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THE EQUIVALENT NUMBER OF CYCLES OF RECORDED ACCELEROGRAMS FOR SOIL LIQUEFACTION STUDIES

by

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16. Abstract (Limit: 200 words)

Four different procedures are studied for determining the equivalent number of cycles of available recorded accelerograms, from the viewpoint of liquefaction of saturated sand deposits. The cyclic shear stresses acting in the soil are assumed to be proportional to the surface accelerations; therefore, the accelerograms are used for the calculations instead of the cyclic stress time histories. The first procedure is based on an equivalence rule for each recorded cycle, derived from a representative cyclic strength curve of sands. The other three methods use the excess pore-water pressure as the equivalence parameter. A number of strong-motion accelerograms recorded during several earthquakes in the western United States are analyzed with the four methods. The corresponding equivalent numbers of cycles are compared among the four methods and correlated with earthquake magnitude, distance to the source, and azimuth.

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Liquefaction	Stresses
Sands	Static loads

b. Identifiers/Open-Ended Terms

Accelerograms
Ground motion
Western Region (United States)
Pore-water pressure

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LIST OF SYMBOLS

(ap)	peak acceleration of any cycle
(ap)ab	peak acceleration in one half-cycle
(ap)l	peak acceleration causing liquefaction in one cycle
(ap)max	maximum peak acceleration of the entire accelerogram
F.S.	factor of safety
N	number of applied equivalent cycles
(N)above	equivalent number of cycles above the time axis
(N)below	equivalent number of cycles below the time axis
(N)a	equivalent number of cycles at the begining of one half cycle
Nl	number of cycles required to cause liquefaction
Rn	cycles ratio
Ru	pore pressure ratio
(Ru)ab	increase in pore pressure ratio in one half cycle
(Ru)a	value of pore pressure ratio at the begining of one half cycle
(Ru)b	value of pore pressure ratio at the end of one half cycle
(t)a	time at the begining of one half cycle
(t)b	time at the end of one half cycle
u	pore-water pressure
σ_o'	effective overburden pressure
α	constant

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ABSTRACT

The primary purpose of this work is to study several procedures for determining the equivalent number of cycles of available recorded accelerograms, from the viewpoint of liquefaction of saturated sand deposits. The cyclic shear stresses acting in the soil are assumed to be proportional to the surface accelerations; therefore, the accelerograms are used for the calculations instead of the cyclic stress time histories. Four different procedures are presented and compared in this work. The first method is that originally proposed by Seed et al., (1975), which is based on an equivalence rule for each recorded cycle, derived from a representative cyclic strength curve of sands.

The other three methods were developed as part of this work, and they use the excess pore-water pressure as the equivalence parameter. In these methods the pore-pressure increment is computed for each half-cycle of the accelerogram under consideration. In Methods 3 and 4 the pore water pressure build-up during a uniform cyclic acceleration time history is assumed to vary linearly with number of cycles, and thus, the location of each half-cycle within the accelerogram does not influence its

contribution to pore pressure build-up. In Method 3, an unlimited pore pressure build-up is accepted, and it is demonstrated that this gives a result essentially identical to that of Method 1 proposed by Seed et al. (1975). In Method 4, the pore pressure build-up is limited to the onset of initial liquefaction, $u/\sigma'_o \leq 1.00$. In Method 2 a nonlinear variation of pore pressure with number of cycles is used, and the pore pressure buid-up is also limited to $u/\sigma'_o \leq 1.00$.

A number of strong-motion accelerograms recorded during several western U.S. earthquakes, including San Fernando 1971 are analized with the four methods. The corresponding equivalent numbers of cycles are compared among the different methods, and correlated with earthquake magnitude, distance to the source, and azimuth.

PART 1

INTRODUCTION

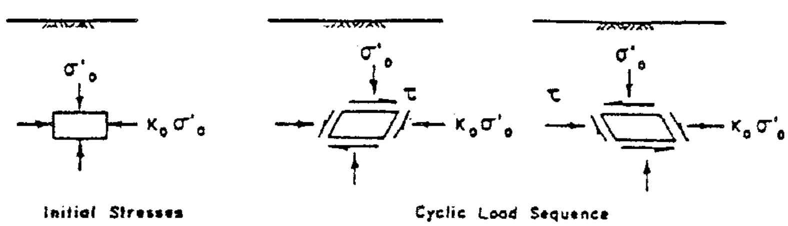
It is not difficult to recall the distress and amazement which confronted soil engineers when they first observed the enormous damage due to soil liquefaction both in Anchorage, Alaska and Niigata, Japan following both 1964 earthquakes. These events probably did more to stimulate geotechnical engineering studies of earthquake-induced liquefaction that any other single factor. Also, the need to consider the problem for the design of nuclear power plants and off-shore structures has played a major role. All of this has led to increasing efforts in the development of procedures for evaluating the liquefaction potential of soil deposits.

This should not be construed to imply that liquefaction of sands is a new subject for geotechnical engineering studies. The major new development of the problem is a recognition of the manner in which it can develop under cyclic loading conditions. Liquefaction induced by static loading has been a familiar topic to virtually all soil engineers since the classical work of Casagrande

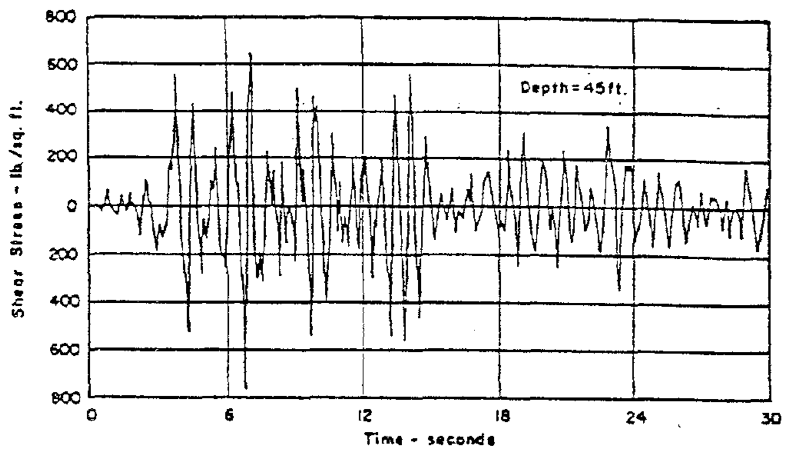
(1936) in this area.

1.1 Causes of Seismic Liquefaction

It is now generally recognized that the basic cause of cyclic liquefaction of saturated cohesionless soil during an earthquake is the build-up of excess pore-water pressures due to the application of cyclic shear stresses or strains induced by the ground motions. These stresses are generally considered to be due primarily to vertical propagation of shear waves in a soil deposit, although other forms of wave motions are also expected to occur. Thus, soil elements can be considered to undergo a series of cyclic stresses as illustrated in Fig. 1-a, with the stress series having a somewhat random pattern but being nevertheless cyclic in nature, as shown in Fig 1-b.



a) IDEALIZED FIELD LOADING CONDITIONS



b) SHEAR STRESS VARIATION DETERMINED BY RESPONSE ANALYSIS

FIG.1 Cyclic Shear Stresses on a Soil Element During Ground Shaking (Seed, 1979)

1.2 Methods for Evaluating the Seismic Liquefaction Potential of Sands Deposits.

There have been basically three methods available for evaluating the cyclic liquefaction potential of a deposit of saturated sand subjected to earthquake shaking:

i) Methods based on observation of the performance of sand deposits in previous earthquakes (Seed and Idriss, 1971; Castro, 1975).

ii) Methods based on cyclic stress-controlled laboratory test results.

iii) Methods based on cyclic strain-controlled laboratory test results (Dobry and Ladd, 1981).

Methods i) and iii) are outside the scope of the present work, and will not be discussed further herein. In what follows, the main aspects of method ii), which is based on stress-controlled test results, are described.

Procedures based on stress-controlled tests for evaluating the cyclic liquefaction potential of soil deposits were first proposed by Seed and Idriss (1967), and involve two independent determinations: (1) an evaluation of the cyclic stresses induced at different levels in the deposit by the earthquake shaking, and (2) a laboratory investigation with cyclic stress-controlled tests, to determine the cyclic stresses, which at given confining pressures representative of specific depths in the deposit, will cause the soil to liquefy or undergo various degrees of cyclic strain. The evaluation of liquefaction potential is based on a comparison of the cyclic stresses induced in the field with the stresses required to cause cyclic liquefaction or an acceptable limit of cyclic strain in representative samples in the laboratory.

Even in its simplest form, this type of approach requires the development of five basic steps (Seed, 1979):

1.- Development of suitable analytical procedures for evaluating the stresses developed in a potentially liquefiable layer in the ground during a given earthquake.

2.- Development of a suitable procedure for representing the irregular stress history produced by an earthquake by an equivalent uniform cyclic stress series. This requires an estimate of the duration of the design earthquake at the site, as measured by the equivalent number of cycles, N.

3.- Development of a suitable test procedure for measuring the cyclic stress condition causing initial liquefaction or a given level of strain in representative samples of soil.

4.- Development of an understanding of all the factors having a significant influence on the liquefaction characteristic of soils.

5.- Development of an understanding of the effects of sample disturbance on the laboratory determination of in-situ properties of natural deposits.

In the rest of the work presented herein, the focus is on step 2, and on the determination of the equivalent number of cycles required to plan laboratory tests and make design decisions.

1.3 Importance of the Earthquake Duration.

It is known that longer earthquake durations tend to increase the damaging effect of earthquakes on the stability of both structures and soil deposits. This parameter, together with the level of shaking and the frequency content, is a very important earthquake characteristic for engineering purposes (Housner, 1975; Seed et al, 1969; Schnabel and Seed, 1972; Seed et al, 1975; Dobry et al., 1978).

While some facilities would not suffer any damage if high shaking levels are applied during short periods of time, they could collapse under the same or even lower accelerations during a longer earthquake. For instance, during the 1966 Parkfield earthquake, with a high peak acceleration (about 0.5g) and short duration, very little structural damage was observed. On the other hand, during the 1971 San Fernando earthquake, the upstream slope of a hydraulic fill dam failed due to liquefaction, apparently near the end of the earthquake. It was concluded (Seed et al., 1975), that if the duration of motion had been shorter, the slide may have not happened at all, while if it had lasted longer the collapse of the whole dam may have occured, flooding the densely populated downstream area.

The earthquake motion may induce a pore-water pressure build-up in saturated soil deposits, which in the case of loose sands may eventually lead to liquefaction (almost total loss of strength). A totally liquefied soil can undergo very large deformations and literally flow over large distances as was the cases in 1964 in the Alaska and Niigata, Japan earthquakes.

1.4 Objectives

The main objectives of this work are: a) to develop several methods of calculating the equivalent number of cycles of an accelerogram, N, b) to compare the different methods among themselves and with the method proposed by Seed et al., (1975), and c) to use these methods to process actual earthquake records, and to establish correlations between N, earthquake magnitude and other parameters.

PART 2

METHOD 1

2.1 Description

Method 1 for calculating the equivalent number of cycles, N, of a recorded accelerogram, is identical to the analytical procedure used by Seed et al, (1975). The essential feature of the method, is the development of a simple way to determine the series of uniform shear stress cycles which is equivalent in its effects, to the irregular shear stress pattern resulting from the earthquake motion. This simple way, which is described in parts 2.1 and 2.2, is based on laboratory cyclic stress-controlled test results. As mentioned before, and as discussed again in part 2.1.1, the method is applied to accelerograms instead of stress time histories.

2.1.1 The Shear Stress Time History

The irregular shear stress time history at a shallow depth below the ground surface (such as shown in Fig. 1) is, for all practical purposes, proportional to the horizontal acceleration time history at the ground surface (Seed and Idriss, 1971). Thus, from the horizontal accelerations records of past earthquakes the equivalent number of stress cycles at any prescribed stress level can readily be determined. Therefore, in the rest of this work, the words stress and acceleration will be used interchangeably for this purpose.

