756.22	2063.32
	0.2	368.77	210.66	459.08	663.42
	0.3	105.87	41.75	123.98	249.73
	0.4	24.83	5.23	34.40	87.44
	0.5	3.10	0.03	7.90	35.99
	0.6	0.00	0.00	0.38	15.88
	0.7	0.00	0.00	0.00	6.44
Ag=0.5g V=600mm/s	0.1	1641.66	1308.64	2025.05	2377.06
	0.2	422.40	244.06	529.74	764.39
	0.3	121.30	48.27	144.10	287.36
	0.4	28.39	6.26	40.77	99.59
	0.5	3.50	0.05	9.54	40.11
	0.6	0.00	0.00	0.45	17.31
	0.7	0.00	0.00	0.00	6.56
Ag=0.6g V=750mm/s	0.1	2135.76	1707.03	2639.28	3095.35
	0.2	546.92	319.61	690.97	995.53
	0.3	157.13	63.27	189.33	373.79
	0.4	36.71	8.47	54.63	128.26
	0.5	4.46	0.09	13.30	50.52
	0.6	0.00	0.00	0.65	21.29
	0.7	0.00	0.00	0.00	7.63
Ag=0.7g V=875mm/s	0.1	2489.63	1995.15	3082.14	3611.54
	0.2	634.64	375.05	807.62	1161.78
	0.3	182.45	74.42	222.97	435.72
	0.4	42.57	10.26	65.59	148.08
	0.5	5.12	0.13	16.68	57.04
	0.6	0.00	0.00	0.87	23.42
	0.7	0.00	0.00	0.00	8.07

Table C.1.8.A

Puget Sound, Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B032

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S04E	N04W	S86W	N86E
Ag=0.2g V=250mm/s	0.1	328.27	382.88	571.49	702.64
	0.2	92.06	80.53	156.91	240.99
	0.3	33.24	19.39	53.36	86.34
	0.4	14.09	4.22	18.34	39.38
	0.5	3.96	0.33	6.65	20.94
	0.6	0.62	0.00	1.66	9.69
	0.7	0.00	0.00	0.37	3.73
Ag=0.3g V=375mm/s	0.1	492.40	574.33	857.23	1053.95
	0.2	138.09	120.79	235.37	361.49
	0.3	49.87	29.09	80.03	129.51
	0.4	21.14	6.33	27.51	59.06
	0.5	5.94	0.49	9.98	31.41
	0.6	0.92	0.00	2.48	14.54
	0.7	0.00	0.00	0.55	5.59
Ag=0.4g V=500mm/s	0.1	656.53	765.77	1142.97	1405.27
	0.2	184.13	161.06	313.82	481.99
	0.3	66.49	38.78	106.71	172.69
	0.4	28.19	8.44	36.68	78.75
	0.5	7.91	0.66	13.31	41.88
	0.6	1.24	0.00	3.31	19.38
	0.7	0.00	0.00	0.73	7.46
Ag=0.5g V=600mm/s	0.1	756.33	882.16	1316.71	1618.87
	0.2	212.11	185.54	361.52	555.25
	0.3	76.59	44.67	122.93	198.94
	0.4	32.47	9.72	42.26	90.72
	0.5	9.12	0.76	15.33	48.25
	0.6	1.42	0.00	3.81	22.33
	0.7	0.00	0.00	0.84	8.59
Ag=0.6g V=750mm/s	0.1	984.80	1148.65	1714.46	2107.91
	0.2	276.19	241.58	470.73	722.98
	0.3	99.73	58.16	160.07	259.04
	0.4	42.29	12.66	55.02	118.13
	0.5	11.87	0.99	19.97	62.82
	0.6	1.85	0.00	4.97	29.07
	0.7	0.00	0.00	1.10	11.18
Ag=0.7g V=875mm/s	0.1	1148.93	1340.09	2000.20	2459.22
	0.2	322.22	281.85	549.19	843.48
	0.3	116.35	67.86	186.75	302.20
	0.4	49.33	14.77	64.19	137.81
	0.5	13.85	1.15	23.29	73.30
	0.6	2.16	0.00	5.80	33.92
	0.7	0.00	0.00	1.28	13.05

Table C.1.8.B

Puget Sound, Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B032

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S04E	N04W	S86W	N86E
Ag=0.2g V=250mm/s	0.1	327.83	381.95	570.68	706.01
	0.2	92.27	80.12	156.49	245.11
	0.3	33.11	19.22	53.40	88.80
	0.4	13.90	4.22	18.55	40.59
	0.5	3.85	0.32	6.81	22.10
	0.6	0.64	0.00	1.79	10.47
	0.7	0.00	0.00	0.40	4.35
Ag=0.3g V=375mm/s	0.1	491.44	572.24	855.44	1061.57
	0.2	138.59	119.89	234.72	370.78
	0.3	49.62	28.78	80.16	135.24
	0.4	20.74	6.35	28.03	61.82
	0.5	5.73	0.52	10.34	34.02
	0.6	0.97	0.00	2.81	16.31
	0.7	0.00	0.00	0.63	7.00
Ag=0.4g V=500mm/s	0.1	654.86	762.08	1139.82	1418.84
	0.2	185.05	159.49	312.61	498.56
	0.3	66.17	38.31	106.97	183.08
	0.4	27.51	8.50	37.55	83.70
	0.5	7.59	0.77	13.96	46.55
	0.6	1.31	0.00	3.94	22.56
	0.7	0.00	0.00	0.87	9.99
Ag=0.5g V=600mm/s	0.1	754.55	876.94	1312.21	1638.48
	0.2	213.53	183.34	359.77	579.19
	0.3	76.26	44.09	123.35	214.13
	0.4	31.57	9.86	43.67	97.95
	0.5	8.73	1.00	16.29	55.00
	0.6	1.54	0.00	4.76	26.93
	0.7	0.00	0.00	1.04	12.28
Ag=0.6g V=750mm/s	0.1	981.95	1140.61	1707.50	2138.63
	0.2	278.55	238.23	468.03	760.52
	0.3	99.37	57.36	160.81	283.08
	0.4	40.99	12.94	57.41	129.58
	0.5	11.35	1.50	21.50	73.43
	0.6	2.04	0.00	6.50	36.68
	0.7	0.00	0.00	1.41	17.03
Ag=0.7g V=875mm/s	0.1	1145.02	1329.29	1990.82	2500.68
	0.2	325.63	277.38	545.60	894.75
	0.3	116.13	66.89	187.90	335.34
	0.4	47.73	15.25	67.64	153.61
	0.5	13.29	2.05	25.44	87.80
	0.6	2.42	0.00	7.93	44.85
	0.7	0.00	0.00	1.71	21.09

Table C.1.9.A

San Fernando Earthquake
8244, Orion Blvd., 1st floor
CIT File No. -- C048

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N00W	S00E	S90W	N80E
Ag=0.2g V=250mm/s	0.1	866.87	624.22	472.01	431.29
	0.2	267.83	225.35	76.84	73.79
	0.3	94.50	98.56	14.84	11.65
	0.4	35.23	47.47	2.57	0.93
	0.5	8.77	21.87	0.03	0.01
	0.6	0.90	9.22	0.00	0.00
	0.7	0.00	4.04	0.00	0.00
Ag=0.3g V=375mm/s	0.1	1300.30	936.33	708.02	646.93
	0.2	401.74	338.02	115.26	110.69
	0.3	141.75	147.84	22.26	17.48
	0.4	52.85	71.21	3.86	1.39
	0.5	13.15	32.81	0.05	0.02
	0.6	1.34	13.83	0.00	0.00
	0.7	0.00	6.06	0.00	0.00
Ag=0.4g V=500mm/s	0.1	1733.73	1248.44	944.03	862.58
	0.2	535.66	450.70	153.68	147.59
	0.3	189.00	197.12	29.68	23.31
	0.4	70.46	94.94	5.15	1.86
	0.5	17.54	43.74	0.06	0.03
	0.6	1.79	18.44	0.00	0.00
	0.7	0.00	8.08	0.00	0.00
Ag=0.5g V=600mm/s	0.1	1997.26	1438.20	1087.52	993.69
	0.2	617.08	519.20	177.04	170.02
	0.3	217.72	227.08	34.19	26.86
	0.4	81.17	109.37	5.93	2.14
	0.5	20.20	50.39	0.07	0.03
	0.6	2.06	21.24	0.00	0.00
	0.7	0.00	9.31	0.00	0.00
Ag=0.6g V=750mm/s	0.1	2600.60	1872.66	1416.04	1293.87
	0.2	803.48	676.04	230.52	221.38
	0.3	283.49	295.68	44.52	34.96
	0.4	105.69	142.41	7.72	2.78
	0.5	26.31	65.62	0.08	0.04
	0.6	2.69	27.66	0.00	0.00
	0.7	0.00	12.12	0.00	0.00
Ag=0.7g V=875mm/s	0.1	3034.03	2184.77	1652.05	1509.52
	0.2	937.40	788.72	268.94	258.27
	0.3	330.74	344.96	51.94	40.79
	0.4	123.31	166.15	9.01	3.25
	0.5	30.69	76.55	0.10	0.05
	0.6	3.14	32.27	0.00	0.00
	0.7	0.00	14.14	0.00	0.00

Table C.1.9.B

San Fernando Earthquake
8244, Orion Blvd., 1st floor
CIT File No. -- C048

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N00W	S00E	S90W	N80E
Ag=0.2g V=250mm/s	0.1	867.64	623.32	472.64	433.54
	0.2	265.78	227.63	76.22	75.33
	0.3	93.47	100.42	14.71	12.12
	0.4	34.93	48.57	2.80	1.09
	0.5	9.00	22.53	0.06	0.02
	0.6	0.71	9.42	0.00	0.00
	0.7	0.00	4.39	0.00	0.00
Ag=0.3g V=375mm/s	0.1	1302.36	934.49	710.81	652.54
	0.2	397.43	343.31	113.93	114.56
	0.3	139.62	152.12	22.08	18.74
	0.4	52.25	73.98	4.45	1.75
	0.5	13.81	34.51	0.18	0.03
	0.6	0.96	14.42	0.00	0.00
	0.7	0.00	6.91	0.00	0.00
Ag=0.4g V=500mm/s	0.1	1738.09	1245.52	950.40	873.25
	0.2	528.47	460.38	151.45	155.22
	0.3	185.68	204.90	29.59	25.80
	0.4	69.56	100.27	6.31	2.55
	0.5	18.90	47.01	0.37	0.05
	0.6	1.20	19.84	0.00	0.00
	0.7	0.00	9.65	0.00	0.00
Ag=0.5g V=600mm/s	0.1	2004.50	1434.49	1098.02	1009.97
	0.2	607.32	533.51	174.03	181.85
	0.3	213.63	238.52	34.39	30.71
	0.4	80.17	117.45	7.75	3.25
	0.5	22.44	55.43	0.60	0.07
	0.6	1.40	23.64	0.00	0.00
	0.7	0.00	11.62	0.00	0.00
Ag=0.6g V=750mm/s	0.1	2613.58	1868.79	1435.74	1320.65
	0.2	789.68	699.05	226.19	240.92
	0.3	278.84	314.05	45.26	41.36
	0.4	104.77	155.58	10.77	4.71
	0.5	30.17	74.08	1.13	0.12
	0.6	2.18	31.93	0.00	0.00
	0.7	0.00	15.81	0.00	0.00
Ag=0.7g V=875mm/s	0.1	3054.73	2182.10	1681.58	1547.58
	0.2	919.95	820.73	263.63	286.45
	0.3	327.03	370.57	53.48	49.96
	0.4	123.14	184.74	13.41	6.36
	0.5	36.49	88.86	1.90	0.21
	0.6	3.08	38.73	0.06	0.00
	0.7	0.00	19.24	0.00	0.00

Table C.1.10.A

San Fernando Earthquake
Old Ridge Route, Castaic
CIT File No. -- D056

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	N69W	S69E
Ag=0.2g V=250mm/s	0.1	349.16	352.43	1202.18	1272.41
	0.2	144.81	125.20	310.58	483.79
	0.3	61.47	64.49	78.68	212.53
	0.4	18.03	36.59	24.35	104.29
	0.5	1.29	19.74	3.73	45.79
	0.6	0.00	9.75	0.22	17.43
	0.7	0.00	4.86	0.00	4.18
Ag=0.3g V=375mm/s	0.1	523.75	528.64	1803.30	1908.62
	0.2	217.21	187.81	465.87	725.71
	0.3	92.20	96.73	118.04	318.80
	0.4	27.05	54.88	36.53	156.41
	0.5	1.93	29.61	5.57	68.66
	0.6	0.00	14.63	0.36	26.15
	0.7	0.00	7.29	0.00	6.25
Ag=0.4g V=500mm/s	0.1	698.33	704.85	2404.41	2544.83
	0.2	289.61	250.41	621.15	967.63
	0.3	122.94	128.98	157.40	425.07
	0.4	36.07	73.17	48.66	208.58
	0.5	2.58	39.48	7.46	91.57
	0.6	0.00	19.50	0.45	34.87
	0.7	0.00	9.73	0.00	8.36
Ag=0.5g V=600mm/s	0.1	804.47	811.99	2769.90	2931.61
	0.2	333.63	288.47	715.56	1114.70
	0.3	141.62	148.58	181.30	489.68
	0.4	41.55	84.29	56.08	240.26
	0.5	2.97	45.48	8.58	105.50
	0.6	0.00	22.47	0.54	40.17
	0.7	0.00	11.20	0.00	9.62
Ag=0.6g V=750mm/s	0.1	1047.49	1057.28	3606.59	3817.24
	0.2	434.42	375.61	931.69	1451.43
	0.3	184.41	193.47	236.08	637.60
	0.4	54.10	109.76	73.02	312.87
	0.5	3.87	59.22	11.19	137.36
	0.6	0.00	29.25	0.72	52.30
	0.7	0.00	14.59	0.00	12.54
Ag=0.7g V=875mm/s	0.1	1222.07	1233.49	4207.71	4453.45
	0.2	506.82	438.21	1086.97	1693.35
	0.3	215.14	225.71	275.44	743.87
	0.4	63.11	128.05	85.19	364.99
	0.5	4.51	69.09	13.03	160.23
	0.6	0.00	34.13	0.81	61.06
	0.7	0.00	17.02	0.00	14.60

Table C.1.10.B

San Fernando Earthquake
Old Ridge Route, Castaic
CIT File No. -- D056

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	N69W	S69E
Ag=0.2g V=250mm/s	0.1	350.13	350.36	1197.20	1277.81
	0.2	146.02	123.15	306.58	489.68
	0.3	62.39	63.49	79.44	218.06
	0.4	18.77	36.03	25.88	109.19
	0.5	1.65	20.02	4.13	48.08
	0.6	0.00	10.44	0.18	18.69
	0.7	0.00	5.67	0.00	5.12
Ag=0.3g V=375mm/s	0.1	525.94	524.00	1792.60	1920.75
	0.2	220.01	183.13	457.10	738.97
	0.3	94.71	94.57	120.20	331.34
	0.4	28.76	53.82	40.13	167.60
	0.5	3.08	30.32	6.61	74.27
	0.6	0.00	16.33	0.31	29.12
	0.7	0.00	9.12	0.00	8.99
Ag=0.4g V=500mm/s	0.1	702.41	696.64	2385.94	2566.48
	0.2	294.68	242.38	606.24	991.22
	0.3	127.83	125.25	161.89	447.71
	0.4	39.22	71.52	55.27	228.62
	0.5	5.18	40.88	9.48	102.72
	0.6	0.37	22.70	0.67	40.39
	0.7	0.00	13.01	0.00	13.97
Ag=0.5g V=600mm/s	0.1	810.45	800.22	2743.74	2962.88
	0.2	341.06	277.44	694.84	1148.80
	0.3	149.06	143.46	188.40	522.71
	0.4	46.34	82.21	66.55	269.91
	0.5	7.55	47.81	11.46	122.94
	0.6	1.14	27.23	1.26	48.53
	0.7	0.00	15.99	0.00	18.60
Ag=0.6g V=750mm/s	0.1	1057.48	1039.01	3570.38	3866.22
	0.2	446.19	359.01	900.28	1504.90
	0.3	196.49	185.77	247.90	689.77
	0.4	61.92	106.89	91.62	361.31
	0.5	12.32	63.27	19.01	166.39
	0.6	2.74	36.88	2.29	66.23
	0.7	0.01	22.15	0.00	27.72
Ag=0.7g V=875mm/s	0.1	1236.34	1208.77	4158.28	4520.31
	0.2	523.08	416.30	1045.59	1766.32
	0.3	232.10	215.59	292.29	815.67
	0.4	74.22	124.60	112.92	433.20
	0.5	17.72	75.04	27.27	201.88
	0.6	4.98	44.71	3.50	82.00
	0.7	0.71	27.41	0.00	36.71

Table C.1.11.A

San Fernando Earthquake
Griffith Park Observatory
CIT File No. -- 0198

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S00W	N00E	S90W	N90E
	0.1	233.78	299.10	368.79	404.39
	0.2	98.19	103.23	130.02	173.51
Ag=0.2g	0.3	48.97	39.47	48.01	68.79
	0.4	24.18	19.62	16.85	27.05
V=250mm/s	0.5	13.22	11.32	5.55	9.90
	0.6	7.21	6.26	1.48	3.15
	0.7	3.85	2.93	0.25	0.68
	0.1	350.67	448.65	553.19	606.59
	0.2	147.28	154.84	195.04	260.27
Ag=0.3g	0.3	73.45	59.21	72.01	103.18
	0.4	36.28	29.44	25.27	40.58
V=375mm/s	0.5	19.82	16.99	8.32	14.86
	0.6	10.82	9.39	2.22	4.73
	0.7	5.77	4.40	0.37	1.03
	0.1	467.56	598.20	737.59	808.78
	0.2	196.37	206.46	260.05	347.02
Ag=0.4g	0.3	97.94	78.95	96.01	137.58
	0.4	48.37	39.25	33.69	54.10
V=500mm/s	0.5	26.43	22.65	11.10	19.81
	0.6	14.42	12.52	2.96	6.30
	0.7	7.69	5.87	0.50	1.37
	0.1	538.63	689.12	849.70	931.72
	0.2	226.22	237.84	299.58	399.77
Ag=0.5g	0.3	112.82	90.95	110.61	158.49
	0.4	55.72	45.21	38.81	62.32
V=600mm/s	0.5	30.45	26.09	12.78	22.82
	0.6	16.62	14.43	3.41	7.26
	0.7	8.86	6.76	0.57	1.58
	0.1	701.34	897.29	1106.38	1213.17
	0.2	294.56	309.69	390.07	520.53
Ag=0.6g	0.3	146.91	118.42	144.02	206.37
	0.4	72.55	58.87	50.54	81.15
V=750mm/s	0.5	39.65	33.97	16.64	29.71
	0.6	21.63	18.79	4.44	9.45
	0.7	11.54	8.80	0.75	2.05
	0.1	818.23	1046.84	1290.78	1415.37
	0.2	343.65	361.30	455.09	607.28
Ag=0.7g	0.3	171.39	138.16	168.02	240.76
	0.4	84.65	68.68	58.96	94.67
V=875mm/s	0.5	46.26	39.64	19.42	34.66
	0.6	25.24	21.92	5.18	11.03
	0.7	13.46	10.27	0.87	2.40

Table C.1.11.B

San Fernando Earthquake
Griffith Park Observatory
CIT File No. -- 0198

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S00W	N00E	S90W	N90E
Ag=0.2g V=250mm/s	0.1	233.82	298.89	369.41	403.89
	0.2	98.48	102.52	130.49	173.31
	0.3	49.61	39.47	48.56	69.10
	0.4	24.73	19.47	16.99	27.60
	0.5	13.42	10.76	5.44	10.68
	0.6	7.43	5.75	1.39	3.54
	0.7	4.03	2.69	0.18	0.79
Ag=0.3g V=375mm/s	0.1	350.86	448.10	554.59	605.51
	0.2	148.05	153.29	196.11	259.92
	0.3	74.93	59.27	73.31	104.05
	0.4	37.59	29.20	25.64	42.03
	0.5	20.31	15.77	8.17	16.72
	0.6	11.31	8.25	2.05	5.64
	0.7	6.18	3.86	0.22	1.27
Ag=0.4g V=500mm/s	0.1	468.02	597.16	740.10	806.90
	0.2	197.88	203.79	261.98	346.53
	0.3	100.62	79.27	98.40	139.31
	0.4	50.82	38.99	34.44	57.02
	0.5	27.42	20.55	10.98	23.31
	0.6	15.30	10.52	2.71	7.96
	0.7	8.43	4.92	0.25	1.82
Ag=0.5g V=600mm/s	0.1	539.40	687.59	853.36	929.05
	0.2	228.56	234.11	302.41	399.18
	0.3	116.75	91.73	114.17	161.20
	0.4	59.38	45.03	40.03	67.03
	0.5	32.05	23.15	12.94	28.07
	0.6	17.93	11.57	3.17	9.73
	0.7	9.94	5.41	0.28	2.41
Ag=0.6g V=750mm/s	0.1	702.69	894.89	1112.16	1209.08
	0.2	298.42	304.04	394.56	519.77
	0.3	153.20	120.08	149.85	210.87
	0.4	78.47	58.82	52.64	89.13
	0.5	42.46	29.50	17.34	38.24
	0.6	23.79	14.38	4.23	13.61
	0.7	13.24	6.71	0.38	3.61
Ag=0.7g V=875mm/s	0.1	820.23	1043.58	1298.70	1409.89
	0.2	349.23	353.86	461.29	606.43
	0.3	180.16	140.96	176.44	247.24
	0.4	92.95	68.89	62.10	106.25
	0.5	50.46	33.70	20.85	46.73
	0.6	28.40	16.26	5.08	17.10
	0.7	15.79	7.45	0.51	4.80

Table C.1.12.A

Imperial Valley Earthquake, 1979
Station 7

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
Ag=0.2g V=250mm/s	0.1	194.94	204.96	47.21	38.86
	0.2	93.43	72.38	14.02	9.35
	0.3	41.44	22.44	5.71	3.84
	0.4	21.29	11.92	2.37	1.66
	0.5	12.90	6.37	0.97	0.62
	0.6	7.71	3.09	0.26	0.10
	0.7	4.14	1.24	0.01	0.00
Ag=0.3g V=375mm/s	0.1	292.41	307.45	70.82	58.29
	0.2	140.14	108.57	21.03	14.03
	0.3	62.15	33.66	8.57	5.76
	0.4	31.93	17.89	3.56	2.49
	0.5	19.34	9.55	1.46	0.93
	0.6	11.57	4.64	0.39	0.15
	0.7	6.21	1.87	0.01	0.00
Ag=0.4g V=500mm/s	0.1	389.88	409.93	94.42	77.73
	0.2	186.86	144.76	28.04	18.70
	0.3	82.87	44.88	11.42	7.68
	0.4	42.57	23.85	4.75	3.32
	0.5	25.79	12.73	1.95	1.24
	0.6	15.42	6.19	0.52	0.20
	0.7	8.28	2.49	0.01	0.00
Ag=0.5g V=600mm/s	0.1	449.15	472.24	108.78	89.54
	0.2	215.26	166.77	32.30	21.54
	0.3	95.47	51.71	13.16	8.85
	0.4	49.04	27.47	5.47	3.83
	0.5	29.71	14.67	2.24	1.43
	0.6	17.77	7.13	0.59	0.23
	0.7	9.54	2.87	0.01	0.00
Ag=0.6g V=750mm/s	0.1	584.83	614.89	141.64	116.59
	0.2	280.29	217.14	42.05	28.05
	0.3	124.31	67.33	17.13	11.53
	0.4	63.86	35.77	7.12	4.98
	0.5	38.69	19.10	2.92	1.86
	0.6	23.13	9.28	0.77	0.30
	0.7	12.42	3.73	0.02	0.00
Ag=0.7g V=875mm/s	0.1	682.30	717.37	165.24	136.02
	0.2	327.00	253.33	49.06	32.72
	0.3	145.02	78.55	19.99	13.45
	0.4	74.50	41.73	8.31	5.81
	0.5	45.14	22.28	3.41	2.18
	0.6	26.99	10.83	0.90	0.35
	0.7	14.50	4.36	0.02	0.00

Table C.1.12.B

Imperial Valley Earthquake, 1979
Station 7

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
Ag=0.2g V=250mm/s	0.1	194.74	205.65	47.42	39.00
	0.2	93.07	73.14	14.13	9.31
	0.3	41.07	22.36	5.82	3.76
	0.4	21.37	11.79	2.46	1.60
	0.5	13.09	6.31	1.04	0.59
	0.6	7.84	3.07	0.32	0.09
	0.7	4.22	1.25	0.02	0.00
Ag=0.3g V=375mm/s	0.1	291.97	308.99	71.29	58.61
	0.2	139.33	110.28	21.28	13.93
	0.3	61.33	33.48	8.81	5.58
	0.4	32.14	17.58	3.76	2.34
	0.5	19.79	9.41	1.60	0.86
	0.6	11.85	4.58	0.53	0.13
	0.7	6.40	1.89	0.05	0.00
Ag=0.4g V=500mm/s	0.1	389.10	412.68	95.27	78.30
	0.2	185.42	147.81	28.50	18.54
	0.3	81.41	44.56	11.85	7.36
	0.4	42.97	23.34	5.11	3.06
	0.5	26.59	12.49	2.20	1.12
	0.6	15.93	6.09	0.78	0.18
	0.7	8.62	2.53	0.10	0.00
Ag=0.5g V=600mm/s	0.1	448.03	476.21	110.01	90.37
	0.2	213.19	171.17	32.96	21.31
	0.3	93.37	51.25	13.78	8.40
	0.4	49.64	26.78	6.01	3.45
	0.5	30.88	14.32	2.61	1.26
	0.6	18.52	7.03	0.98	0.20
	0.7	10.05	2.94	0.17	0.00
Ag=0.6g V=750mm/s	0.1	583.09	621.11	143.59	117.90
	0.2	277.06	224.04	43.10	27.68
	0.3	121.06	66.61	18.12	10.82
	0.4	64.96	34.73	7.98	4.40
	0.5	40.60	18.56	3.49	1.60
	0.6	24.38	9.16	1.38	0.26
	0.7	13.26	3.85	0.29	0.00
Ag=0.7g V=875mm/s	0.1	679.96	725.93	167.93	137.82
	0.2	322.62	262.75	50.49	32.24
	0.3	140.63	77.58	21.34	12.50
	0.4	76.20	40.35	9.49	5.05
	0.5	47.82	21.57	4.20	1.82
	0.6	28.75	10.71	1.75	0.30
	0.7	15.66	4.52	0.43	0.00