2.1.2 The Weighting Curve

In order to obtain the uniform stress cycles, the cyclic strength curve shown in Fig. 2 is used. This curve was obtained from typical laboratory results on saturated sands, as detailed in Appendix A. In Fig. 2, the ratio $ap/(ap)_1$ is plotted versus the number of cycles required for liquefaction, where ap = peak acceleration of any cycle within the accelerogram, and $(ap)_1$ = peak acceleration causing liquefaction in one cycle. If we further define (ap)max = maximum peak acceleration of the entire accelerogram, and F.S. = $(ap)_1/(ap)max$, then Fig. 2 can be interpreted to correspond to an accelerogram having a Safety Factor F.S. = 1.00, and the ordinates can be interpreted to mean ap/(ap)max.

In Method 1, each half-cycle of an irregular accelerogram, is transformed into an equivalent number of uniform stress cycles, by means of a weighting factor obtained from Fig. 2, and from the Safety Factor, F.S., as explained in Appendix A. An additional parameter which needs to be defined is the value of the peak uniform acceleration used, as a percentage of the maximum acceleration of the accelerogram, (ap)max. Following Seed et al., (1975), the percentage used in this work is 65% of (ap)max. This means that the uniform cyclic acceleration series has an amplitude equal to 65% of the maximum acceleration of the accelerogram, (ap)max.

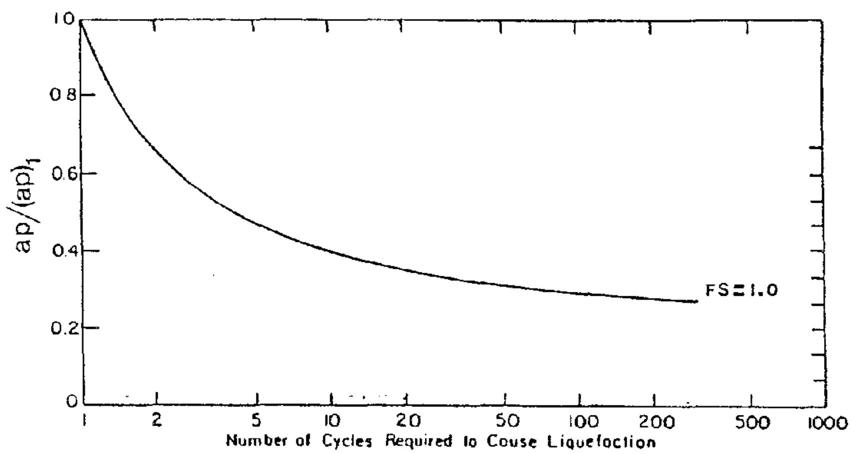


FIG.2 Representative Relationship Between $ap/(ap)_1$ and the Number of Cycles Required to cause Liquefaction

2.2 Procedure for Method 1 (Seed et al., 1975)

The procedure to obtain the equivalent number of cycles at 0.65 (ap)max, is applied twice by Seed et al. (1975) for the same accelerogram. In the first analysis, only the part of the accelerogram located above the time axis is considered, and the equivalent number of cycles, N(above), is computed. For the second analysis, only the part of the accelerogram below the time axis is considered and the equivalent number of cycles, N(below) is computed. Both analyses are independent of each other, even though the procedure is identical for the two cases. The final equivalent number of cycles, is the average of the cycles found in both cases, that means N = 1/2(N(above) + N(below)).

The following steps must be considered in order to obtain the desired equivalent number of cycles for the accelerogram, N:

a.- The equivalent number of cycles representative of any record depends greatly on the choice of the maximum acceleration considered to be representative of the site in question. Where both components of a record motion have about the same maximum acceleration, (ap)max, this presents no problem. But when the two components at any site have quite differents values of (ap)max, the appropiate number of cycles representative of the effects of the motions depends on the degree of conservantism adopted. From some studies of this aspect, it is possible to say that the strongest component of motion at a site dominates the liquefaction potential (Seed et al., 1975). Therefore, the first step is to choose the maximum peak acceleration that will be representative of the site in question.

b.- Choose the acceleration level, as a fraction of (ap)max, selected for the uniform acceleration series. In this work, and following Seed et al., (1975) the value adopted is 0.65 (ap)max.

c.- Count up the number of cycles in the accelerogram corresponding to different acceleration levels. Above the time axis for N(above), and below the time axis for N(below).

d.- Use the Weighting curve procedure, (see Appendix A), for obtaining the conversion factor to 0.65 (ap)max for each acceleration level, and multiply the number of cycles obtained in step (c) by the respective factor.

e.- Add all numbers of cycles at all acceleration levels obtained in step (d), and obtain the equivalent numbers of cycles, N(above) and N(below) respectively. Finally, compute N = 1/2(N(above) + N(below)). This later value, N, is the desired equivalent number of cycles of the accelerogram in question.

This is the procedure used by Seed et al., (1975) to obtain the number of equivalent cycles of recorded accelerograms. Method 1 was incorporated into the first part of the computer program included in Appendix F.

In this method it is useful to obtain curves similar to that shown in Fig. 2, but for values of F.S. different from 1.00. This has been done in Fig. 3 for F.S. = 1.50; 1.75 and 2.00. In Fig. 3, ap/(ap)max is plotted versus number of cycles. Fig. 3 was obtained from Fig. 2 by means of the expression: $ap/(ap)max = ((F.S.)(ap))/(ap)_1$ Therefore, the curve labelled "F.S.= 1.00" in Fig. 3 is identical to the curve of Fig. 2.

For the development of Method 1, Seed et al., (1975) used the weighting curve shown in Fig. 3 with a safety factor, F.S = 1.50, which means that the curve is developed for a condition where the acceleration required to cause failure in one cycle is equal to 1.5 times the maximun acceleration of the earthquake, (ap)max. For the present work safety factors of 1.00, 1.50, 1.75 and 2.00 are used.

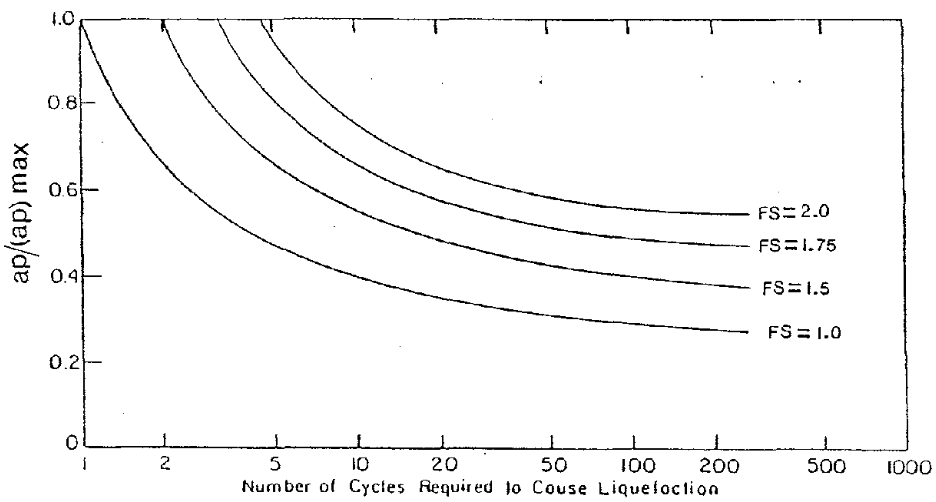


FIG.3 Representative Relationship Between ap/(ap)max and Number of Cycles Required to Cause Liquefaction

2.3 Examples

An illustration of Method 1 follows, in Examples 1 and 2, using respectively each of the components of the motion recorded at the Orion Blvd. site in San Fernando earthquake 1971, and for F.S.= 1.50. The conversion factor listed in the examples for different values of ap/(ap)max were obtained from Fig. 3, for F.S. = 1.50. These same conversion factors are listed in Table A-2 for F.S. = 1.50 and in Tables A-1, A-3 and A-4 for F.S. = 1.00, F.S. = 1.75 and F.S. = 2.00 respectively. For example, the conversion factor = 0.20 for ap/(ap)max = 0.50 and F.S. = 1.5 was obtained as follows:

From Fig. 3:

6 cycles of ap = 0.65(ap)max are required to cause liquefaction

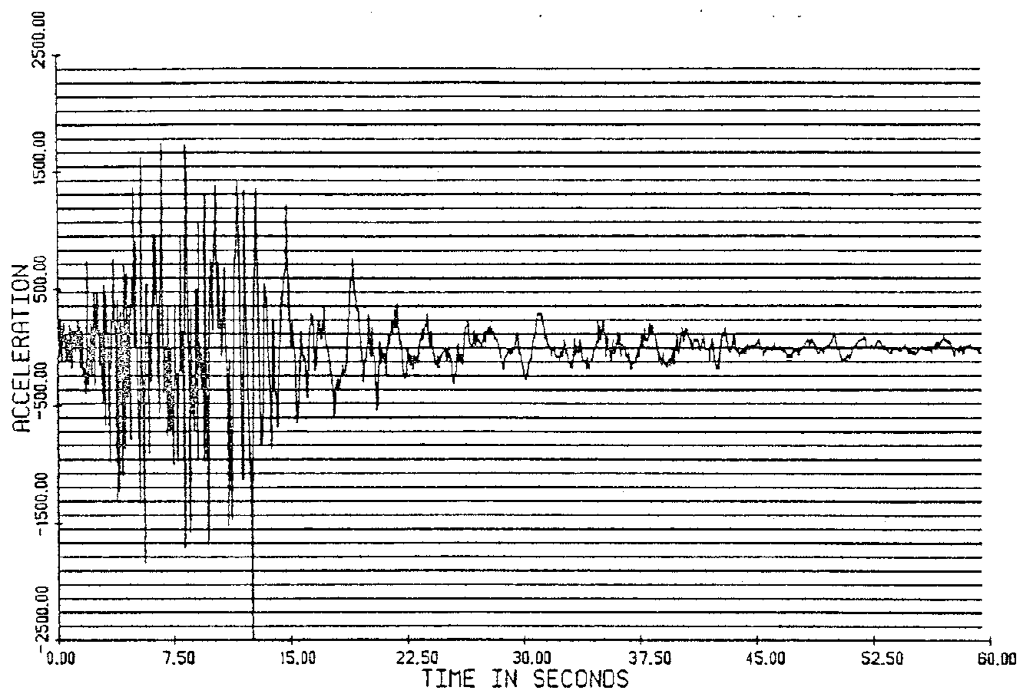
28 cycles of ap = 0.50(ap)max are required to cause liquefaction

therefore, 1 cycle of 0.50(ap)max is equivalent to

6/28 = 0.20 cycles of 0.65(ap)max, and the conversion factor = 0.20

EXAMPLE 1

EVALUATION OF THE EQUIVALENT UNIFORM STRESS CYCLES FOR ORION BOULEVARD RECORD (Component North-South)