Table C.1.13.A

Imperial Valley Earthquake, 1979
Station 10

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N50E	S50W	N40W	S40E
Ag=0.2g V=250mm/s	0.1	280.84	159.50	236.94	261.46
	0.2	112.48	42.91	74.48	117.91
	0.3	43.87	16.31	28.28	57.14
	0.4	11.81	6.08	12.90	32.77
	0.5	1.29	2.36	4.67	18.85
	0.6	0.07	0.78	1.37	10.11
	0.7	0.00	0.04	0.34	4.46
Ag=0.3g V=375mm/s	0.1	421.27	239.25	355.42	392.19
	0.2	168.73	64.35	111.72	176.87
	0.3	65.80	24.45	42.42	85.71
	0.4	17.72	9.12	19.35	49.16
	0.5	1.93	3.56	7.00	28.28
	0.6	0.11	1.17	2.06	15.16
	0.7	0.00	0.05	0.51	6.68
Ag=0.4g V=500mm/s	0.1	561.69	319.01	473.89	522.92
	0.2	224.97	85.80	148.97	235.82
	0.3	87.73	32.61	56.56	114.28
	0.4	23.62	12.15	25.80	65.55
	0.5	2.57	4.74	9.33	37.71
	0.6	0.15	1.56	2.75	20.22
	0.7	0.00	0.06	0.68	8.91
Ag=0.5g V=600mm/s	0.1	647.06	367.50	545.92	602.41
	0.2	259.17	98.84	171.61	271.67
	0.3	101.06	37.57	65.15	131.65
	0.4	27.22	14.01	29.72	75.51
	0.5	2.96	5.46	10.75	43.44
	0.6	0.17	1.79	3.17	23.29
	0.7	0.00	0.07	0.78	10.26
Ag=0.6g V=750mm/s	0.1	842.53	478.51	710.83	784.39
	0.2	337.45	128.71	223.45	353.73
	0.3	131.60	48.92	84.83	171.42
	0.4	35.43	18.24	38.70	98.32
	0.5	3.86	7.11	14.00	56.56
	0.6	0.22	2.34	4.12	30.33
	0.7	0.00	0.10	1.01	13.37
Ag=0.7g V=875mm/s	0.1	982.96	558.26	829.30	915.12
	0.2	393.69	150.16	260.69	412.69
	0.3	153.53	57.06	98.97	199.99
	0.4	41.35	21.27	45.15	114.71
	0.5	4.51	8.29	16.33	65.99
	0.6	0.26	2.73	4.81	35.38
	0.7	0.00	0.11	1.18	15.59

Table C.1.13.B

Imperial Valley Earthquake, 1979
Station 10

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N50E	S50W	N40W	S40E
	0.1	280.13	157.16	236.99	261.59
	0.2	111.67	42.88	74.61	117.54
Ag=0.2g	0.3	43.24	16.49	28.46	56.72
	0.4	11.10	6.08	12.94	32.17
V=250mm/s	0.5	1.22	2.28	4.67	18.38
	0.6	0.04	0.67	1.38	9.54
	0.7	0.00	0.04	0.28	4.05
	0.1	419.65	233.98	355.52	392.49
	0.2	166.90	64.34	112.02	176.04
Ag=0.3g	0.3	64.38	24.90	42.83	84.82
	0.4	16.13	9.20	19.46	47.82
V=375mm/s	0.5	1.78	3.38	7.00	27.23
	0.6	0.05	0.91	2.08	13.89
	0.7	0.00	0.05	0.39	5.81
	0.1	558.83	309.64	474.09	523.47
	0.2	221.76	85.80	149.37	234.45
Ag=0.4g	0.3	85.23	33.45	57.30	112.76
	0.4	20.82	12.38	26.00	63.20
V=500mm/s	0.5	2.32	4.44	9.34	35.90
	0.6	0.06	1.15	2.78	17.98
	0.7	0.00	0.06	0.47	7.43
	0.1	642.97	354.03	546.22	603.21
	0.2	254.61	98.88	172.43	269.81
Ag=0.5g	0.3	97.47	38.82	66.25	129.52
	0.4	23.20	14.43	30.03	72.18
V=600mm/s	0.5	2.61	5.05	10.76	40.88
	0.6	0.07	1.26	3.23	20.14
	0.7	0.00	0.07	0.50	8.21
	0.1	836.17	457.51	711.32	785.67
	0.2	330.43	128.81	224.98	350.99
Ag=0.6g	0.3	126.00	50.94	86.59	168.16
	0.4	29.21	19.00	39.20	93.20
V=750mm/s	0.5	3.32	6.51	14.04	52.61
	0.6	0.11	1.56	4.24	25.51
	0.7	0.00	0.11	0.66	10.26
	0.1	974.58	529.70	829.99	916.89
	0.2	384.25	150.39	263.01	409.11
Ag=0.7g	0.3	145.96	59.91	101.43	195.64
	0.4	32.94	22.45	45.85	107.83
V=875mm/s	0.5	3.79	7.56	16.42	60.68
	0.6	0.16	1.76	4.98	28.95
	0.7	0.00	0.13	0.81	11.51

Table C.1.14.A

Imperial Valley Earthquake, 1979
Bonds Corner

Newmark's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
Ag=0.2g V=250mm/s	0.1	763.76	732.58	408.94	643.07
	0.2	326.24	280.59	108.03	242.61
	0.3	161.82	112.93	32.21	96.40
	0.4	79.86	48.54	9.34	35.82
	0.5	40.55	19.51	1.88	13.39
	0.6	21.24	5.18	0.06	4.32
	0.7	9.62	0.44	0.00	0.57
Ag=0.3g V=375mm/s	0.1	1145.64	1098.86	613.42	964.61
	0.2	489.35	420.89	162.05	363.91
	0.3	242.73	169.39	48.32	144.59
	0.4	119.79	72.82	14.02	53.73
	0.5	60.82	29.27	2.83	20.09
	0.6	31.86	7.76	0.08	6.48
	0.7	14.43	0.66	0.00	0.86
Ag=0.4g V=500mm/s	0.1	1527.52	1465.15	817.89	1286.14
	0.2	652.47	561.18	216.06	485.21
	0.3	323.64	225.85	64.42	192.79
	0.4	159.72	97.09	18.68	71.64
	0.5	81.10	39.02	3.77	26.79
	0.6	42.47	10.35	0.11	8.64
	0.7	19.23	0.89	0.00	1.14
Ag=0.5g V=600mm/s	0.1	1759.70	1687.86	942.20	1481.63
	0.2	751.65	646.48	248.90	558.97
	0.3	372.83	260.18	74.21	222.09
	0.4	184.00	111.85	21.53	82.53
	0.5	93.43	44.95	4.34	30.86
	0.6	48.93	11.92	0.13	9.95
	0.7	22.16	1.02	0.00	1.31
Ag=0.6g V=750mm/s	0.1	2291.28	2197.73	1226.83	1929.21
	0.2	978.70	841.77	324.09	727.82
	0.3	485.46	338.78	96.63	289.19
	0.4	239.58	145.63	28.02	107.46
	0.5	121.65	58.53	5.66	40.18
	0.6	63.71	15.53	0.17	12.96
	0.7	28.85	1.33	0.00	1.71
Ag=0.7g V=875mm/s	0.1	2673.16	2564.02	1431.30	2250.75
	0.2	1141.82	982.07	378.10	849.12
	0.3	566.37	395.24	112.74	337.38
	0.4	279.52	169.91	32.70	125.37
	0.5	141.92	68.29	6.60	46.87
	0.6	74.33	18.12	0.20	15.12
	0.7	33.66	1.55	0.00	1.99

TaBle C.1.14.B

Imperial Valley Earthquake, 1979
Bonds Corner

Newmark's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
Ag=0.2g V=250mm/s	0.1	764.29	732.65	407.59	644.09
	0.2	326.26	280.02	108.04	243.40
	0.3	162.40	113.29	32.25	97.16
	0.4	80.55	49.15	9.46	36.27
	0.5	41.37	19.96	2.04	13.45
	0.6	21.90	5.75	0.08	4.31
	0.7	10.35	0.89	0.00	0.59
Ag=0.3g V=375mm/s	0.1	1146.83	1099.05	610.46	966.90
	0.2	489.47	419.64	162.12	365.77
	0.3	244.09	170.27	48.46	146.34
	0.4	121.38	74.25	14.30	54.77
	0.5	62.73	30.35	3.17	20.24
	0.6	33.40	9.09	0.15	6.48
	0.7	16.09	1.73	0.00	0.92
Ag=0.4g V=500mm/s	0.1	1529.65	1465.48	812.74	1290.22
	0.2	652.77	559.07	216.26	488.62
	0.3	326.12	227.48	64.74	196.00
	0.4	162.63	99.75	19.22	73.50
	0.5	84.57	41.11	4.38	27.06
	0.6	45.31	12.86	0.23	8.67
	0.7	22.19	2.89	0.00	1.28
Ag=0.5g V=600mm/s	0.1	1762.80	1688.36	934.93	1487.55
	0.2	752.22	643.59	249.26	563.97
	0.3	376.48	262.61	74.75	226.84
	0.4	188.39	115.80	22.34	85.24
	0.5	98.61	48.15	5.24	31.27
	0.6	53.11	15.67	0.31	10.05
	0.7	26.43	4.04	0.00	1.53
Ag=0.6g V=750mm/s	0.1	2296.14	2198.62	1215.66	1938.57
	0.2	979.84	837.43	324.77	735.82
	0.3	491.31	342.73	97.58	296.85
	0.4	246.76	151.97	29.35	111.73
	0.5	130.21	63.76	7.12	40.93
	0.6	70.46	21.54	0.48	13.23
	0.7	35.65	6.22	0.00	2.07
Ag=0.7g V=875mm/s	0.1	2679.81	2565.45	1416.31	2263.64
	0.2	1143.66	976.34	379.18	860.34
	0.3	574.66	400.83	114.16	348.12
	0.4	289.69	178.71	34.59	131.23
	0.5	154.09	75.86	8.68	48.04
	0.6	83.87	26.49	0.67	15.71
	0.7	43.12	8.44	0.00	2.51

Section C2

Computed Relative Displacements

using Zarrabi's Model

Table C.2.1.A

El Centro Earthquake, Imperial Valley
CIT File No. -- A001

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S00E	N00E	S90W	S90E
Ag=0.2g V=250mm/s	0.1	271.64	374.68	287.55	235.17
	0.2	96.76	146.84	68.08	61.79
	0.3	39.27	47.45	20.18	13.82
	0.4	19.15	17.39	6.29	2.29
	0.5	10.29	4.56	1.00	0.02
	0.6	5.75	0.42	0.02	0.00
	0.7	2.96	0.03	0.00	0.00
Ag=0.3g V=375mm/s	0.1	421.12	578.51	442.04	361.54
	0.2	152.21	228.60	105.71	95.91
	0.3	62.19	74.66	31.64	21.62
	0.4	30.56	27.54	9.94	3.62
	0.5	16.53	7.28	1.59	0.02
	0.6	9.29	0.68	0.02	0.00
	0.7	4.81	0.05	0.00	0.00
Ag=0.4g V=500mm/s	0.1	580.00	793.70	603.92	493.95
	0.2	212.25	315.91	145.77	132.18
	0.3	87.18	104.12	44.02	30.04
	0.4	43.06	38.60	13.91	5.07
	0.5	23.38	10.25	2.23	0.03
	0.6	13.16	0.97	0.02	0.00
	0.7	6.82	0.07	0.00	0.00
Ag=0.5g V=600mm/s	0.1	689.49	940.24	712.56	582.85
	0.2	254.88	376.53	173.41	157.19
	0.3	105.05	125.01	52.72	35.93
	0.4	52.02	46.51	16.76	6.11
	0.5	28.27	12.39	2.70	0.03
	0.6	15.90	1.17	0.03	0.00
	0.7	8.22	0.08	0.00	0.00
Ag=0.6g V=750mm/s	0.1	925.12	1257.87	949.79	776.97
	0.2	344.64	506.25	232.83	210.93
	0.3	142.28	168.96	71.16	48.47
	0.4	70.45	62.97	22.69	8.25
	0.5	38.21	16.78	3.65	0.05
	0.6	21.41	1.57	0.03	0.00
	0.7	11.00	0.11	0.00	0.00
Ag=0.7g V=875mm/s	0.1	1110.30	1506.13	1133.62	927.40
	0.2	415.84	608.48	279.60	253.18
	0.3	171.64	203.74	85.76	58.39
	0.4	84.79	75.94	27.37	9.95
	0.5	45.77	20.18	4.40	0.07
	0.6	25.47	1.88	0.05	0.00
	0.7	12.94	0.12	0.00	0.00

Table C.2.1.B

El Centro Earthquake, Imperial Valley
CIT File No. -- A001

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S00E	N00E	S90W	S90E
Ag=0.2g V=250mm/s	0.1	271.95	374.32	286.83	235.89
	0.2	97.59	146.32	67.67	61.99
	0.3	39.97	48.42	19.76	14.42
	0.4	19.40	17.39	5.99	2.77
	0.5	10.46	4.32	0.88	0.03
	0.6	5.96	0.42	0.00	0.00
	0.7	3.19	0.03	0.00	0.00
Ag=0.3g V=375mm/s	0.1	421.92	577.66	440.37	363.31
	0.2	154.28	227.41	104.81	96.41
	0.3	63.87	76.18	30.69	23.00
	0.4	31.19	27.56	9.25	4.75
	0.5	16.97	6.72	1.33	0.07
	0.6	9.81	0.66	0.00	0.00
	0.7	5.35	0.05	0.00	0.00
Ag=0.4g V=500mm/s	0.1	581.68	792.20	600.87	497.37
	0.2	216.25	313.75	144.19	133.21
	0.3	90.35	106.28	42.26	32.79
	0.4	44.33	38.65	12.65	7.22
	0.5	24.22	9.25	1.75	0.26
	0.6	14.17	0.94	0.00	0.00
	0.7	7.85	0.08	0.00	0.00
Ag=0.5g V=600mm/s	0.1	692.34	938.08	708.12	588.15
	0.2	261.06	373.42	171.48	158.84
	0.3	109.87	127.67	50.14	40.27
	0.4	54.05	46.60	14.88	9.40
	0.5	29.58	10.92	2.00	0.54
	0.6	17.45	1.13	0.00	0.00
	0.7	9.78	0.11	0.00	0.00
Ag=0.6g V=750mm/s	0.1	929.82	1254.50	942.74	785.68
	0.2	354.92	501.38	230.20	213.84
	0.3	150.18	172.68	67.01	55.72
	0.4	74.03	63.16	19.82	13.70
	0.5	40.37	14.45	2.57	1.06
	0.6	23.94	1.53	0.00	0.00
	0.7	13.51	0.16	0.00	0.00
Ag=0.7g V=875mm/s	0.1	1117.79	1501.67	1123.91	940.32
	0.2	430.59	601.94	276.44	257.55
	0.3	182.88	208.41	80.01	68.88
	0.4	90.14	76.27	23.52	17.74
	0.5	48.85	17.01	2.93	1.72
	0.6	29.03	1.83	0.00	0.07
	0.7	16.40	0.21	0.00	0.00

Table C.2.2.A

Kern County Earthquake, Taft Lincoln School. Zarrabi's Model
CIT File No. -- A004 kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	S69E	N69W
Ag=0.2g V=250mm/s	0.1	448.69	346.46	375.80	461.58
	0.2	155.22	126.40	131.50	163.08
	0.3	58.35	56.43	61.86	63.60
	0.4	20.41	22.52	29.56	31.78
	0.5	7.44	7.60	12.84	17.25
	0.6	2.61	1.31	4.60	8.89
	0.7	0.79	0.19	2.09	3.41
Ag=0.3g V=375mm/s	0.1	692.92	533.88	580.90	715.37
	0.2	242.65	196.86	205.44	255.69
	0.3	91.81	88.70	97.52	100.63
	0.4	32.41	35.71	46.99	50.57
	0.5	11.91	12.15	20.57	27.64
	0.6	4.21	2.11	7.42	14.33
	0.7	1.27	0.32	3.39	5.53
Ag=0.4g V=500mm/s	0.1	950.93	731.16	799.43	989.39
	0.2	336.63	272.19	284.81	355.75
	0.3	128.01	123.57	136.17	140.95
	0.4	45.52	50.08	66.01	71.12
	0.5	16.80	17.13	29.05	39.04
	0.6	5.96	3.00	10.51	20.30
	0.7	1.80	0.45	4.82	7.84
Ag=0.5g V=600mm/s	0.1	1126.74	864.65	949.70	1180.75
	0.2	402.55	324.55	340.37	426.12
	0.3	153.67	148.24	163.62	169.75
	0.4	54.88	60.35	79.62	85.83
	0.5	20.31	20.70	35.10	47.20
	0.6	7.21	3.62	12.70	24.54
	0.7	2.18	0.55	5.80	9.46
Ag=0.6g V=750mm/s	0.1	1507.58	1154.91	1277.21	1590.00
	0.2	542.63	436.50	458.54	575.49
	0.3	207.63	200.24	221.20	229.85
	0.4	74.31	81.72	107.81	116.23
	0.5	27.48	28.04	47.48	63.85
	0.6	9.71	4.88	17.09	33.10
	0.7	2.91	0.73	7.75	12.69
Ag=0.7g V=875mm/s	0.1	1805.23	1380.83	1544.42	1914.56
	0.2	653.47	524.76	551.89	693.95
	0.3	250.32	241.38	266.67	277.28
	0.4	89.54	98.53	129.87	139.99
	0.5	32.99	33.70	56.98	76.63
	0.6	11.57	5.83	20.34	39.47
	0.7	3.44	0.86	9.12	14.99

Table C.2.2.B

Kern County Earthquake, Taft Lincoln School. Zarrabi's Model
CIT File No. -- A004 kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	S69E	N69W
	0.1	447.98	347.82	372.89	465.04
	0.2	153.48	128.19	127.93	167.14
Ag=0.2g	0.3	57.27	58.28	58.96	67.11
	0.4	19.67	23.73	27.59	33.63
V=250mm/s	0.5	6.44	8.74	11.54	18.52
	0.6	2.00	2.24	4.06	10.20
	0.7	0.61	0.41	1.73	4.55
	0.1	691.12	537.35	573.88	726.01
	0.2	238.51	201.25	197.09	265.76
Ag=0.3g	0.3	89.30	93.27	90.89	109.20
	0.4	30.70	39.30	42.42	55.15
V=375mm/s	0.5	9.57	15.09	17.55	30.86
	0.6	2.83	4.46	6.16	17.54
	0.7	0.86	0.87	2.54	8.36
	0.1	947.29	738.29	785.74	1010.64
	0.2	328.84	280.65	269.48	375.19
Ag=0.4g	0.3	123.41	132.36	124.10	157.39
	0.4	42.46	57.65	57.77	79.95
V=500mm/s	0.5	12.49	22.92	23.53	45.42
	0.6	3.62	7.59	8.22	26.45
	0.7	1.09	1.73	3.23	13.32
	0.1	1120.62	876.63	928.76	1214.77
	0.2	390.86	337.78	317.68	456.67
Ag=0.5g	0.3	146.91	161.79	145.85	195.04
	0.4	50.47	73.05	67.56	99.59
V=600mm/s	0.5	13.93	29.92	27.00	57.50
	0.6	4.03	10.97	9.36	33.94
	0.7	1.16	3.07	3.47	17.88
	0.1	1497.71	1176.13	1239.32	1648.11
	0.2	523.99	459.20	422.27	626.53
Ag=0.6g	0.3	197.36	222.82	192.94	271.75
	0.4	67.49	103.84	88.73	139.18
V=750mm/s	0.5	17.42	43.64	35.06	81.38
	0.6	5.01	17.49	11.88	48.42
	0.7	1.37	5.68	4.11	26.40
	0.1	1791.66	1412.95	1483.15	1999.51
	0.2	628.50	558.17	501.98	767.18
Ag=0.7g	0.3	236.80	274.03	227.73	337.11
	0.4	80.47	131.28	103.75	172.88
V=875mm/s	0.5	19.47	56.55	40.59	102.13
	0.6	5.54	24.13	13.32	60.86
	0.7	1.40	8.85	4.24	34.06

Table C.2.3.A

Eureka Earthquake, Eureka Federal Building — Zarrabi's Model
CIT File No. -- A008 — kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N11W	S11E	N79E	S79W
Ag=0.2g V=250mm/s	0.1	147.29	95.04	200.53	233.18
	0.2	42.33	22.57	101.31	87.96
	0.3	16.41	5.34	50.67	42.84
	0.4	6.58	0.53	26.71	23.24
	0.5	1.97	0.00	14.68	12.80
	0.6	0.15	0.00	6.98	6.21
	0.7	0.00	0.00	2.46	2.18
Ag=0.3g V=375mm/s	0.1	227.86	146.05	312.56	364.05
	0.2	65.94	35.00	158.67	139.12
	0.3	25.80	8.35	80.25	67.75
	0.4	10.42	0.84	42.52	37.03
	0.5	3.15	0.00	23.53	20.52
	0.6	0.23	0.00	11.26	10.02
	0.7	0.00	0.00	3.98	3.54
Ag=0.4g V=500mm/s	0.1	313.26	199.47	432.79	505.01
	0.2	91.20	48.22	220.47	194.96
	0.3	35.92	11.59	112.50	94.86
	0.4	14.61	1.17	59.81	52.11
	0.5	4.44	0.01	33.23	28.99
	0.6	0.33	0.00	15.95	14.20
	0.7	0.00	0.00	5.65	5.02
Ag=0.5g V=600mm/s	0.1	371.98	235.26	517.01	605.39
	0.2	108.79	57.32	263.97	235.09
	0.3	43.08	13.88	135.54	114.20
	0.4	17.61	1.40	72.18	62.91
	0.5	5.37	0.01	40.17	35.04
	0.6	0.41	0.00	19.27	17.16
	0.7	0.00	0.00	6.81	6.06
Ag=0.6g V=750mm/s	0.1	498.98	313.47	696.70	818.64
	0.2	146.37	76.89	356.08	318.85
	0.3	58.18	18.71	183.51	154.56
	0.4	23.85	1.90	97.72	85.19
	0.5	7.27	0.01	54.32	47.39
	0.6	0.54	0.00	25.98	23.13
	0.7	0.00	0.00	9.12	8.11
Ag=0.7g V=875mm/s	0.1	599.11	373.98	839.15	989.07
	0.2	176.06	92.27	428.82	385.51
	0.3	70.14	22.53	221.31	186.38
	0.4	28.76	2.29	117.64	102.57
	0.5	8.75	0.01	65.15	56.84
	0.6	0.65	0.00	30.95	27.55
	0.7	0.00	0.00	10.76	9.55

Table C.2.3.B

Eureka Earthquake, Eureka Federal Building
CIT File No. -- A008

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N11W	S11E	N79E	S79W
Ag=0.2g V=250mm/s	0.1	146.28	95.96	200.70	232.47
	0.2	41.60	23.41	101.69	87.35
	0.3	15.96	5.43	50.62	42.50
	0.4	6.32	0.54	26.44	22.94
	0.5	1.85	0.00	14.42	12.63
	0.6	0.11	0.00	6.78	6.06
	0.7	0.00	0.00	2.33	2.08
Ag=0.3g V=375mm/s	0.1	225.44	148.19	312.86	362.26
	0.2	64.26	36.98	159.51	137.63
	0.3	24.71	8.57	80.11	66.93
	0.4	9.81	0.88	41.88	36.31
	0.5	2.86	0.00	22.91	20.13
	0.6	0.15	0.00	10.78	9.65
	0.7	0.00	0.00	3.68	3.29
Ag=0.4g V=500mm/s	0.1	308.72	203.41	433.18	501.43
	0.2	88.09	51.86	221.95	192.13
	0.3	33.91	12.01	112.20	93.31
	0.4	13.48	1.25	58.62	50.78
	0.5	3.90	0.00	32.08	28.28
	0.6	0.18	0.00	15.04	13.53
	0.7	0.00	0.00	5.09	4.56
Ag=0.5g V=600mm/s	0.1	365.01	241.14	517.38	599.53
	0.2	104.15	62.73	266.10	230.78
	0.3	40.08	14.50	135.08	111.86
	0.4	15.92	1.56	70.41	60.94
	0.5	4.55	0.00	38.43	34.00
	0.6	0.17	0.00	17.91	16.19
	0.7	0.00	0.00	6.00	5.38
Ag=0.6g V=750mm/s	0.1	487.47	322.94	697.08	808.96
	0.2	138.88	85.64	359.42	311.87
	0.3	53.35	19.75	182.78	150.78
	0.4	21.13	2.17	94.91	82.11
	0.5	5.95	0.00	51.52	45.74
	0.6	0.17	0.00	23.79	21.61
	0.7	0.00	0.00	7.86	7.03
Ag=0.7g V=875mm/s	0.1	582.69	387.29	839.53	975.41
	0.2	165.54	104.55	433.50	375.77
	0.3	63.39	24.05	220.33	181.12
	0.4	24.99	2.70	113.78	98.38
	0.5	6.91	0.00	61.27	54.59
	0.6	0.15	0.00	27.94	25.52
	0.7	0.00	0.00	9.12	8.11

Table C.2.4.A

Eureka Earthquake, Ferndale City Hall
CIT File No. -- A009

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N44E	S44W	N46W	S46E
Ag=0.2g V=250mm/s	0.1	477.03	407.18	262.17	183.21
	0.2	239.11	140.51	121.81	56.58
	0.3	123.50	62.91	59.42	23.05
	0.4	58.47	30.96	33.78	10.01
	0.5	25.56	12.66	17.39	3.51
	0.6	5.70	3.15	10.48	1.28
	0.7	1.12	0.25	5.83	0.25
Ag=0.3g V=375mm/s	0.1	737.28	638.38	407.61	281.68
	0.2	373.96	218.95	191.66	88.28
	0.3	195.23	98.99	94.69	36.29
	0.4	93.11	49.12	54.00	15.92
	0.5	40.96	20.23	27.97	5.62
	0.6	9.19	5.06	16.92	2.07
	0.7	1.82	0.41	9.46	0.40
Ag=0.4g V=500mm/s	0.1	1012.66	888.39	563.70	384.92
	0.2	518.93	302.85	267.37	122.24
	0.3	273.25	138.02	133.40	50.62
	0.4	131.03	68.95	76.16	22.37
	0.5	57.88	28.53	39.57	7.94
	0.6	12.99	7.17	23.99	2.93
	0.7	2.58	0.57	13.43	0.57
Ag=0.5g V=600mm/s	0.1	1200.91	1066.15	672.66	454.24
	0.2	620.71	361.25	321.14	145.95
	0.3	328.93	165.65	161.28	60.79
	0.4	158.23	83.11	92.03	26.99
	0.5	69.99	34.48	47.84	9.60
	0.6	15.72	8.66	28.97	3.54
	0.7	3.12	0.69	16.18	0.69
Ag=0.6g V=750mm/s	0.1	1608.04	1443.20	905.52	605.47
	0.2	836.81	486.01	434.14	196.48
	0.3	445.29	223.82	218.78	82.15
	0.4	214.40	112.54	124.59	36.55
	0.5	94.70	46.70	64.61	12.99
	0.6	21.22	11.68	38.98	4.77
	0.7	4.18	0.92	21.64	0.93
Ag=0.7g V=875mm/s	0.1	1926.65	1746.23	1089.57	722.53
	0.2	1007.65	584.43	523.49	236.38
	0.3	537.23	269.82	263.91	99.02
	0.4	258.32	135.66	149.80	44.04
	0.5	113.66	56.13	77.31	15.59
	0.6	25.33	13.95	46.35	5.70
	0.7	4.94	1.10	25.47	1.10