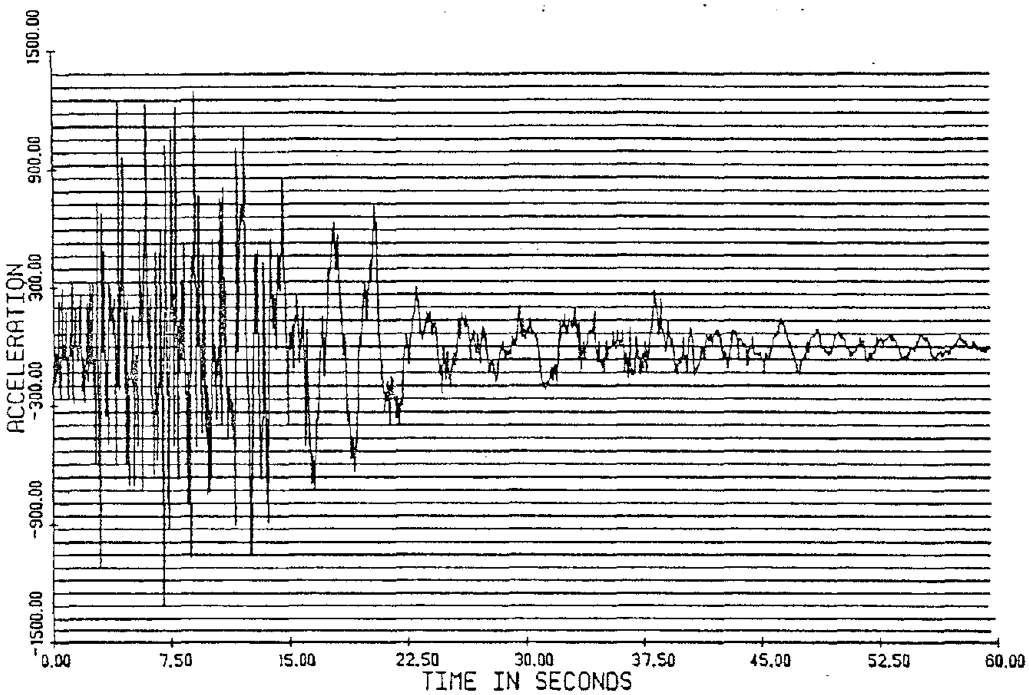
ORION BLVD. RECORD, N-S COMP. SAN FERNANDO EARTHQUAKE, 1971

ap/(ap) max	ABOVE HORIZONTAL AXIS: NUMBER OF STRESS CYCLES	CONVERSION FACTOR	EQUIVALENT NO. OF CYCLES AT 0.65(ap) max	BELOW HORIZONTAL AXIS: NUMBER OF STRESS CYCLES	CONVERSION FACTOR	EQUIVALENT NO. OF CYCLES AT 0.65(ap) max
1.00 (ap)max	---	---	---	1	3.00	3.00
0.95	---	---	---	---	---	---
0.90	---	---	---	---	---	
0.85	---	---	---	1	---	---
0.80	---	---	---	---	---	---
0.75	---	---	---	---	---	---
0.70	2	1.20	2.40	2	1.20	2.40
0.65	1	1.00	1.00	2	1.00	2.00
0.60	---	---	---	2	0.70	1.40
0.55	6	0.40	2.40	---	---	---
0.50	1	0.20	0.20	3	0.20	0.60
0.45	1	0.10	0.10	2	0.10	0.20
0.40	2	0.04	0.08	3	0.04	0.12
0.35	1	0.02	0.02	6	0.02	0.02
0.30	---	---	---	---	---	---
		TOTAL	6.20		TOTAL	9.84

AVERAGE NUMBER OF CYCLES AT 0.65(ap)max = 8.0

EXAMPLE 2

EVALUATION OF THE EQUIVALENT UNIFORM STRESS CYCLES FOR ORION BOULEVARD RECORD (Component East-West)



ORION BLVD. RECORD, E-W COMP. SAN FERNANDO EARTHQUAKE, 1971

ap/(ap) max	ABOVE HORIZONTAL AXIS: NUMBER OF STRESS CYCLES	ABOVE HORIZONTAL AXIS: CONVERSION FACTOR	ABOVE HORIZONTAL AXIS: EQUIVALENT NO. OF CYCLES AT 0.65(ap)max	BELOW HORIZONTAL AXIS: NUMBER OF STRESS CYCLES	BELOW HORIZONTAL AXIS: CONVERSION FACTOR	BELOW HORIZONTAL AXIS: EQUIVALENT NO. OF CYCLES AT 0.65(ap)max
1.00 (ap) max	---	---	---	1	3.00	3.00
0.95	3	2.70	8.10	---	---	---
0.90	1	2.40	2.40	---	---	---
0.85	2	2.05	4.10	1	2.05	2.05
0.80	---	---	---	2	1.70	3.40
0.75	3	1.40	4.20	---	---	---
0.70	---	---	---	2	1.20	2.40
0.65	1	1.00	1.00	1	1.00	1.00
0.60	2	0.70	1.40	1	0.70	0.70
0.55	3	0.40	1.20	3	0.40	1.20
0.50	1	0.20	0.20	5	0.20	1.00
0.45	3	0.10	0.30	5	0.10	0.50
0.40	3	0.04	0.12	---	---	---
0.35	5	0.02	0.10	7	0.02	0.14
0.30	---	---	---	---	---	---
		TOTAL	23.12		TOTAL	15.39

AVERAGE NUMBER OF CYCLES at 0.65(ap)max = 19.30

2.4 Discussion

For Method 1, the effect of one cycle on the liquefaction process of the soil is considered to be the same no matter what the position of the cycle is in the stress time history. Therefore, in this method the analysis of the entire accelerogram is always done because there is no explicit way to know if initial liquefaction did occur at some intermediate point during the shaking.

PART 3

METHOD 2

3.1 Description

The method developed in this section uses the law of development of excess pore pressure in saturated sands, measured experimentally during cyclic stress controlled tests, to compute the equivalent number of cycles, N. This law is used in conjunction with the curves of Fig. 3.

3.2 Pore Water Pressure Development During an Earthquake Motion

By observing the rate of pore-water pressure development during cyclic stress controlled tests, it has been found that the rate of build-up generally lies within a fairly narrow range, when plotted in the normalized form shown in Figs. 4 and 5. Thus, for example, tests on different sands in cyclic triaxial tests, show data falling within the band shown in Fig. 4 (Lee and Albaisa, 1974), and tests on sands in cyclic simple shear tests show data falling within the band presented in Fig. 5. (De Alba et al, 1975). The use of such data and the assumption that other sands will exhibit similar characteristic, provides a reasonable basis for the practical assessment of pore-water pressure build-up in sand deposits.

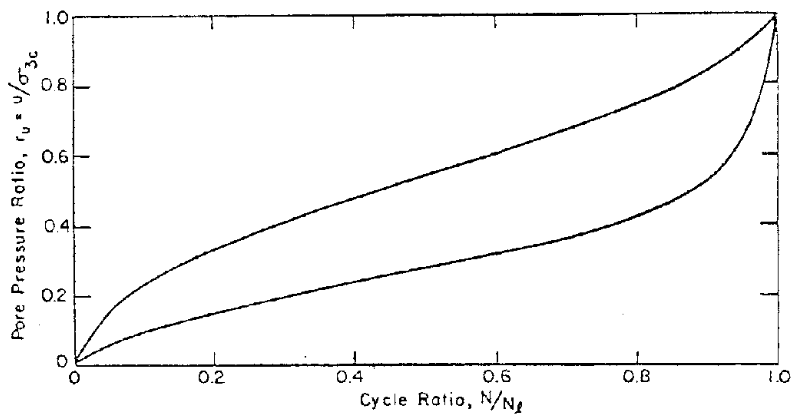


FIG.4 Rate of Pore Pressure Build-up in Triaxial Tests (Lee and Albaisa, 1974)

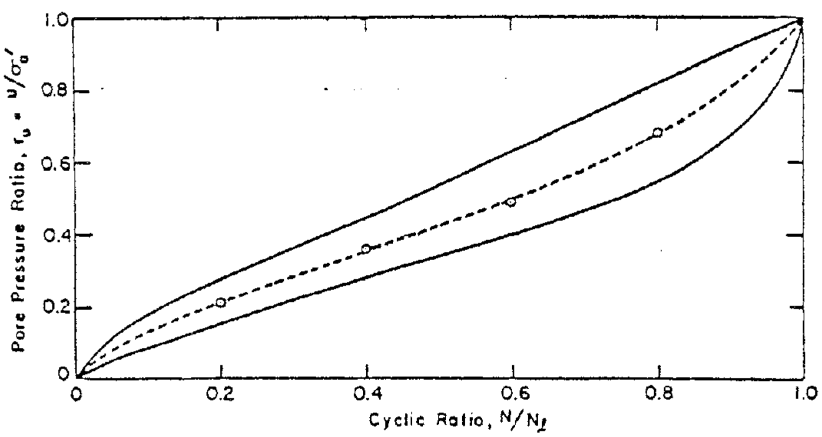


FIG.5 Rate of Pore-Water Pressure Build-up in Cyclic Simple Shear Tests (De Alba et al., 1975)

For the purpose of developing Method 2, it appears that the curve shown by the dashed line in Fig. 5, representative of sands with relative density of about 60%, provides the best general representation of the rate of pore pressure development in sands exhibiting a serious liquefaction potential problem. Accordingly, this curve has been adopted as a convenient basis for predicting the rate of pore-water pressure generation in Method 2.

If the excess pore pressure ratio, Ru, is defined as:

$$Ru = u/\sigma_o' \qquad (3.1)$$

and the cycles ratio Rn is defined as:

$$Rn = N/N1 \qquad (3.2)$$

where:

u = excess pore-water pressure

σ_o' = initial effective overburden pressure

N = the number of applied equivalent cycles

N1 = the number of cycles required to cause initial liquefaction, defined by Ru = 1.00.

Then, the following expression may be shown to fit the characteristics of the curve presented in Fig. 5 as used by Seed et al., (1975).

$$Rn = (1/2(1.00 - \cos \pi Ru))^{\alpha} \qquad (3.3)$$

The value of α is a function of the soil properties and test conditions. For the dashed line in Fig. 5, a value of $\alpha = 0.7$ provides the best fit. In fact, the dashed line was plotted from Eq. (3.3) with $\alpha = 0.7$.

Where required, the pore pressure ratio Ru may be expressed in terms of the cycle ratio Rn by inverting Eq. (3.3):

$$Ru = (1/2) + (1/\pi)\arcsin(2(N/Nl)^{1/\alpha} - 1.00) \qquad (3.4)$$

Having established this relationship, the rate of generation of pore-water pressure in a soil deposit, and the equivalent number of cycles at 0.65 (ap)max, can both be found using equations (3.3) and (3.4). This is Method 2, as explained below in part 3.3.

3.3 Procedure for Method 2

Method 2 uses equations (3.3) and (3.4) to calculate the pore pressure build-up, Ru, versus time, for an arbitrary accelerogram. This is done by combining equations (3.1) and (3.2) with Fig. 3. It is assumed here that the cyclic strength curve for the selected F.S., in Fig. 3 corresponds to the number of equivalent cycles, Nl, of initial liquefaction failure, i.e. Ru = 1.00.

To apply the procedure to an arbitrary accelerogram, it is further assumed that the increment of excess pore pressure, δ(Ru)ab, produced by an acceleration half-cycle between times t(a) and t(b) and having a peak (ap)ab is (see Fig. 6):

δ(Ru)ab = f((Ru)a, (ap)ab)

and (Ru)b = (Ru)a + (Ru)ab

that is, δ(Ru)ab and (Ru)b are function only of the pore pressure at the beginning of the half-cycle, (Ru)a, and of the peak acceleration (ap)ab. This function, f((Ru)a; (ap)ab) or more conveniently, (Ru)b can be evaluated numerically for each half-cycle.