Table C.2.4.B

Eureka Earthquake, Ferndale City Hall
CIT File No. -- A009

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N44E	S44W	N46W	S46E
	0.1	475.62	409.31	260.22	184.36
	0.2	237.13	141.86	120.10	57.90
Ag=0.2g	0.3	122.19	64.13	58.43	23.58
	0.4	57.60	32.34	32.86	10.33
V=250mm/s	0.5	24.73	13.97	16.72	3.67
	0.6	5.36	4.09	9.91	1.31
	0.7	1.01	0.34	5.31	0.27
	0.1	733.93	643.78	402.84	284.37
	0.2	369.28	222.22	187.55	91.41
Ag=0.3g	0.3	192.11	101.92	92.27	37.55
	0.4	90.98	52.48	51.78	16.68
V=375mm/s	0.5	38.98	23.42	26.33	6.03
	0.6	8.39	7.40	15.56	2.14
	0.7	1.56	0.62	8.19	0.45
	0.1	1006.43	899.10	554.62	389.95
	0.2	510.24	309.08	259.62	128.13
Ag=0.4g	0.3	267.45	143.58	128.80	53.01
	0.4	126.99	75.32	71.97	23.82
V=500mm/s	0.5	54.15	34.62	36.50	8.74
	0.6	11.65	11.70	21.43	3.08
	0.7	2.09	1.01	11.04	0.67
	0.1	1191.51	1083.27	658.84	461.81
	0.2	607.72	370.88	309.42	155.04
Ag=0.5g	0.3	320.23	174.15	154.30	64.46
	0.4	152.14	92.90	85.71	29.20
V=600mm/s	0.5	64.40	43.81	43.21	10.86
	0.6	13.82	15.68	25.13	3.78
	0.7	2.39	1.40	12.61	0.84
	0.1	1592.80	1472.54	882.93	617.86
	0.2	815.80	502.10	415.13	211.81
Ag=0.6g	0.3	431.26	237.78	207.45	88.30
	0.4	204.54	128.74	114.38	40.18
V=750mm/s	0.5	85.66	62.03	57.19	15.10
	0.6	18.32	23.35	32.84	5.17
	0.7	3.01	2.21	16.05	1.16
	0.1	1905.21	1789.44	1057.78	740.11
	0.2	978.23	607.63	496.90	258.55
Ag=0.7g	0.3	517.71	289.63	248.13	107.93
	0.4	244.54	158.71	135.59	49.19
V=875mm/s	0.5	101.02	77.85	67.07	18.64
	0.6	21.70	30.55	37.92	6.27
	0.7	3.35	3.77	18.03	1.43

Table C.2.5.A

Long Beach Earthquake, Vernon CMD Building. Zarrabi's Model
CIT File No. -- B021 kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S08W	N08E	N82W	S82E
Ag=0.2g V=250mm/s	0.1	180.90	216.10	141.55	136.43
	0.2	36.40	55.84	49.16	28.18
	0.3	15.44	15.95	16.83	7.31
	0.4	8.63	5.36	7.67	3.70
	0.5	4.69	2.32	3.25	2.21
	0.6	2.25	0.79	0.92	1.15
	0.7	0.70	0.18	0.02	0.56
Ag=0.3g V=375mm/s	0.1	278.66	333.56	224.18	209.52
	0.2	56.81	87.25	76.86	44.14
	0.3	24.41	25.32	26.74	11.55
	0.4	13.77	8.53	12.19	5.91
	0.5	7.54	3.71	5.19	3.56
	0.6	3.62	1.27	1.47	1.86
	0.7	1.13	0.30	0.04	0.91
Ag=0.4g V=500mm/s	0.1	381.54	457.66	314.97	285.99
	0.2	78.72	120.94	106.63	61.36
	0.3	34.16	35.55	37.60	16.16
	0.4	19.36	11.99	17.12	8.33
	0.5	10.66	5.22	7.32	5.03
	0.6	5.13	1.79	2.09	2.64
	0.7	1.60	0.42	0.05	1.30
Ag=0.5g V=600mm/s	0.1	451.17	542.18	381.36	337.10
	0.2	94.04	144.50	127.53	73.48
	0.3	41.11	42.92	45.45	19.44
	0.4	23.37	14.49	20.65	10.06
	0.5	12.87	6.31	8.85	6.08
	0.6	6.21	2.16	2.52	3.19
	0.7	1.93	0.49	0.06	1.56
Ag=0.6g V=750mm/s	0.1	602.69	725.26	520.34	448.81
	0.2	126.62	194.65	171.94	99.15
	0.3	55.63	58.22	61.72	26.29
	0.4	31.65	19.62	27.97	13.61
	0.5	17.43	8.55	11.99	8.21
	0.6	8.37	2.92	3.41	4.29
	0.7	2.58	0.67	0.08	2.09
Ag=0.7g V=875mm/s	0.1	724.93	868.21	633.95	534.94
	0.2	152.32	234.23	207.09	119.46
	0.3	67.10	70.30	74.63	31.67
	0.4	38.14	23.63	33.71	16.36
	0.5	20.91	10.27	14.41	9.83
	0.6	9.99	3.48	4.07	5.10
	0.7	3.06	0.79	0.10	2.45

Table C.2.5.B

Long Beach Earthquake, Vernon CMD Building. Zarrabi's Model
CIT File No. -- B021 kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S08W	N08E	N82W	S82E
	0.1	181.30	216.47	144.60	136.19
	0.2	36.77	55.33	50.49	28.47
Ag=0.2g	0.3	15.68	16.26	18.38	7.60
	0.4	8.88	5.64	8.14	4.02
V=250mm/s	0.5	4.89	2.60	3.52	2.52
	0.6	2.37	1.00	0.98	1.42
	0.7	0.76	0.16	0.02	0.71
	0.1	279.70	334.73	231.79	209.06
	0.2	57.73	86.12	80.07	44.92
Ag=0.3g	0.3	25.00	26.16	30.55	12.28
	0.4	14.37	9.42	13.36	6.68
V=375mm/s	0.5	8.02	4.50	5.87	4.30
	0.6	3.96	1.81	1.69	2.52
	0.7	1.27	0.30	0.05	1.28
	0.1	383.65	460.21	330.01	285.32
	0.2	80.48	119.06	112.76	62.94
Ag=0.4g	0.3	35.32	37.35	44.94	17.59
	0.4	20.54	13.93	19.42	9.79
V=500mm/s	0.5	11.59	6.91	8.67	6.45
	0.6	5.78	3.09	2.66	3.91
	0.7	1.88	0.76	0.09	2.02
	0.1	454.63	546.58	405.19	336.36
	0.2	96.73	142.28	136.99	76.03
Ag=0.5g	0.3	42.94	45.96	56.74	21.66
	0.4	25.21	17.65	24.28	12.28
V=600mm/s	0.5	14.33	9.06	11.03	8.26
	0.6	7.23	4.50	3.56	5.15
	0.7	2.37	1.35	0.22	2.72
	0.1	613.71	733.38	560.82	444.70
	0.2	131.08	191.83	187.70	103.47
Ag=0.6g	0.3	58.68	63.65	80.42	30.01
	0.4	34.73	25.07	34.10	17.25
V=750mm/s	0.5	19.82	13.26	15.73	11.79
	0.6	10.06	7.10	5.32	7.51
	0.7	3.31	2.85	0.53	4.16
	0.1	741.35	880.94	693.16	531.08
	0.2	157.99	231.19	229.79	125.75
Ag=0.7g	0.3	71.44	78.56	101.31	37.07
	0.4	42.52	31.60	42.65	21.51
V=875mm/s	0.5	24.32	17.16	19.91	14.87
	0.6	12.38	9.76	7.01	9.66
	0.7	4.08	4.68	1.14	5.55

Table C.2.6.A

Lower California Earthquake,
Imperial Valley
CIT File No. -- B024

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S00W	N00E	S90W	N90E
Ag=0.2g V=250mm/s	0.1	875.05	738.92	764.46	883.80
	0.2	259.36	259.25	280.53	335.50
	0.3	109.64	106.10	100.71	166.14
	0.4	40.43	37.84	33.92	83.78
	0.5	13.69	12.80	10.68	39.76
	0.6	4.07	4.99	2.99	15.58
	0.7	0.67	1.24	0.78	5.19
Ag=0.3g V=375mm/s	0.1	1364.79	1139.00	1179.03	1365.63
	0.2	404.68	403.41	436.61	523.52
	0.3	172.67	166.76	158.36	261.78
	0.4	64.41	60.06	53.84	133.14
	0.5	21.89	20.48	17.10	63.67
	0.6	6.54	8.03	4.83	25.12
	0.7	1.13	2.02	1.26	8.42
Ag=0.4g V=500mm/s	0.1	1889.73	1560.27	1615.95	1875.11
	0.2	560.41	557.19	603.21	724.99
	0.3	240.93	232.30	220.69	365.39
	0.4	90.65	84.28	75.58	187.04
	0.5	30.88	28.90	24.13	89.88
	0.6	9.27	11.39	6.84	35.58
	0.7	1.59	2.86	1.79	11.95
Ag=0.5g V=600mm/s	0.1	2257.31	1845.63	1912.50	2222.97
	0.2	669.24	663.79	718.81	865.64
	0.3	289.35	278.63	264.81	438.89
	0.4	109.46	101.61	91.13	225.58
	0.5	37.31	34.94	29.17	108.62
	0.6	11.21	13.76	8.27	43.00
	0.7	1.91	3.47	2.16	14.40
Ag=0.6g V=750mm/s	0.1	3042.31	2465.77	2556.41	2975.59
	0.2	901.26	888.38	966.27	1165.29
	0.3	391.07	376.28	357.78	593.20
	0.4	148.33	137.58	123.41	305.40
	0.5	50.54	47.25	39.48	146.94
	0.6	15.10	18.57	11.14	57.95
	0.7	2.55	4.63	2.89	19.28
Ag=0.7g V=875mm/s	0.1	3666.78	2948.87	3058.71	3564.21
	0.2	1084.61	1067.31	1161.24	1401.65
	0.3	471.53	453.49	431.32	715.03
	0.4	178.72	165.84	148.77	367.90
	0.5	60.73	56.73	47.41	176.38
	0.6	18.04	22.14	13.29	69.06
	0.7	3.04	5.48	3.41	22.72

Table C.2.6.B

Lower California Earthquake,
Imperial Valley
CIT File No. -- B024

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in			
		S00W	N00E	S90W	N90E
	0.1	873.63	740.79	768.39	879.70
	0.2	257.62	261.30	285.03	332.01
Ag=0.2g	0.3	109.36	107.91	106.68	163.17
	0.4	41.35	39.51	36.88	81.74
V=250mm/s	0.5	13.76	13.69	12.91	39.17
	0.6	4.14	5.41	4.02	15.90
	0.7	0.60	1.27	1.33	5.60
	0.1	1361.22	1143.60	1189.08	1356.18
	0.2	400.86	409.00	447.48	515.47
Ag=0.3g	0.3	172.17	171.11	172.79	254.86
	0.4	66.81	64.12	61.19	128.46
V=375mm/s	0.5	22.11	22.74	22.64	62.31
	0.6	6.76	9.05	7.53	25.90
	0.7	0.88	2.09	2.64	9.42
	0.1	1882.73	1569.19	1635.87	1857.95
	0.2	554.01	568.30	623.86	710.35
Ag=0.4g	0.3	240.43	240.54	247.96	352.83
	0.4	95.53	92.10	89.76	178.57
V=500mm/s	0.5	31.37	33.49	35.00	87.43
	0.6	9.69	13.40	12.25	37.09
	0.7	1.13	3.01	4.48	13.86
	0.1	2246.24	1859.56	1944.12	2197.63
	0.2	660.54	679.11	750.47	844.02
Ag=0.5g	0.3	289.07	291.26	306.26	420.39
	0.4	117.18	113.74	113.03	213.25
V=600mm/s	0.5	38.45	42.62	46.12	105.04
	0.6	11.88	16.91	16.92	45.31
	0.7	1.20	3.71	6.36	17.30
	0.1	3023.82	2489.33	2610.19	2935.01
	0.2	888.49	918.62	1018.50	1130.71
Ag=0.6g	0.3	391.56	397.26	425.66	563.68
	0.4	161.28	157.88	160.01	286.02
V=750mm/s	0.5	52.98	60.73	67.75	141.28
	0.6	16.27	23.84	26.10	61.71
	0.7	1.45	5.16	9.91	23.95
	0.1	3640.11	2983.25	3137.33	3507.64
	0.2	1074.45	1111.10	1235.92	1353.72
Ag=0.7g	0.3	473.33	483.63	527.52	674.02
	0.4	197.60	195.13	201.46	341.48
V=875mm/s	0.5	64.79	76.89	87.91	168.61
	0.6	19.70	29.74	35.38	74.30
	0.7	1.49	6.37	13.56	29.16