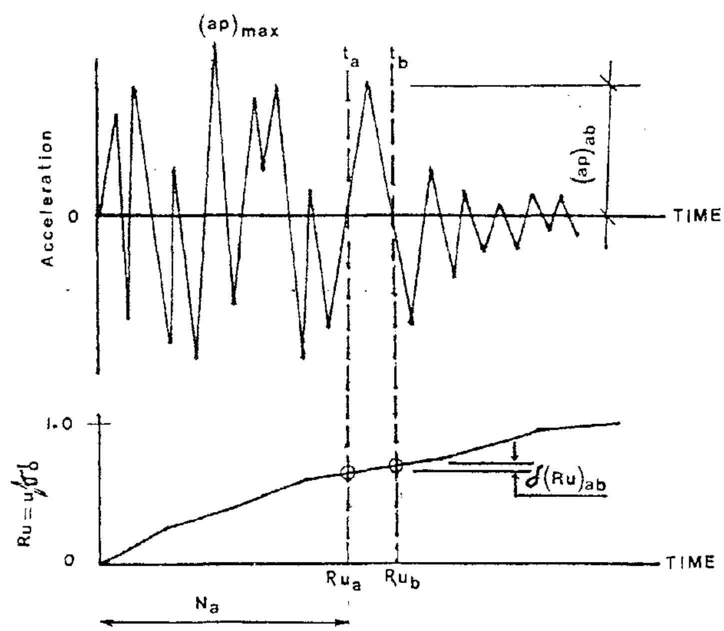


FIG.6 Increment of Pore-Water Pressure in Half-Cycle

The specific procedure to obtain, for a given accelerogram and a given safety factor, F.S., the equivalent number of cycles at 0.65 (ap)max is described in the following steps:

a.- Read the first half-cycle peak acceleration, (ap), in the accelerogram. This half-cycle may be above or below the time axis.

b.- From the curve in Fig. 3, selected for the given S.F., obtain the number of cycles that cause initial liquefaction, Nl, for the value of (ap) founded in step (a).

c.- Using equation (3.3), with the initial normalized pore pressure, Ru(a) = 0 at the begining of the accelerogram, and the value of Nl determined in step (b), above, find the current number of equivalent cycles, Na.

$$Rn = Na/Nl = (1/2(1.00 - \cos\pi(Ru)a))^{\alpha} \quad (3.3\text{-a})$$

$$Na = Nl(1/2(1.00 - \cos\pi(Ru)a))^{\alpha} = 0 \quad (3.3\text{-b})$$

d.- Using equation (3.4) find the pore pressure ratio at the end of the subsequent half-cycle, (Ru)b:

$$(Ru)b = 1/2+1/\pi \arcsin(2((Na+1/2)^{1/\alpha}/Nl) -1.00) \quad (3.4\text{-a})$$

Na = 0.0 for the first half-cycle

e.- Start againg in step (a), reading the next value of peak acceleration, ap, and for the initial pore-water pressure at the beginning of the next half-cycle use the incremented value founded in step (d). Continue with this procedure until (Ru)b = 1.00, which means that the soil has reached initial liquefaction , or until the end of the accelerogram if always (Ru)b < 1.00 and the earthquake did not produce liquefaction for the site in question.

f.- Using equation (3.3) with Nl for 0.65 (ap)max and the final value of (Ru)b determined in step (d), find the equivalent number of cycles at 0.65 (ap)max.

$$N = Nl(1/2(1.00 - \cos \pi Ru(b)))^{\alpha} \qquad (3.3\text{-c})$$

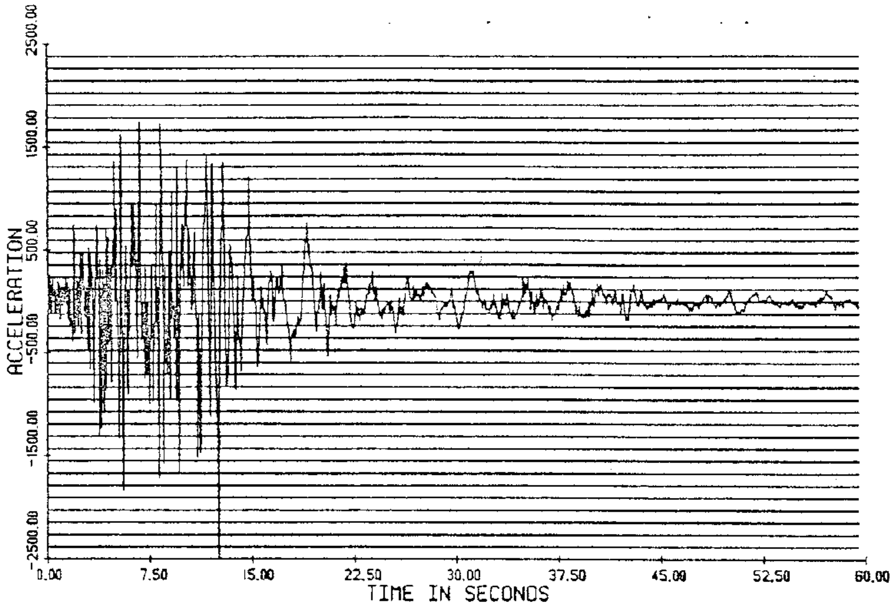
(Ru)b = the last increment of pore pressure calculated in step (e).

3.4 Examples

An illustration of the method is presented in Examples 3 and 4, using each of the components of the motion recorded at the Orion Blvd. site in San Fernando earthquake 1971, and for F.S.= 1.50. This method corresponds to the second part of the computer program included in Appendix F.

EXAMPLE 3

EVALUATION OF THE EQUIVALENT UNIFORM STRESS CYCLES FOR ORION BOULEVARD RECORD (Component North-South)



ORION BLVD. RECORD. N-S COMP. SAN FERNANDO EARTHQUAKE, 1971

SAFETY FACTOR = 1.50
METHOD 2

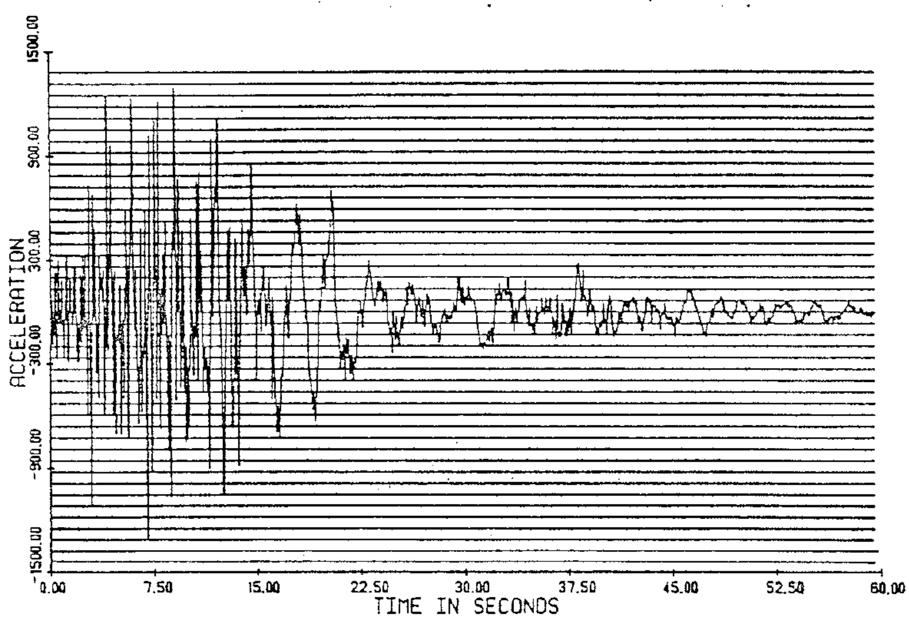
PEAK ACCELERATION mm/sec^2	NORMALIZED ACCELERATION ap/(ap)max	$N\ell$	(Ru)b	N	(Ru)a
1295	0.52	20.80	0.00	0.00	0.04
1228	0.49	52.00	0.04	1.25	0.06
1091	0.44	139.60	0.06	4.70	0.06
1371	0.55	16.00	0.06	0.60	0.09
1331	0.53	23.20	0.09	1.59	0.11
1625	0.65	6.00	0.11	0.54	0.18
1837	0.73	4.68	0.18	0.81	0.26
1747	0.70	5.00	0.26	1.40	0.33
1000	0.40	160.00	0.33	60.83	0.34
1771	0.68	5.60	0.34	2.15	0.40
1734	0.69	5.80	0.40	2.74	0.46
1575	0.63	7.68	0.46	4.29	0.51
1071	0.43	119.20	0.51	74.37	0.51
1321	0.53	23.20	0.51	14.57	0.53
1679	0.67	6.40	0.53	4.16	0.59
1378	0.55	16.00	0.59	11.64	0.61
1517	0.61	6.56	0.61	4.98	0.68
1410	0.56	10.24	0.68	8.55	0.74
1125	0.45	58.00	0.74	51.28	0.75
1344	0.54	25.60	0.75	22.85	0.77
2500	1.00	2.00	0.77	1.82	1.00

(ap) max = 2500.0 mm/sec^2

N = 6 cycles

EXAMPLE 4

EVALUATION OF THE EQUIVALENT UNIFORM STRESS CYCLES FOR ORION BOULEVARD RECORD (Component East-West)



ORION BLVD. RECORD, E-W COMP. SAN FERNANDO EARTHQUAKE, 1971

SAFETY FACTOR = 1.5
METHOD 2

PEAK ACCELERATION mm/sec^2	NORMALIZED ACCELERATION ap/(ap)max	Nℓ	(Ru)b	N	(Ru)a
597	0.45	58.00	0.00	0.00	0.02
735	0.56	10.24	0.02	0.09	0.08
1120	0.85	2.90	0.08	0.17	0.23
682	0.52	20.80	0.23	4.78	0.25
583	0.44	139.60	0.25	35.44	0.25
1239	0.94	2.44	0.25	0.63	0.39
964	0.73	4.68	0.39	2.16	0.47
586	0.44	139.60	0.47	79.47	0.47
700	0.53	23.20	0.47	13.29	0.48
702	0.53	23.20	0.48	13.79	0.50
591	0.45	58.00	0.50	35.72	0.51
719	0.55	16.00	0.51	9.99	0.53
1233	0.94	2.44	0.53	1.60	0.71
595	0.45	58.00	0.71	49.92	0.72
575	0.44	139.60	0.72	121.36	0.72
596	0.45	58.00	0.72	50.63	0.73
1317	1.00	2.00	0.73	1.76	1.00

(ap) max = 1317.0 mm/sec^2

N = 6 cycles

3.5 Discussion

Method 2 considers the position of each half-cycle in the accelerogram as an increment of the pore-water pressure in the soil deposit. Therefore, the effect of one half-cycle on the liquefaction of the soil depends on the history of previous half-cycles. If the value of pore pressure is Ru = 1.00, which is the maximum normalized value, there is initial liquefaction. This may or may not happen before the end of the accelerogram. In Method 2, unlike Method 1, it is possible to know the time at which initial liquefaction occurs.

PART 4

METHODS 3 AND 4

4.1 Description

In Method 2, already discussed in Part 3, the pore pressure build-up during a uniform cyclic acceleration time history was assumed to vary as shown by the dashed line in Fig. 5. In Methods 3 and 4, the pore pressure build-up during a uniform cyclic acceleration time history is assumed to vary linearly with number of cycles, as shown in Fig. 7. Using the same assumptions and symbols as in Part 3, the increment of the pore pressure $\delta(Ru)ab$, corresponding to a half-cycle with a peak acceleration (ap)ab (see Fig. 6), is:

$$\delta(Ru)ab = 1/(2N1) \qquad (4.1)$$

$$(Ru)b = (Ru)a + \delta(Ru)ab$$

where N1 is obtained from (ap)ab and from Fig. 3 for the corresponding F.S., and where $\delta(Ru)ab$ is <u>not</u> a function of the pore pressure at the beginning of the half-cycle, (Ru)a.

Therefore, in Methods 3 and 4 the location of each half-cycle in an arbitrary accelerogram does not influence its contribution to pore pressure build-up. If Fig. 7 is used, it is possible to make the analysis of the stress time history under two differents points of view:

1.- Study the acceleration time history of the site in question until the end, and keep computing Ru even if initial liquefaction occurs, and Ru becomes equal to 1.00. In this procedure values of Ru $\geq$ 1.00 are accepted. This is the procedure used for the analysis in METHOD 3. It can be demostrated that this method is conceptually identical to Method 1, discussed before.

2.- Study the acceleration time history of the site in question but imposing the condition Ru $\leq$ 1.00. This is a realistic limitation, as the soil can not build-up pore-pressure beyond initial liquefaction. In this procedure, the soil gets, either a condition of initial liquefaction Ru = 1.0 during the accelerogram, or Ru < 1.00 at the end of the accelerogrma. This is the procedure used for the analysis in METHOD 4.

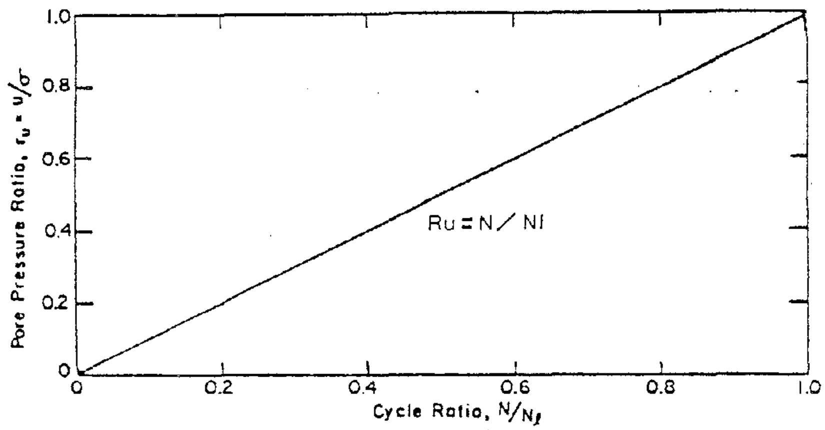


FIG.7 Linear Rate of Pore Water Pressure Build-up

In Methods 3 and 4, the straight-line showed in Fig. 7 provides the representation of pore pressure build-up with the number of cycles, and is used for predicting the rate of pore water pressure generation in both methods. Equations similar to Eq. (3.3) and (3.4), but now based on the linear pore pressure law of Fig. 7, must be considered:

4.1.1 Linear Variation

For the assumed linear variation of Ru, the pore pressure ratio at time (t)a in Fig. 6 is equal to the cycle ratio.

$$(Rn)a = Na/Nl = (Ru)a \quad (4.2)$$

$$Na = (Ru)a \times Nl \quad (4.3)$$

where Nl must be obtained from Fig. 3 for (ap)ab and for the selected F.S. The pore pressure ratio at time (t)b, (Ru)b, can be obtained by inverting Eq. (4.3) and using (Na + 1/2) instead of Na.

(Ru)b = (Na + (1/2))/Nl (4.4)

Having established this relationship, the rate of generation of pore-water pressure and the equivalent number of cycles for Methods 3 and 4, can be found using equations (4.2), (4.3), and (4.4) in the following procedure.

4.2 Procedure for Methods 3 and 4

4.2.1 Procedure for Method 3

a.- As in Method 2, read the first peak acceleration, (ap) in the accelerogram, and start with the initial pore pressure (Ru)a = 0.0

b.- From the curve in Fig. 3, selected for a given safety factor, find the number of cycles that cause liquefaction, Nl, for this value of (ap).

c.- Using equation (4.3), find the value of Na.

Na = (Ru)a x Nl

For the first half-cycle, Na = (Ru)a = 0

d.- The pore-water pressure after the half-cycle is found using equation (4.4) with the values computed in steps (b) and (c)

(Ru)b = (Na + (1/2))/Nl

e.- Start again in step (a), reading the new value for (ap) and using the increment of pore pressure found in step (d) above. Continue with this procedure until the end of the accelerogram.

f.- When the last value of pore pressure is found, read in the weighting curve Nl for 0.65 (ap)max.

g.- Substitute in equation (4.3), Nl determined in step (f), and the last value of (Ru)b (i.e at the end of the accelerogram), and find the equivalent number of cycles at 0.65 (ap)max, N.

N = (Ru)b X Nl

4.2.2 Procedure for Method 4

a.- As in Method 2, read the first peak acceleration (ap) in the accelerogram, and start with the initial pore pressure (Ru)a = 0.0

b.- From the curve in Fig. 3, selected for a given safety factor, find the number of cycles that cause liquefaction, Nl, for this value of (ap).

c.- Using equation (4.3), find the value of Na.

Na = (Ru)a X Nl

For the first half-cycle, (Ru)a = 0

d.- The pore-water pressure increment after the half-cycle is found using equation (4.4) with the values computed in steps (b) and (c).

(Ru)b = (Na + (1/2))/Nl

e.- Start againg in step (a), reading the new value for (ap) and using the increment of pore pressure found in step (d). Continue with this procedure until the value of pore-water pressure (Ru)b = 1.00, which means that the soil has reached initial liquefaction or, until the end of the accelerogram if always Ru < 1.00, which means that the earthquake did not produce liquefaction for the site in question.

f.- When the last value of pore pressure (Ru)b is found, either (Ru)b < 1.0 or (Ru)b = 1.0, read in the weighting curve of Fig. 3, Nl for 0.65 (ap)max.

g.- Substitute in equatiòn (4.3), Nl determined in step (f), and the last value of (Ru)b, and find the equivalent number of cycles at 0.65 (ap)max, N.

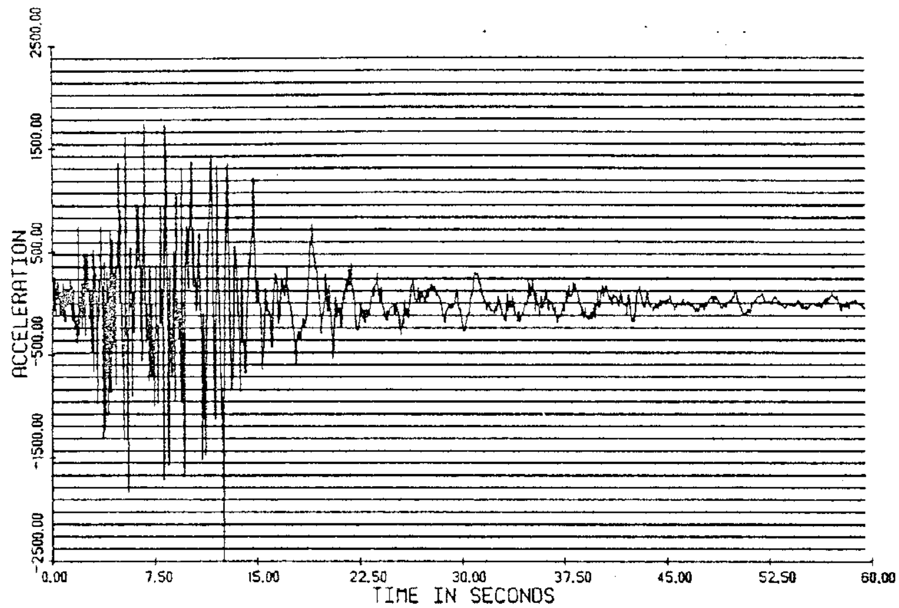
N = (Ru)b x Nl

4.3 Examples

Both methods are illustrated by Examples 5 and 6, using each of the components of the motion recorded at Orion Blvd. site in San Fernando earthquake 1971, and for F.S.= 1.50. This method corresponds to the third part of the computer program included in Appendix F. For both components, (Ru)b > 1.0 at the end of the earthquake, indicating that the liquefaction ocurred up to the time at which Ru = 1.0, the calculations shown in Examples 5 and 6 are valid for both Methods 3 and 4. However, for times beyond the instant at which Ru = 1.0, the calculations shown in Examples 5 and 6 are applicable only to Method 3.

EXAMPLE 5

EVALUATION OF THE EQUIVALENT UNIFORM STRESS CYCLES FOR ORION BOULEVARD RECORD (Component North-South)



ORION BLVD. RECORD, N-S COMP. SAN FERNANDO EARTHQUAKE, 1971

SAFETY FACTOR = 1.50

METHOD 3

PEAK ACCELERATION mm/sec^2	NORMALIZED ACCELERATION ap/(ap)max	Nℓ	(Ru)b	N	(Ru)a
1295	0.52	20.80	0.00	0.00	0.02
1228	0.49	52.00	0.02	1.25	0.03
1091	0.44	139.60	0.03	4.70	0.04
1371	0.55	16.00	0.04	0.60	0.07
1331	0.53	23.20	0.07	1.59	0.09
1625	0.65	6.00	0.09	0.54	0.17
1837	0.73	4.68	0.17	0.81	0.28
1747	0.70	5.00	0.28	1.40	0.38
1000	0.40	160.00	0.38	60.83	0.38
1771	0.68	5.60	0.38	2.15	0.47
1734	0.69	5.80	0.47	2.74	0.56
1575	0.63	7.68	0.56	4.29	0.62
1071	0.43	119.20	0.62	74.37	0.63
1321	0.53	23.20	0.63	14.57	0.65
1679	0.67	6.40	0.65	4.16	0.73
1378	0.55	16.00	0.73	11.64	0.76
1517	0.61	6.56	0.76	4.98	0.84
1410	0.56	10.24	0.84	8.55	0.88
1125	0.45	58.00	0.88	51.28	0.89
1344	0.54	25.60	0.89	22.85	0.91
2500	1.00	2.00	0.91	1.82	1.16
1364	0.55	16.00	1.16	18.60	1.19
1222	0.49	32.00	1.19	62.06	1.20

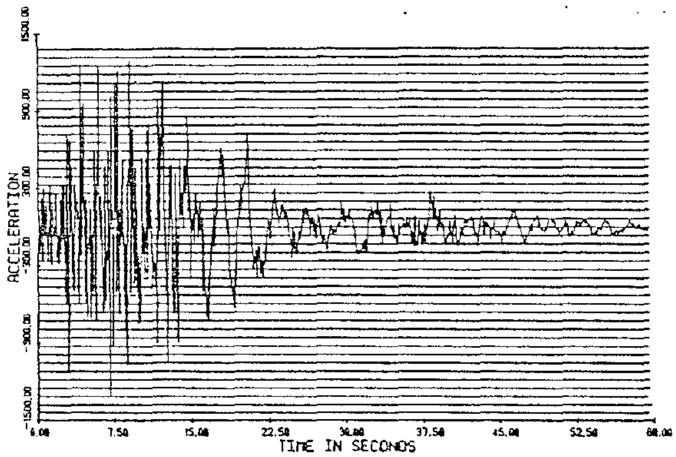
(ap) max = 2500.0 mm/sec^2

N = 6.0 x 1.2 = 7.2 cycles (METHOD 3)

N = 6.0 x 1.0 = 6.0 cycles (METHOD 4)

EXAMPLE 6

EVALUATION OF THE EQUIVALENT UNIFORM STRESS CYCLES FOR ORION BOULEVARD RECORD (Component East-West)



ORION BLVD. RECORD, E-W COMP. SAN FERNANDO EARTHQUAKE, 1971

SAFETY FACTOR = 1.5
METHOD 3

PEAK ACCELERATION mm/sec²	NORMALIZED ACCELERATION ap/(ap)max	Nℓ	(Ru)b	N	(Ru)a
597	0.45	58.0	0.00	0.00	0.01
735	0.56	10.24	0.01	0.09	0.06
1120	0.85	2.90	0.06	0.17	0.23
682	0.52	20.80	0.23	4.78	0.25
583	0.44	139.60	0.25	35.44	0.26
1239	0.94	2.44	0.26	0.63	0.46
964	0.73	4.68	0.46	2.16	0.57
586	0.44	139.60	0.57	79.47	0.57
700	0.53	23.20	0.57	13.29	0.59
702	0.53	23.20	0.59	13.79	0.62
591	0.45	58.00	0.62	35.72	0.62
719	0.55	16.00	0.62	9.99	0.66
1233	0.94	2.44	0.66	1.60	0.86
595	0.45	58.00	0.86	49.92	0.87
575	0.44	139.60	0.87	121.36	0.87
596	0.45	58.00	0.87	50.63	0.88
1317	1.00	2.00	0.88	1.76	1.13
1024	0.78	3.92	1.13	4.44	1.26
880	0.67	6.40	1.26	8.06	1.34
1104	0.84	3.38	1.34	4.52	1.49
1214	0.92	2.32	1.49	3.45	1.70
673	0.51	18.40	1.70	31.29	1.73
527	0.40	160.00	1.73	276.45	1.73
1069	0.81	3.02	1.73	5.23	1.90
1294	0.98	2.12	1.90	4.02	2.13
766	0.58	13.12	2.13	27.98	2.17
748	0.57	11.68	2.17	25.35	2.21
546	0.41	78.40	2.21	173.52	2.22
758	0.58	13.12	2.22	29.12	2.26
809	0.61	6.56	2.26	14.36	2.34
902	0.68	5.60	2.34	13.08	2.43
1007	0.76	3.64	2.43	8.83	2.56
1127	0.86	2.58	2.56	6.61	2.76
1056	0.80	3.50	2.76	9.65	2.90
667	0.51	18.40	2.90	53.35	2.93
890	0.68	5.60	2.93	16.39	3.02
539	0.41	78.40	3.02	236.47	3.02
843	0.64	8.24	3.02	24.91	3.08
722	0.55	16.00	3.08	49.33	3.11
626	0.48	46.00	3.11	143.27	3.13
632	0.48	46.00	3.13	143.77	3.14
712	0.54	25.60	3.14	80.29	3.16

(ap) max = 1317.0 mm/sec²

N = 6.0 x 3.16 = 18.96 cycles (METHOD 3)
N = 6.0 x 1.00 = 6.00 cycles (METHOD 4)

4.4 Discussion

For Methods 3 and 4 the pore pressure build-up during a uniform cyclic acceleration time history is assumed to vary linearly with number of cycles, and thus, the location of each half-cycle in the accelerogram does not influence its contribution to the pore-pressure build-up. Based on this fact it is possible to analyze the acceleration time history in two different ways: a) it is possible to stop the analysis at the time when initial liquefaction occurs, Ru = 1.00, that is the procedure developed in Method 4, and b) it is possible to make the analysis until the end of the accelerogram, even if Ru > 1.00, which is the procedure developed in Method 3.