Table C.2.7.A

Western Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B029

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N04W	S04E	N86E	S86W
Ag=0.2g V=250mm/s	0.1	503.78	394.21	615.35	734.58
	0.2	136.78	73.84	163.66	240.25
	0.3	39.91	15.18	44.24	93.07
	0.4	9.69	1.81	12.12	35.00
	0.5	1.33	0.00	2.60	16.00
	0.6	0.00	0.00	0.17	7.80
	0.7	0.00	0.00	0.00	3.91
Ag=0.3g V=375mm/s	0.1	776.45	604.45	946.95	1138.18
	0.2	213.27	114.44	254.10	374.74
	0.3	62.61	23.75	69.40	146.52
	0.4	15.33	2.85	19.18	55.71
	0.5	2.13	0.00	4.14	25.68
	0.6	0.00	0.00	0.28	12.59
	0.7	0.00	0.00	0.00	6.35
Ag=0.4g V=500mm/s	0.1	1063.59	825.55	1295.08	1566.99
	0.2	295.15	157.50	350.26	518.79
	0.3	87.08	32.96	96.52	204.37
	0.4	21.47	4.00	26.87	78.33
	0.5	2.99	0.00	5.84	36.30
	0.6	0.00	0.00	0.39	17.84
	0.7	0.00	0.00	0.00	9.01
Ag=0.5g V=600mm/s	0.1	1258.10	973.81	1529.61	1862.24
	0.2	352.27	187.07	416.57	619.26
	0.3	104.34	39.44	115.65	245.34
	0.4	25.86	4.81	32.37	94.51
	0.5	3.61	0.01	7.05	43.87
	0.6	0.00	0.00	0.47	21.55
	0.7	0.00	0.00	0.00	10.86
Ag=0.6g V=750mm/s	0.1	1680.96	1297.69	2040.81	2498.43
	0.2	474.24	250.79	559.10	833.50
	0.3	140.85	53.18	156.10	331.47
	0.4	35.01	6.50	43.83	127.96
	0.5	4.90	0.01	9.55	59.31
	0.6	0.00	0.00	0.64	29.01
	0.7	0.00	0.00	0.00	14.52
Ag=0.7g V=875mm/s	0.1	2010.74	1548.42	2434.71	2998.99
	0.2	570.72	300.78	671.13	1002.56
	0.3	169.78	64.07	188.13	399.46
	0.4	42.24	7.85	52.87	154.07
	0.5	5.90	0.01	11.49	71.09
	0.6	0.00	0.00	0.76	34.51
	0.7	0.00	0.00	0.00	17.08

Table C.2.7.B

Western Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B029

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N04W	S04E	N86E	S86W
Ag=0.2g V=250mm/s	0.1	502.66	395.61	616.49	734.62
	0.2	135.14	74.56	164.13	240.07
	0.3	39.38	15.21	44.87	92.66
	0.4	9.49	1.86	12.49	34.08
	0.5	1.26	0.01	2.79	14.98
	0.6	0.00	0.00	0.15	7.04
	0.7	0.00	0.00	0.00	3.24
Ag=0.3g V=375mm/s	0.1	773.87	608.70	949.70	1137.60
	0.2	209.47	116.14	255.30	374.25
	0.3	61.38	23.84	70.95	145.51
	0.4	14.88	3.01	20.11	53.50
	0.5	1.94	0.01	4.64	23.23
	0.6	0.00	0.00	0.24	10.77
	0.7	0.00	0.00	0.00	4.74
Ag=0.4g V=500mm/s	0.1	1058.89	833.48	1300.27	1564.04
	0.2	288.22	160.74	352.60	517.79
	0.3	84.84	33.19	99.50	202.47
	0.4	20.67	4.33	28.74	74.22
	0.5	2.67	0.03	6.84	31.72
	0.6	0.00	0.00	0.34	14.44
	0.7	0.00	0.00	0.00	6.01
Ag=0.5g V=600mm/s	0.1	1251.21	983.08	1537.56	1857.30
	0.2	342.09	192.02	420.27	617.69
	0.3	101.07	39.86	120.33	242.50
	0.4	24.69	5.41	35.63	88.41
	0.5	3.15	0.05	8.66	37.05
	0.6	0.00	0.00	0.43	16.49
	0.7	0.00	0.00	0.00	6.41
Ag=0.6g V=750mm/s	0.1	1670.04	1313.46	2051.87	2490.02
	0.2	458.01	258.95	565.38	830.99
	0.3	135.68	54.10	163.99	327.01
	0.4	33.19	7.61	49.65	118.29
	0.5	4.19	0.08	12.56	48.45
	0.6	0.00	0.00	0.63	20.98
	0.7	0.00	0.00	0.00	7.65
Ag=0.7g V=875mm/s	0.1	1995.66	1571.43	2454.59	2986.93
	0.2	548.35	312.44	680.38	999.24
	0.3	162.71	65.72	199.60	393.51
	0.4	39.80	9.54	61.65	140.92
	0.5	4.96	0.13	16.25	56.22
	0.6	0.00	0.00	0.87	23.55
	0.7	0.00	0.00	0.00	8.17

Table C.2.8.A

Puget Sound, Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B032

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S04E	N04W	S86W	N86E
Ag=0.2g V=250mm/s	0.1	232.38	269.40	407.12	509.57
	0.2	66.82	57.75	114.12	177.90
	0.3	24.57	14.23	39.43	65.64
	0.4	10.64	3.17	13.89	30.02
	0.5	3.05	0.25	5.16	16.30
	0.6	0.49	0.00	1.31	7.71
	0.7	0.00	0.00	0.29	3.03
Ag=0.3g V=375mm/s	0.1	358.88	414.61	630.37	795.79
	0.2	104.33	89.65	178.29	279.93
	0.3	38.64	22.31	62.00	104.46
	0.4	16.87	5.02	22.06	47.79
	0.5	4.88	0.41	8.25	26.13
	0.6	0.78	0.00	2.11	12.43
	0.7	0.00	0.00	0.48	4.91
Ag=0.4g V=500mm/s	0.1	492.64	567.12	867.34	1103.36
	0.2	144.56	123.57	247.17	390.51
	0.3	53.86	31.01	86.40	146.96
	0.4	23.67	7.03	30.97	67.23
	0.5	6.88	0.57	11.64	36.91
	0.6	1.11	0.00	2.99	17.62
	0.7	0.00	0.00	0.68	6.97
Ag=0.5g V=600mm/s	0.1	583.90	670.16	1030.28	1319.53
	0.2	172.71	146.97	295.45	469.11
	0.3	64.64	37.13	103.68	177.56
	0.4	28.52	8.46	37.35	81.13
	0.5	8.32	0.69	14.08	44.61
	0.6	1.34	0.00	3.62	21.28
	0.7	0.00	0.00	0.82	8.39
Ag=0.6g V=750mm/s	0.1	781.52	894.75	1381.84	1779.71
	0.2	232.68	195.91	398.21	634.51
	0.3	87.35	50.11	140.07	240.86
	0.4	38.63	11.46	50.58	109.84
	0.5	11.26	0.93	19.06	60.32
	0.6	1.81	0.00	4.88	28.67
	0.7	0.00	0.00	1.10	11.22
Ag=0.7g V=875mm/s	0.1	936.28	1069.54	1658.57	2145.38
	0.2	280.11	235.17	479.58	765.82
	0.3	105.32	60.39	168.88	290.78
	0.4	46.58	13.82	60.97	132.23
	0.5	13.54	1.12	22.90	72.34
	0.6	2.17	0.00	5.82	34.13
	0.7	0.00	0.00	1.29	13.22

Table C.2.8.B

Puget Sound, Washington Earthquake
Olympia, Washington, Highway Test Lab.
CIT File No. -- B032

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S04E	N04W	S86W	N86E
Ag=0.2g V=250mm/s	0.1	232.04	268.74	406.60	512.26
	0.2	66.96	57.44	113.70	181.01
	0.3	24.47	14.11	39.47	67.55
	0.4	10.49	3.17	14.05	30.97
	0.5	2.97	0.25	5.28	17.21
	0.6	0.50	0.00	1.42	8.33
	0.7	0.00	0.00	0.32	3.53
Ag=0.3g V=375mm/s	0.1	358.10	413.10	629.25	802.45
	0.2	104.66	88.94	177.41	287.36
	0.3	38.44	22.08	62.12	109.17
	0.4	16.55	5.03	22.48	50.13
	0.5	4.71	0.43	8.55	28.35
	0.6	0.82	0.00	2.39	13.98
	0.7	0.00	0.00	0.55	6.15
Ag=0.4g V=500mm/s	0.1	491.19	564.37	865.43	1116.35
	0.2	145.19	122.27	245.72	404.51
	0.3	53.60	30.64	86.69	156.02
	0.4	23.09	7.09	31.72	71.69
	0.5	6.60	0.67	12.22	41.13
	0.6	1.18	0.00	3.56	20.56
	0.7	0.00	0.00	0.81	9.35
Ag=0.5g V=600mm/s	0.1	581.72	665.96	1027.69	1339.72
	0.2	173.69	145.07	293.77	490.34
	0.3	64.35	36.66	104.17	191.45
	0.4	27.73	8.59	38.62	87.97
	0.5	7.96	0.90	14.97	51.02
	0.6	1.45	0.00	4.51	25.75
	0.7	0.00	0.00	1.02	12.03
Ag=0.6g V=750mm/s	0.1	778.03	888.18	1378.01	1813.31
	0.2	234.36	194.24	395.65	669.15
	0.3	87.03	49.44	140.98	263.71
	0.4	37.45	11.74	52.82	121.08
	0.5	10.77	1.42	20.54	70.75
	0.6	1.99	0.00	6.38	36.26
	0.7	0.00	0.00	1.42	17.11
Ag=0.7g V=875mm/s	0.1	931.46	1060.64	1653.58	2193.37
	0.2	282.63	232.66	476.25	814.60
	0.3	105.11	59.57	170.28	323.18
	0.4	45.08	14.31	64.30	148.13
	0.5	13.00	2.00	25.02	86.93
	0.6	2.42	0.00	7.97	45.20
	0.7	0.00	0.00	1.73	21.37

Table C.2.9.A

San Fernando Earthquake
8244, Orion Blvd., 1st floor
CIT File No. -- C048

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N00W	S00E	S90W	N80E
	0.1	611.95	444.62	329.66	300.43
	0.2	193.08	163.90	54.96	52.61
Ag=0.2g	0.3	69.67	73.58	10.88	8.52
	0.4	26.52	36.16	1.93	0.70
V=250mm/s	0.5	6.75	17.04	0.02	0.01
	0.6	0.71	7.35	0.00	0.00
	0.7	0.00	3.28	0.00	0.00
	0.1	943.57	688.77	505.50	460.05
	0.2	300.50	256.24	85.19	81.41
Ag=0.3g	0.3	109.45	116.24	17.03	13.33
	0.4	42.00	57.56	3.04	1.10
V=375mm/s	0.5	10.77	27.32	0.03	0.01
	0.6	1.14	11.86	0.00	0.00
	0.7	0.00	5.33	0.00	0.00
	0.1	1292.91	948.10	689.03	626.13
	0.2	415.17	355.45	117.26	111.87
Ag=0.4g	0.3	152.42	162.60	23.67	18.50
	0.4	58.86	80.94	4.26	1.53
V=500mm/s	0.5	15.17	38.60	0.05	0.02
	0.6	1.61	16.81	0.00	0.00
	0.7	0.00	7.56	0.00	0.00
	0.1	1529.70	1130.46	811.22	736.08
	0.2	494.77	425.00	139.30	132.70
Ag=0.5g	0.3	182.79	195.63	28.33	22.12
	0.4	70.91	97.67	5.13	1.84
V=600mm/s	0.5	18.33	46.65	0.06	0.03
	0.6	1.94	20.30	0.00	0.00
	0.7	0.00	9.11	0.00	0.00
	0.1	2044.16	1525.00	1077.96	977.77
	0.2	665.14	572.77	186.76	177.69
Ag=0.6g	0.3	246.88	264.68	38.21	29.83
	0.4	96.02	132.23	6.94	2.50
V=750mm/s	0.5	24.84	63.08	0.08	0.03
	0.6	2.62	27.33	0.00	0.00
	0.7	0.00	12.18	0.00	0.00
	0.1	2445.27	1839.22	1284.17	1162.68
	0.2	799.49	689.49	224.02	212.90
Ag=0.7g	0.3	297.63	319.16	46.05	35.93
	0.4	115.82	159.22	8.38	3.01
V=875mm/s	0.5	29.88	75.63	0.10	0.05
	0.6	3.14	32.51	0.00	0.00
	0.7	0.00	14.33	0.00	0.00

Table C.2.9.B

San Fernando Earthquake
8244, Orion Blvd., 1st floor
CIT File No. -- C048

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N00W	S00E	S90W	N80E
Ag=0.2g V=250mm/s	0.1	612.51	444.13	330.09	302.02
	0.2	191.60	165.60	54.53	53.71
	0.3	68.90	74.98	10.79	8.86
	0.4	26.29	37.01	2.10	0.81
	0.5	6.92	17.56	0.05	0.01
	0.6	0.56	7.51	0.00	0.00
	0.7	0.00	3.57	0.00	0.00
Ag=0.3g V=375mm/s	0.1	945.10	687.98	507.36	464.19
	0.2	297.27	260.40	84.27	84.27
	0.3	107.81	119.66	16.91	14.29
	0.4	41.53	59.83	3.51	1.38
	0.5	11.30	28.75	0.14	0.03
	0.6	0.81	12.39	0.00	0.00
	0.7	0.00	6.08	0.00	0.00
Ag=0.4g V=500mm/s	0.1	1296.33	948.14	693.38	634.26
	0.2	409.60	363.48	115.73	117.73
	0.3	149.75	169.15	23.64	20.49
	0.4	58.13	85.56	5.23	2.11
	0.5	16.34	41.52	0.32	0.05
	0.6	1.08	18.11	0.00	0.00
	0.7	0.00	9.04	0.00	0.00
Ag=0.5g V=600mm/s	0.1	1536.23	1135.04	817.86	748.68
	0.2	486.96	437.44	137.26	142.07
	0.3	179.40	205.74	28.58	25.34
	0.4	70.08	105.01	6.72	2.80
	0.5	20.35	51.37	0.54	0.07
	0.6	1.32	22.62	0.00	0.00
	0.7	0.00	11.38	0.00	0.00
Ag=0.6g V=750mm/s	0.1	2057.11	1534.32	1091.24	999.53
	0.2	653.38	593.64	183.95	193.58
	0.3	242.94	281.59	39.02	35.34
	0.4	95.29	144.67	9.72	4.23
	0.5	28.48	71.29	1.07	0.10
	0.6	2.12	31.59	0.00	0.00
	0.7	0.00	15.89	0.00	0.00
Ag=0.7g V=875mm/s	0.1	2466.36	1854.68	1305.26	1195.51
	0.2	783.20	719.64	220.78	236.83
	0.3	294.51	343.56	47.69	44.12
	0.4	115.84	177.31	12.54	5.91
	0.5	35.54	87.87	1.85	0.20
	0.6	3.07	39.05	0.06	0.00
	0.7	0.00	19.50	0.00	0.00