PART 5

EVALUATION OF THE DIFFERENT METHODS

For the evaluation of the different methods, a total of 129 horizontal ground strong-motion accelerograms recorded in western U.S. between 1933 and 1971, with magnitudes between 5.3 and 7.1 (see Appendices B and C) were used for this study. The accelerogram records used for all the calculations were obtained from standard tapes issued by CALTECH.

The accelerograms are divided in three different sets. The first one corresponds to 22 accelerograms of different earthquakes at several sites in the west coast of the U.S., with magnitudes ranging between 5.3 and 7.1. This set is similar to that presented by Seed et al., (1975). The main characteristics of these records, including the computed numbers of cycles, are summarized in Tables B-1, B-2, B-3 and B-4 of Appendix B. For each of these records, the corresponding equivalent numbers of cycles, N, obtained using the four different safety factors, were compared among the Methods, and N was also correlated with the magnitude of the earthquake. These comparisons and correlations are discussed later herein.

The second set corresponds to 11 accelerograms of different earthquakes at several rock sites in the west coast of the U.S., with magnitudes ranging between 5.3 and 7.6. This set was obtained from Dobry et al., (1978). The main characteristics of these records, including the computed number of cycles, are summarized in Table B-5 of Appendix B. The values of N computed for these rock sites records were also correlated with earthquake magnitude, as explained later herein.

The third set corresponds to 96 strong-motion accelerograms recorded on rock and soil sites during the 1971 San Fernando, California earthquake, and was obtained from Bond (1980). The range of distances between station and source of energy release is between 21.9 and 150.2 Km., while the magnitude of this earthquake was 6.6. The computation of N are summarized in Tables C-1 and C-2 of Appendix C, for F.S.= 1.5 and 2.0, respectively. For this third set of accelerograms, all sites were classified in two groups: soil sites and rock sites. It was decided to study first the soil site accelerograms, and then consider the influence of rock. The corresponding equivalent numbers of cycles for this San Fernando set of accelerograms, using F.S.= 1.5 and

2.0, and for Methods 1 and 4, are plotted versus epicenter distance and azimuth for the soil sites in Appendix D. In this Appendix plots are presented for all components of the records, and also for the strongest components only, as recomended by Seed et al., (1975). Appendix E presents the same plots shown in Appendix D, but for the rock sites recorded in San Fernando Earthquake.

5.1 General Conditions for the Analysis.

The computation of the equivalent number of cycles, N, for each of these accelerograms, was performed for Methods 1 through 4, for an acceleration level of 0.65 (ap)max, and using the procedures described herein in Parts 2, 3 and 4. In all the calculations, which were repeated for safety factors, F.S. = 1.00, 1.50, 1.75 and 2.00, the representative laboratory cyclic strength curve shown in Figs. 2 and 3 was used. The analysis conditions for the four different methods can be summarized as follows:

METHOD No.	SOURCE	PORE PRESSURE LAW	LIMIT
1	Seed et al (1975)	Linear	Unlimited ($Ru \gtrsim 1.0$)
2	This work	Nonlinear	Limited to initial Liquefaction ($Ru \leq 1.00$)
3	This work	Linear	Unlimited ($Ru \gtrsim 1.00$)
4	This work	Linear	Limited to initial Liquefaction ($Ru \leq 1.00$)

NOTE: Methods 1 and 3 are conceptually identical but slightly different computational procedures were used in them.

5.2 Comparison of the Methods

5.2.1 Methods 1 and 3

In Method 3 the effect of one half-cycle in the liquefaction of the soil is considered to be the same no matter what its position is in the acceleration time history. It is demostrated later herein that this assumption is conceptually identical to that used for Method 1 by Seed et al., (1975). For both methods, 1 and 3, the analysis of the entire accelerogram is always done, and it should be expected that the equivalent number of cycles, N, computed by Methods 1 and 3, should be almost identical for any accelerogram.

Methods 1 and 3 can be proven to be conceptually equivalent as follows (in this demostration it is assumed that a value of F.S. has been selected, and that the corresponding curve in Fig. 3 can be used to obtain the number of cycles, N1, required to cause liquefaction under a uniform cyclic acceleration (ap)b).

For Method 1:

N1 cycles of (ap)ab produce $Ru = u/\sigma_o' = 1.00$

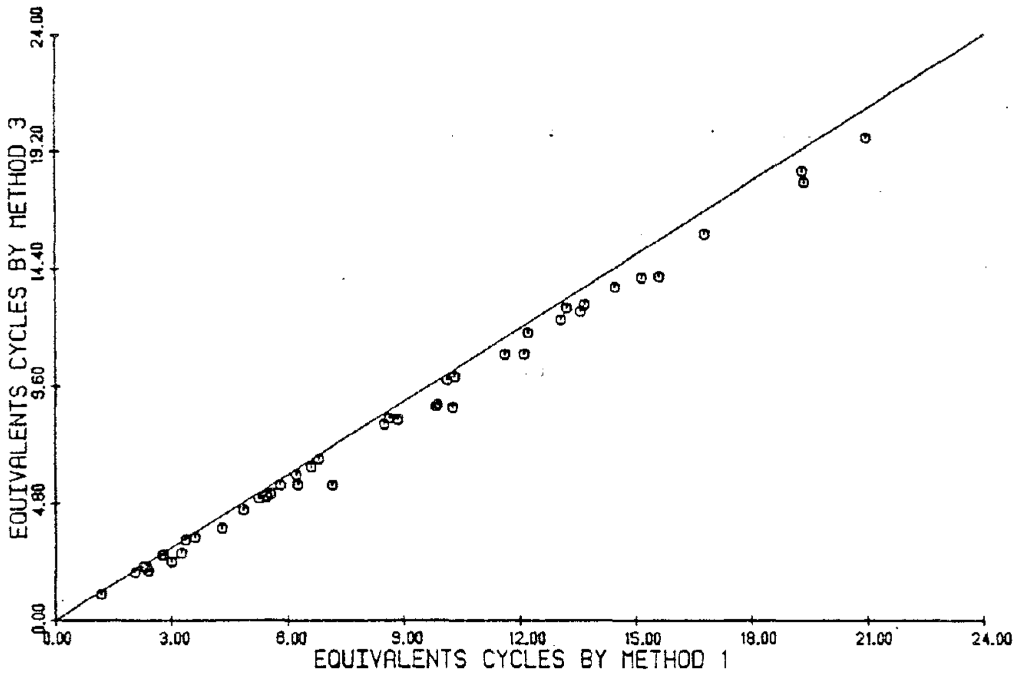
then:

1.00 cycle of (ap)ab produce $(Ru) = u/\sigma_o' = 1.0/N1$

0.50 cycle of (ap)ab produce $(Ru)ab = u/\sigma_o' = 1/(2N1)$

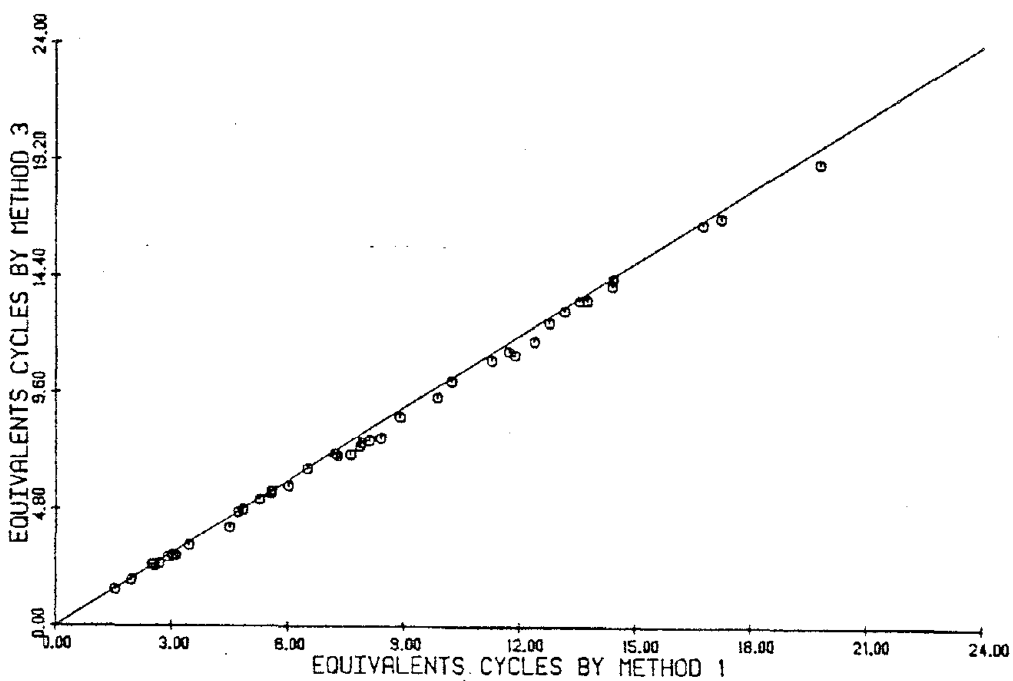
For Method 3; and as already shown in Eq. (4.4), 0.50 cycles of (ap)ab also produce an increment of (Ru)ab = 1/(2N1). Therefore, (Ru)ab is always the same between Methods 1 and 3, for any given half-cycle of the accelerogram, (ap)ab, and this value of (Ru)ab does not depend on the location of the half-cycle.

Therefore, for a given recorded accelerogram, the values of N computed using Methods 1 and 3 should be expected to be very similar or identical. This is confirmed by a comparison of the corresponding results tabulated in Appendices B and C. Also, the values corresponding to the first accelerogram set (see beginning of Part 5), have been plotted in Figs. 8 through 11 for the factors of safety used in this work. These comparisons confirm the equivalence between the two methods. However, some slight differences are noted in Fig. 8 for F.S.= 1.00, with the value of N for Method 3 being somewhat smaller than N computed by Method 1. For F.S. $\geq$ 1.50, there is not significant difference between the two methods, as illustrated by Figs. 9, 10 and 11.



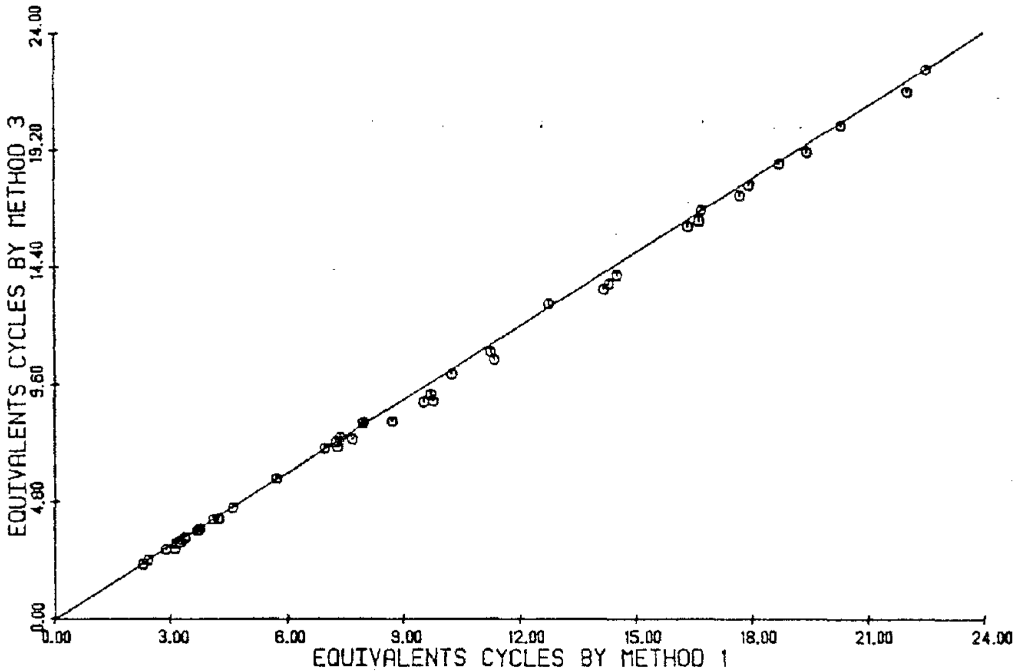
METHOD 1 VS METHOD 3 WITH SAFETY FACTOR = 1.00

FIGURE 8



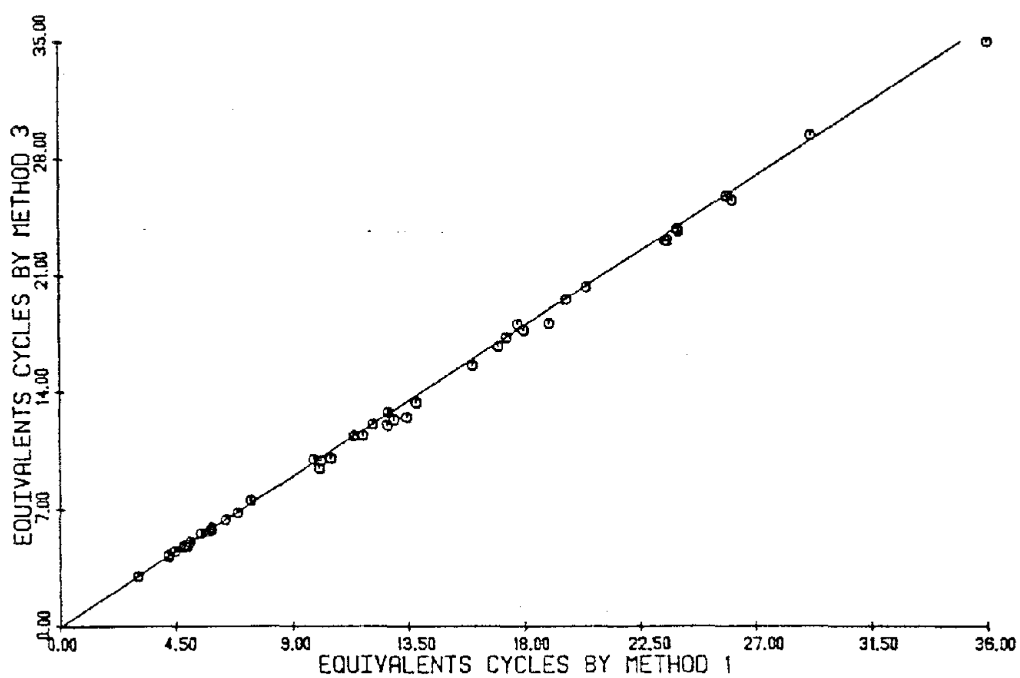
METHOD 1 VS METHOD 3 WITH SAFETY FACTOR = 1.50

FIGURE 9



METHOD 1 VS METHOD 3 WITH SAFETY FACTOR = 1.75

FIGURE 10



METHOD 1 VS METHOD 3 WITH SAFETY FACTOR = 2.00

FIGURE 11

5.2.2 Methods 2 and 4

Methods 2 and 4, like Method 3, compute the increment of pore-water pressure in the soil deposit cause by each half-cycle of the accelerogram. Unlike Method 3, in Methods 2 and 4 the computation of N is not necessarily done for the whole accelerogram but is stopped if initial liquefaction (Ru=1.00) occurs. The only difference between Methods 2 and 4 is that, while in Method 4 the increment of Ru for a uniform cyclic acceleration follows a linear variation with number of cycles, in Method 2 the increment follows a non-linear variation. Figure 12 illustrates this difference.

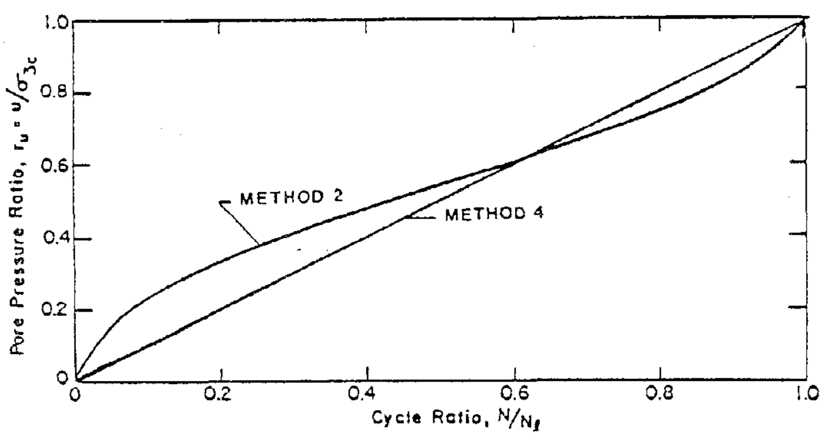
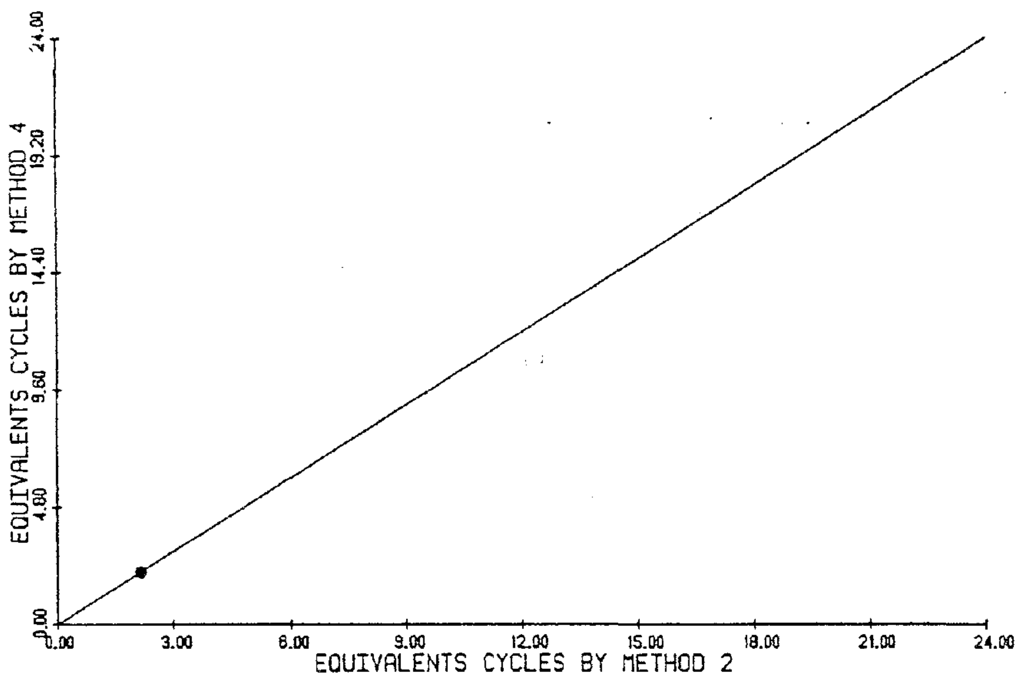


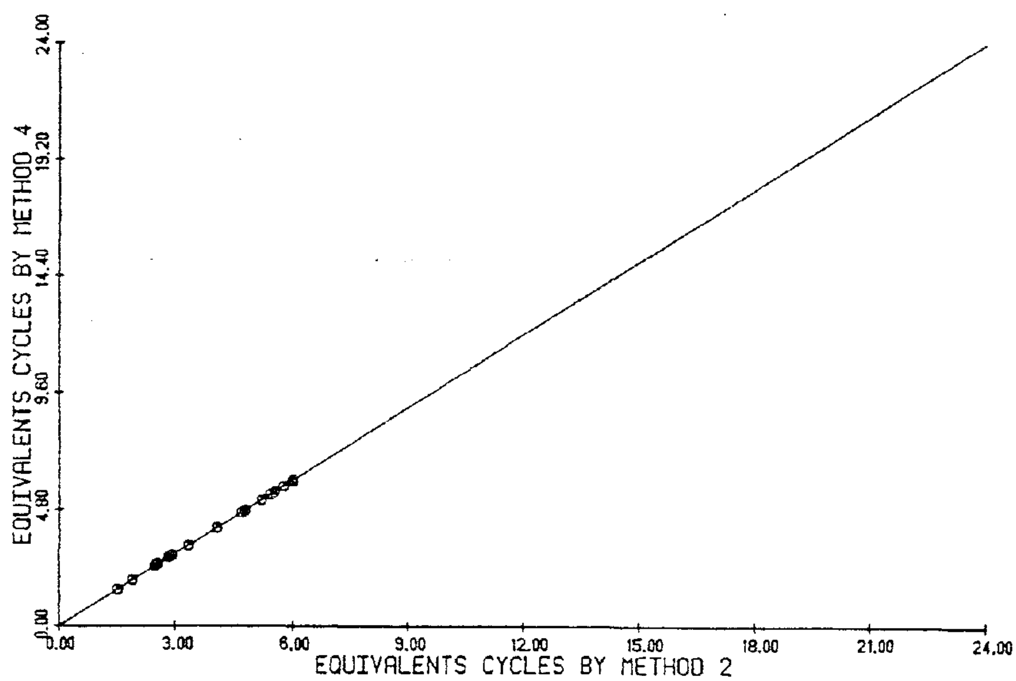
FIG.12 Linear and Nonlinear Rate of Pore-Water Pressure Build-up used for Methods 2 and 4.

The evaluation of the accelerograms presented in Appendices B and C, show that Methods 2 and 4 give essentially the same numerical results. Therefore, Methods 2 and 4 are practically equivalent, no matter what is the the value of the safety factor chosen. This practical equivalence is demostrated by the results in Figs. 13, 14, 15 and 16, which corresponds to the first accelerogram set discussed at the beginning of Part 5.