Table C.2.10.A

San Fernando Earthquake
Old Ridge Route, Castaic
CIT File No. -- D056

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	N69W	S69E
Ag=0.2g V=250mm/s	0.1	245.40	251.41	840.38	895.38
	0.2	104.09	91.37	224.40	350.25
	0.3	45.13	48.25	58.05	157.94
	0.4	13.53	28.03	18.38	79.26
	0.5	0.99	15.46	2.88	35.59
	0.6	0.00	7.80	0.18	13.84
	0.7	0.00	3.96	0.00	3.37
Ag=0.3g V=375mm/s	0.1	379.52	389.77	1289.76	1382.09
	0.2	161.81	143.09	349.35	546.39
	0.3	70.78	76.32	91.26	249.06
	0.4	21.40	44.72	29.16	126.04
	0.5	1.58	24.84	4.58	56.98
	0.6	0.00	12.60	0.31	22.33
	0.7	0.00	6.44	0.00	5.48
Ag=0.4g V=500mm/s	0.1	521.49	536.92	1759.22	1895.86
	0.2	223.29	198.78	483.07	756.49
	0.3	98.41	106.85	127.12	347.87
	0.4	29.96	62.98	40.93	177.13
	0.5	2.22	35.13	6.47	80.48
	0.6	0.00	17.86	0.40	31.63
	0.7	0.00	9.13	0.00	7.77
Ag=0.5g V=600mm/s	0.1	618.61	638.38	2072.54	2245.44
	0.2	265.83	237.92	576.09	903.02
	0.3	117.88	128.57	152.50	418.06
	0.4	36.06	76.04	49.29	213.70
	0.5	2.68	42.45	7.82	97.28
	0.6	0.00	21.56	0.49	38.24
	0.7	0.00	10.99	0.00	9.39
Ag=0.6g V=750mm/s	0.1	828.70	856.64	2758.48	3002.83
	0.2	357.06	320.81	774.91	1215.26
	0.3	159.08	173.88	206.02	565.21
	0.4	48.82	102.89	66.77	289.32
	0.5	3.63	57.32	10.56	131.56
	0.6	0.00	28.99	0.67	51.54
	0.7	0.00	14.68	0.00	12.54
Ag=0.7g V=875mm/s	0.1	993.54	1028.14	3287.57	3593.47
	0.2	428.88	386.15	931.82	1461.36
	0.3	191.71	209.47	248.34	681.32
	0.4	58.91	123.73	80.52	348.50
	0.5	4.38	68.62	12.72	157.85
	0.6	0.00	34.44	0.81	61.38
	0.7	0.00	17.25	0.00	14.78

Table C.2.10.B

San Fernando Earthquake
Old Ridge Route, Castaic
CIT File No. -- D056

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N21E	S21W	N69W	S69E
Ag=0.2g V=250mm/s	0.1	246.72	249.93	836.97	900.19
	0.2	104.98	89.95	221.61	354.79
	0.3	45.81	47.58	58.59	162.16
	0.4	14.09	27.67	19.55	83.04
	0.5	1.27	15.73	3.19	37.38
	0.6	0.00	8.37	0.13	14.87
	0.7	0.00	4.63	0.00	4.13
Ag=0.3g V=375mm/s	0.1	382.73	386.42	1282.39	1394.32
	0.2	163.95	139.89	343.29	557.35
	0.3	72.71	74.88	92.97	259.44
	0.4	22.77	44.08	31.99	135.20
	0.5	2.51	25.58	5.44	61.83
	0.6	0.00	14.15	0.27	24.94
	0.7	0.00	8.08	0.00	7.91
Ag=0.4g V=500mm/s	0.1	527.89	530.92	1746.55	1920.48
	0.2	227.41	192.99	472.52	777.48
	0.3	102.38	104.37	130.80	367.87
	0.4	32.65	62.05	46.37	194.69
	0.5	4.48	36.68	8.22	90.63
	0.6	0.33	20.93	0.58	36.85
	0.7	0.00	12.29	0.00	13.08
Ag=0.5g V=600mm/s	0.1	628.90	629.64	2054.92	2285.16
	0.2	272.24	229.86	561.26	935.46
	0.3	124.24	125.15	158.61	449.02
	0.4	40.38	74.93	58.37	241.02
	0.5	6.88	45.07	10.51	113.95
	0.6	1.07	26.33	1.17	46.55
	0.7	0.00	15.77	0.00	18.24
Ag=0.6g V=750mm/s	0.1	846.68	842.76	2734.94	3070.99
	0.2	367.85	308.35	752.31	1269.13
	0.3	169.91	168.59	216.58	616.57
	0.4	56.22	101.37	83.58	335.74
	0.5	11.71	61.86	18.11	160.28
	0.6	2.68	36.78	2.25	65.69
	0.7	0.01	22.35	0.00	27.95
Ag=0.7g V=875mm/s	0.1	1020.79	1008.72	3256.66	3693.36
	0.2	444.65	369.14	902.03	1538.19
	0.3	207.54	202.19	264.07	754.56
	0.4	69.81	121.77	106.54	415.68
	0.5	17.39	75.14	26.65	199.91
	0.6	4.99	45.29	3.50	82.86
	0.7	0.72	27.80	0.00	-------

Table C.2.11.A

San Fernando Earthquake
Griffith Park Observatory
CIT File No. -- 0198

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S00W	N00E	S90W	N90E
Ag=0.2g V=250mm/s	0.1	169.13	212.38	261.12	287.50
	0.2	71.63	75.00	94.21	125.99
	0.3	36.59	29.57	35.66	51.19
	0.4	18.51	15.06	12.75	20.50
	0.5	10.34	8.87	4.29	7.67
	0.6	5.75	4.99	1.17	2.49
	0.7	3.12	2.38	0.20	0.56
Ag=0.3g V=375mm/s	0.1	264.10	328.59	403.33	445.03
	0.2	112.17	117.19	146.99	196.79
	0.3	57.84	46.78	56.19	80.73
	0.4	29.51	24.04	20.25	32.55
	0.5	16.60	14.25	6.86	12.28
	0.6	9.30	8.06	1.88	4.02
	0.7	5.07	3.87	0.33	0.90
Ag=0.4g V=500mm/s	0.1	365.83	452.06	553.60	612.08
	0.2	155.82	162.48	203.53	272.78
	0.3	80.96	65.52	78.45	112.80
	0.4	41.54	33.87	28.43	45.72
	0.5	23.47	20.15	9.69	17.33
	0.6	13.18	11.43	2.67	5.69
	0.7	7.19	5.49	0.46	1.28
Ag=0.5g V=600mm/s	0.1	443.36	537.38	656.13	726.80
	0.2	186.50	194.16	243.02	326.01
	0.3	97.41	78.88	94.28	135.61
	0.4	50.15	40.90	34.28	55.13
	0.5	28.37	24.35	11.71	20.94
	0.6	15.91	13.80	3.22	6.88
	0.7	8.66	6.61	0.56	1.54
Ag=0.6g V=750mm/s	0.1	610.16	720.97	878.14	974.43
	0.2	251.48	261.48	327.17	439.28
	0.3	131.76	106.71	127.49	183.45
	0.4	67.88	55.35	46.43	74.66
	0.5	38.33	32.90	15.85	28.34
	0.6	21.41	18.58	4.35	9.28
	0.7	11.59	8.84	0.75	2.06
Ag=0.7g V=875mm/s	0.1	748.53	865.08	1046.99	1169.08
	0.2	302.76	314.51	393.61	528.85
	0.3	158.80	128.58	153.75	221.28
	0.4	81.65	66.56	55.97	89.98
	0.5	45.90	39.38	19.04	34.04
	0.6	25.45	22.09	5.19	11.07
	0.7	13.64	10.40	0.88	2.43

Table C.2.11.B

San Fernando Earthquake
Griffith Park Observatory
CIT File No. -- 0198

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S00W	N00E	S90W	N90E
Ag=0.2g V=250mm/s	0.1	169.28	212.13	261.55	287.24
	0.2	71.88	74.48	94.51	125.89
	0.3	37.08	29.55	36.04	51.45
	0.4	18.92	14.94	12.85	20.93
	0.5	10.50	8.43	4.20	8.27
	0.6	5.93	4.59	1.10	2.81
	0.7	3.28	2.19	0.14	0.64
Ag=0.3g V=375mm/s	0.1	264.70	327.94	404.35	444.57
	0.2	112.89	116.04	147.69	196.73
	0.3	59.04	46.80	57.10	81.53
	0.4	30.59	23.83	20.52	33.77
	0.5	17.03	13.24	6.73	13.82
	0.6	9.74	7.09	1.74	4.79
	0.7	5.45	3.40	0.19	1.11
Ag=0.4g V=500mm/s	0.1	368.85	450.65	555.50	611.59
	0.2	157.35	160.47	204.84	272.94
	0.3	83.26	65.73	80.19	114.52
	0.4	43.67	33.62	29.02	48.28
	0.5	24.41	18.30	9.56	20.41
	0.6	14.02	9.61	2.43	7.19
	0.7	7.91	4.61	0.23	1.70
Ag=0.5g V=600mm/s	0.1	450.74	535.31	659.05	726.58
	0.2	189.05	191.31	245.00	326.59
	0.3	100.97	79.47	96.96	138.48
	0.4	53.49	40.69	35.30	59.48
	0.5	29.94	21.63	11.83	25.79
	0.6	17.22	11.09	2.99	9.23
	0.7	9.75	5.30	0.27	2.35
Ag=0.6g V=750mm/s	0.1	623.60	718.00	883.09	974.97
	0.2	255.93	257.14	330.48	440.66
	0.3	137.72	108.05	132.07	188.47
	0.4	73.48	55.24	48.28	82.32
	0.5	41.14	28.59	16.48	36.53
	0.6	23.60	14.24	4.14	13.38
	0.7	13.32	6.75	0.38	3.62
Ag=0.7g V=875mm/s	0.1	768.26	861.29	1059.19	1170.90
	0.2	309.42	308.79	398.44	531.27
	0.3	167.37	130.98	160.67	228.75
	0.4	89.74	66.68	58.87	101.42
	0.5	50.16	33.51	20.42	45.97
	0.6	28.68	16.40	5.09	17.18
	0.7	16.00	7.55	0.51	4.86

Table C.2.12.A

Imperial Valley Earthquake, 1979
Station 7

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
Ag=0.2g V=250mm/s	0.1	140.99	145.89	33.45	27.18
	0.2	69.23	53.70	10.14	6.77
	0.3	32.30	16.88	4.23	2.84
	0.4	16.42	9.13	1.80	1.26
	0.5	10.13	4.97	0.75	0.48
	0.6	6.16	2.46	0.20	0.08
	0.7	3.37	1.01	0.01	0.00
Ag=0.3g V=375mm/s	0.1	220.41	226.19	51.70	41.69
	0.2	109.19	84.72	15.81	10.56
	0.3	51.93	26.77	6.66	4.48
	0.4	26.27	14.56	2.85	1.99
	0.5	16.29	7.97	1.20	0.77
	0.6	9.96	3.97	0.33	0.13
	0.7	5.46	1.64	0.01	0.00
Ag=0.4g V=500mm/s	0.1	306.26	311.74	71.03	56.87
	0.2	152.63	118.46	21.87	14.61
	0.3	73.66	37.56	9.29	6.24
	0.4	37.07	20.50	4.00	2.79
	0.5	23.05	11.27	1.70	1.08
	0.6	14.12	5.63	0.46	0.18
	0.7	7.75	2.32	0.01	0.00
Ag=0.5g V=600mm/s	0.1	367.19	370.92	84.30	66.99
	0.2	183.59	142.57	26.10	17.44
	0.3	89.47	45.28	11.15	7.50
	0.4	44.80	24.75	4.83	3.37
	0.5	27.86	13.62	2.05	1.30
	0.6	17.05	6.80	0.56	0.22
	0.7	9.34	2.80	0.01	0.00
Ag=0.6g V=750mm/s	0.1	496.33	498.03	113.01	89.16
	0.2	248.39	193.04	35.13	23.49
	0.3	121.66	61.32	15.07	10.14
	0.4	60.63	33.50	6.54	4.56
	0.5	37.62	18.40	2.78	1.77
	0.6	22.93	9.16	0.75	0.29
	0.7	12.48	3.74	0.02	0.00
Ag=0.7g V=875mm/s	0.1	599.16	597.87	135.59	106.25
	0.2	299.58	233.02	42.26	28.26
	0.3	146.80	73.91	18.18	12.22
	0.4	72.85	40.30	7.88	5.50
	0.5	45.01	22.05	3.34	2.12
	0.6	27.25	10.90	0.90	0.35
	0.7	14.69	4.41	0.02	0.00

Table C.2.12.B

Imperial Valley Earthquake, 1979
Station 7

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
Ag=0.2g V=250mm/s	0.1	140.80	146.37	33.61	27.27
	0.2	68.97	54.23	10.22	6.74
	0.3	32.03	16.83	4.31	2.78
	0.4	16.49	9.02	1.86	1.21
	0.5	10.28	4.92	0.80	0.45
	0.6	6.26	2.44	0.25	0.07
	0.7	3.43	1.01	0.02	0.00
Ag=0.3g V=375mm/s	0.1	219.95	227.34	52.11	41.91
	0.2	108.60	85.95	16.02	10.48
	0.3	51.31	26.64	6.85	4.33
	0.4	26.45	14.31	3.02	1.87
	0.5	16.67	7.86	1.32	0.71
	0.6	10.20	3.92	0.45	0.11
	0.7	5.63	1.66	0.05	0.00
Ag=0.4g V=500mm/s	0.1	305.35	313.91	71.85	57.26
	0.2	151.56	120.73	22.28	14.47
	0.3	72.53	37.33	9.66	5.98
	0.4	37.43	20.08	4.32	2.57
	0.5	23.77	11.06	1.92	0.97
	0.6	14.59	5.55	0.70	0.16
	0.7	8.07	2.36	0.10	0.00
Ag=0.5g V=600mm/s	0.1	365.83	374.18	85.62	67.57
	0.2	182.03	145.92	26.74	17.23
	0.3	87.81	44.95	11.73	7.11
	0.4	45.38	24.15	5.32	3.04
	0.5	28.96	13.30	2.39	1.14
	0.6	17.78	6.71	0.92	0.19
	0.7	9.84	2.87	0.17	0.00
Ag=0.6g V=750mm/s	0.1	494.13	503.29	115.26	90.07
	0.2	245.93	198.40	36.19	23.13
	0.3	119.01	60.77	16.02	9.51
	0.4	61.72	32.56	7.36	4.03
	0.5	39.49	17.89	3.33	1.51
	0.6	24.17	9.04	1.36	0.25
	0.7	13.32	3.86	0.29	0.00
Ag=0.7g V=875mm/s	0.1	596.08	605.22	138.89	107.52
	0.2	296.15	240.50	43.77	27.76
	0.3	143.11	73.15	19.52	11.35
	0.4	74.56	39.01	9.05	4.78
	0.5	47.68	21.36	4.12	1.77
	0.6	29.02	10.78	1.75	0.30
	0.7	15.87	4.57	0.43	0.00

Table C.2.13.A

Imperial Valley Earthquake, 1979
Station 10

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in N50E	S50W	N40W	S40E
Ag=0.2g V=250mm/s	0.1	200.27	115.02	173.39	187.49
	0.2	81.12	31.14	54.87	86.79
	0.3	32.28	12.15	21.00	42.91
	0.4	8.93	4.61	9.79	25.20
	0.5	0.99	1.83	3.63	14.71
	0.6	0.06	0.61	1.09	8.06
	0.7	0.00	0.02	0.27	3.63
Ag=0.3g V=375mm/s	0.1	310.21	181.50	272.86	291.53
	0.2	126.32	48.65	86.41	136.42
	0.3	50.68	19.20	33.10	67.98
	0.4	14.19	7.33	15.55	40.24
	0.5	1.58	2.93	5.81	23.60
	0.6	0.09	0.99	1.75	13.01
	0.7	0.00	0.04	0.44	5.88
Ag=0.4g V=500mm/s	0.1	426.86	254.20	381.03	402.72
	0.2	174.81	67.43	120.68	190.12
	0.3	70.54	26.84	46.22	95.37
	0.4	19.91	10.29	21.84	56.72
	0.5	2.23	4.13	8.20	33.35
	0.6	0.13	1.40	2.48	18.43
	0.7	0.00	0.06	0.63	8.35
Ag=0.5g V=600mm/s	0.1	507.04	306.97	458.77	480.06
	0.2	208.76	80.58	145.19	228.15
	0.3	84.56	32.29	55.54	114.95
	0.4	24.00	12.41	26.35	68.51
	0.5	2.69	5.00	9.92	40.30
	0.6	0.16	1.69	3.00	22.26
	0.7	0.00	0.07	0.76	10.05
Ag=0.6g V=750mm/s	0.1	680.09	417.99	622.72	645.61
	0.2	281.14	108.58	197.02	308.24
	0.3	114.15	43.70	75.09	155.63
	0.4	32.51	16.81	35.68	92.73
	0.5	3.64	6.77	13.42	54.46
	0.6	0.21	2.29	4.05	29.95
	0.7	0.00	0.10	1.01	13.43
Ag=0.7g V=875mm/s	0.1	816.38	509.24	755.20	776.25
	0.2	338.39	130.74	238.55	371.58
	0.3	137.58	52.74	90.53	187.60
	0.4	39.19	20.27	42.98	111.51
	0.5	4.39	8.13	16.10	65.24
	0.6	0.26	2.73	4.83	35.62
	0.7	0.00	0.11	1.20	15.80

Table C.2.13.B

Imperial Valley Earthquake, 1979
Station 10

Zarrabi's Model
kv≠0 analysis

A, V	N/A	Relative Displacement (mm) in N50E	S50W	N40W	S40E
Ag=0.2g V=250mm/s	0.1	199.72	113.18	173.48	187.52
	0.2	80.49	31.13	55.05	86.47
	0.3	31.81	12.29	21.13	42.55
	0.4	8.40	4.63	9.81	24.72
	0.5	0.94	1.77	3.62	14.33
	0.6	0.04	0.52	1.09	7.60
	0.7	0.00	0.02	0.23	3.29
Ag=0.3g V=375mm/s	0.1	308.93	177.28	273.08	291.53
	0.2	124.82	48.62	86.84	135.65
	0.3	49.57	19.53	33.40	67.22
	0.4	12.91	7.42	15.63	39.09
	0.5	1.46	2.78	5.80	22.70
	0.6	0.05	0.78	1.76	11.91
	0.7	0.00	0.04	0.34	5.11
Ag=0.4g V=500mm/s	0.1	424.50	246.58	381.51	402.64
	0.2	171.85	67.42	121.50	188.72
	0.3	68.48	27.49	46.79	93.97
	0.4	17.54	10.53	22.00	54.57
	0.5	2.00	3.86	8.19	31.68
	0.6	0.06	1.02	2.51	16.37
	0.7	0.00	0.06	0.43	6.95
Ag=0.5g V=600mm/s	0.1	503.59	295.83	459.61	479.86
	0.2	204.10	80.60	146.51	226.13
	0.3	81.49	33.30	56.41	112.88
	0.4	20.48	12.85	26.59	65.33
	0.5	2.36	4.62	9.91	37.83
	0.6	0.07	1.18	3.05	19.23
	0.7	0.00	0.07	0.49	8.02
Ag=0.6g V=750mm/s	0.1	674.59	400.35	624.32	645.31
	0.2	273.46	108.67	199.25	305.12
	0.3	109.23	45.39	76.56	152.36
	0.4	26.83	17.60	36.10	87.67
	0.5	3.13	6.19	13.44	50.54
	0.6	0.11	1.52	4.15	25.18
	0.7	0.00	0.11	0.66	10.30
Ag=0.7g V=875mm/s	0.1	808.72	484.35	757.81	775.96
	0.2	327.59	130.95	241.82	367.44
	0.3	130.72	55.21	92.69	183.17
	0.4	31.28	21.48	43.63	104.56
	0.5	3.69	7.40	16.17	59.88
	0.6	0.16	1.76	4.99	29.15
	0.7	0.00	0.13	0.82	11.65

Table C.2.14.A

Imperial Valley Earthquake, 1979
Bonds Corner

Zarrabi's Model
kv=0 analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
Ag=0.2g V=250mm/s	0.1	548.59	514.57	286.24	453.91
	0.2	237.14	202.74	77.75	175.31
	0.3	120.92	83.75	23.73	71.37
	0.4	61.19	36.76	7.03	27.16
	0.5	31.73	15.07	1.45	10.37
	0.6	16.93	4.08	0.04	3.41
	0.7	7.81	0.36	0.00	0.46
Ag=0.3g V=375mm/s	0.1	853.17	791.87	439.58	700.22
	0.2	370.69	315.95	120.91	273.22
	0.3	191.13	131.94	37.28	112.34
	0.4	97.61	58.37	11.13	43.16
	0.5	50.97	24.09	2.31	16.59
	0.6	27.34	6.56	0.07	5.49
	0.7	12.67	0.58	0.00	0.74
Ag=0.4g V=500mm/s	0.1	1178.83	1083.00	599.95	960.00
	0.2	514.15	437.04	166.91	377.99
	0.3	267.47	184.16	51.90	156.71
	0.4	137.48	81.95	15.60	60.61
	0.5	72.08	33.98	3.26	23.41
	0.6	38.75	9.29	0.10	7.77
	0.7	17.99	0.82	0.00	1.05
Ag=0.5g V=600mm/s	0.1	1405.62	1279.15	707.24	1136.54
	0.2	614.60	521.32	198.79	450.97
	0.3	321.83	221.24	62.23	188.16
	0.4	166.02	98.83	18.79	73.10
	0.5	87.13	41.07	3.93	28.30
	0.6	46.81	11.24	0.12	9.40
	0.7	21.67	0.99	0.00	1.27
Ag=0.6g V=750mm/s	0.1	1891.35	1706.50	941.85	1519.65
	0.2	827.93	701.32	267.09	606.77
	0.3	435.34	299.13	84.04	254.30
	0.4	224.75	133.85	25.44	99.00
	0.5	117.73	55.62	5.33	38.31
	0.6	63.01	15.18	0.16	12.68
	0.7	28.98	1.32	0.00	1.70
Ag=0.7g V=875mm/s	0.1	2275.74	2038.01	1123.14	1818.61
	0.2	996.03	843.26	320.88	729.68
	0.3	524.67	360.73	101.31	306.58
	0.4	270.40	161.35	30.70	119.31
	0.5	141.00	66.86	6.42	46.02
	0.6	74.95	18.13	0.20	15.15
	0.7	34.11	1.57	0.00	2.01

Table C.2.14.B

Imperial Valley Earthquake, 1979
Bonds Corner

Zarrabi's Model
$kv \neq 0$ analysis

A, V	N/A	Relative Displacement (mm) in S50W	N50E	S40E	N40W
	0.1	549.14	514.70	285.42	454.64
	0.2	237.24	202.38	77.76	175.87
Ag=0.2g	0.3	121.41	84.06	23.77	71.92
	0.4	61.76	37.24	7.13	27.50
V=250mm/s	0.5	32.41	15.43	1.56	10.42
	0.6	17.47	4.54	0.07	3.40
	0.7	8.42	0.71	0.00	0.47
	0.1	854.72	792.29	437.74	701.94
	0.2	371.10	315.22	121.00	274.58
Ag=0.3g	0.3	192.41	132.78	37.39	113.65
	0.4	99.05	59.59	11.37	43.95
V=375mm/s	0.5	52.65	25.03	2.59	16.70
	0.6	28.72	7.71	0.12	5.49
	0.7	14.15	1.51	0.00	0.80
	0.1	1182.18	1084.03	596.72	963.18
	0.2	515.18	435.92	167.16	380.57
Ag=0.4g	0.3	270.02	185.88	52.17	159.20
	0.4	140.31	84.38	16.07	62.12
V=500mm/s	0.5	75.35	35.91	3.79	23.64
	0.6	41.45	11.59	0.20	7.80
	0.7	20.79	2.68	0.00	1.18
	0.1	1411.30	1281.09	702.68	1141.41
	0.2	616.50	519.99	199.26	454.87
Ag=0.5g	0.3	325.82	224.00	62.71	191.99
	0.4	170.51	102.63	19.53	75.40
V=600mm/s	0.5	92.25	44.18	4.76	28.66
	0.6	50.97	14.85	0.29	9.49
	0.7	25.89	3.94	0.00	1.48
	0.1	1901.51	1710.24	934.90	1527.76
	0.2	831.43	699.60	268.00	613.26
Ag=0.6g	0.3	441.99	303.86	84.94	260.71
	0.4	232.32	140.19	26.71	102.77
V=750mm/s	0.5	126.41	60.88	6.71	39.00
	0.6	69.88	21.17	0.46	12.96
	0.7	35.85	6.25	0.00	2.07
	0.1	2291.00	2044.07	1113.92	1830.39
	0.2	1001.32	841.24	322.37	739.09
Ag=0.7g	0.3	534.25	367.61	102.71	315.88
	0.4	281.25	170.39	32.54	124.68
V=875mm/s	0.5	153.50	74.60	8.45	47.13
	0.6	84.72	26.62	0.67	15.73
	0.7	43.70	8.55	0.00	2.54

Appendix D

Statistics Terms and Theorems

1. Mean, E[X]

$$E[X] = \frac{1}{n}\sum_{i=1}^{n} X_i$$

2. Variance, Var[X]

$$Var[X] = \frac{1}{n-1}\sum_{i=1}^{n} (X_i - E[X])^2$$

3. Standard Deviation, σ[X]

$$\sigma[X] = \sqrt{Var[X]}$$

4. Coefficient of Variation, V_x

$$V_x = \frac{\sigma[X]}{E[X]}$$

5. If X 's are independent, then

$$\text{for } Y = X_1 X_2 \; .... \; X_n$$

$$E[Y] = E[X_1]E[X_2] \; .... \; E[X_n]$$

$$Var[Y] = \prod (E[X_i]^2 + Var[X_i]) - E[Y]^2$$

$$V_y^2 = \prod (1 + V_{x_i}^2) - 1$$

6. If $X=e^Y$ then

$$Var[Y] = \ln (1 + V_x^2)$$

$$E[Y] = \ln(E[X]) - 0.5 \; Var[Y]$$

7. Central limit theorem states that if all X_i's are random variables, then the sum of X_i's will be approximately normally distributed.