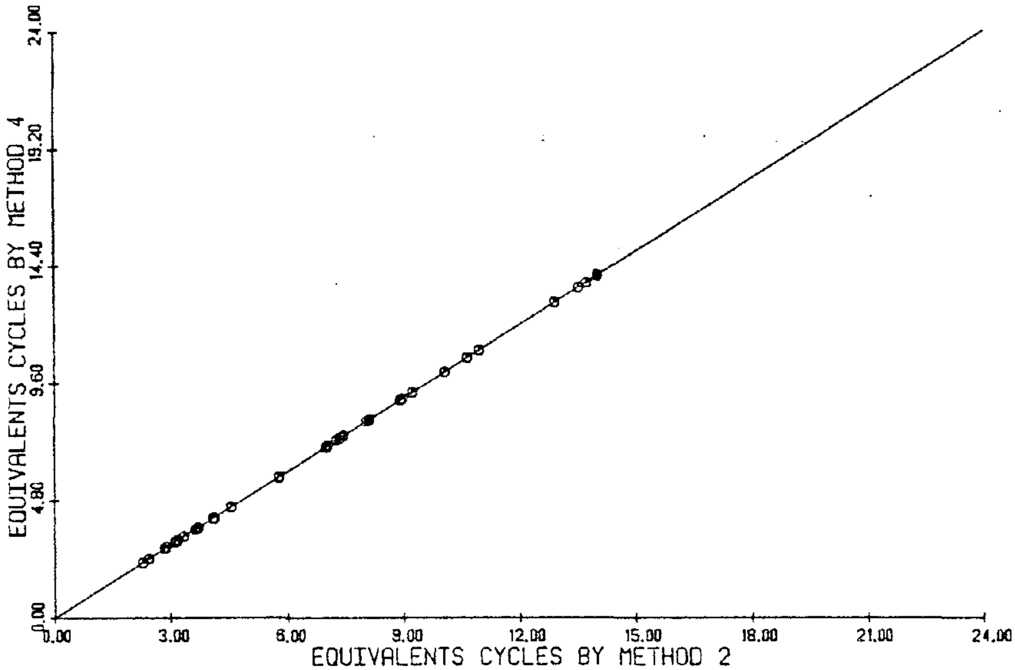
METHOD 2 VS METHOD 4 WITH SAFETY FACTOR = 1.00

FIGURE 13



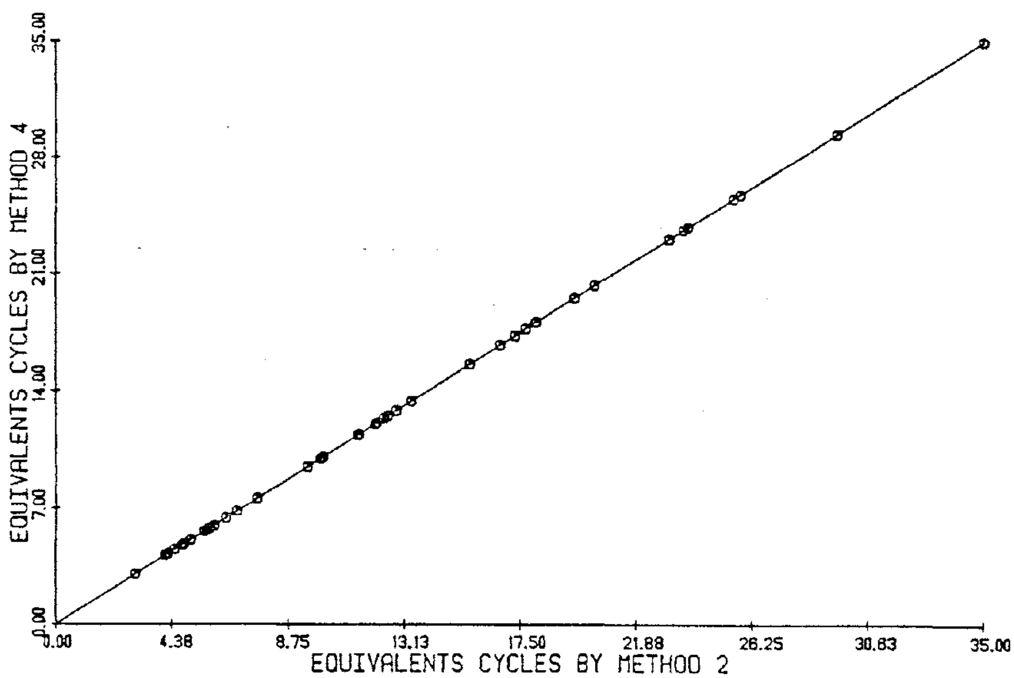
METHOD 2 VS METHOD 4 WITH SAFETY FACTOR = 1.50

FIGURE 14



METHOD 2 VS METHOD 4 WITH SAFETY FACTOR = 1.75

FIGURE 15



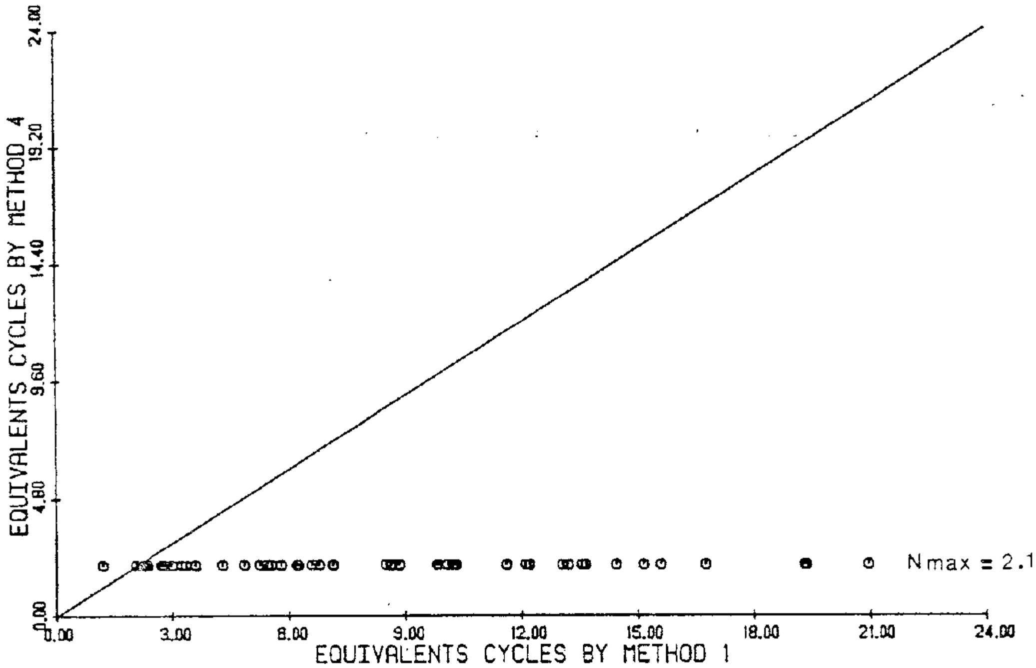
METHOD 2 VS METHOD 4 WITH SAFETY FACTOR = 2.00

FIGURE 16

5.2.3 Methods 1 and 4

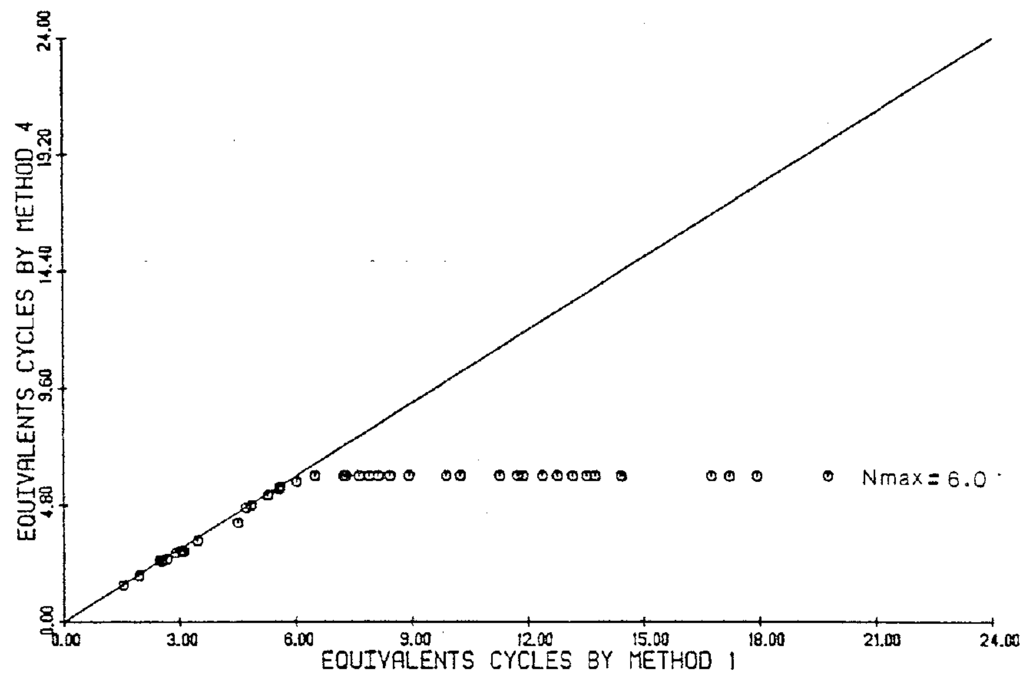
The preceding discussiones about the four methods showed that Methods 1 and 3 are conceptually and practically equivalent, and that Methods 2 and 4 are also equivalent in practice. That is, the method used by Seed et al., (1975) is identical to using a linear variation law for the pore pressure and allowing Ru to exceed 1.00 (Methods 1 and 3); and also there is little diference between using a linear or non-linear law (Methods 2 and 4). In what follows, a comparison is made between Methods 1 and 4, to establish the influence of limiting Ru to Ru = 1.00, on the value of N.

Comparisons between N for Methods 1 and 4, obtained from Appendices B and C, are plotted in Figs. 17 through 20 for the different factors of safety, and for the first set of accelerograms. The plots show the variation between Methods 1 and 4 when a different safety factor is applied for the same accelerogram. In Fig. 20 for a safety factor F.S.= 2.00, both Methods 1 and 4 give practically identical results in all cases, as the correlation Ru = 1.0 was not reached in any accelerogram. However, for safety factors $1.0 \leq$ F.S. ≤ 1.75 the difference between Methods 1 and 4 increases as F.S. decreases. In Fig. 17, for F.S.= 1.0, N from Method 4



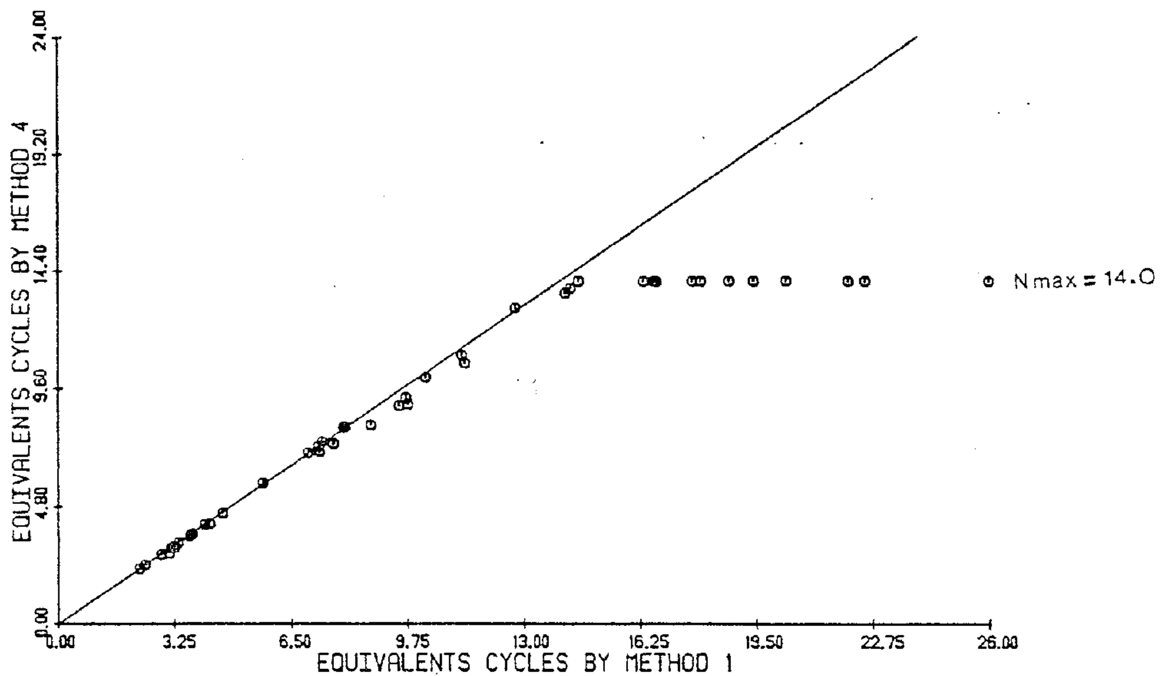
METHOD 1 VS METHOD 4 WITH SAFETY FACTOR = 1.00

FIGURE 17



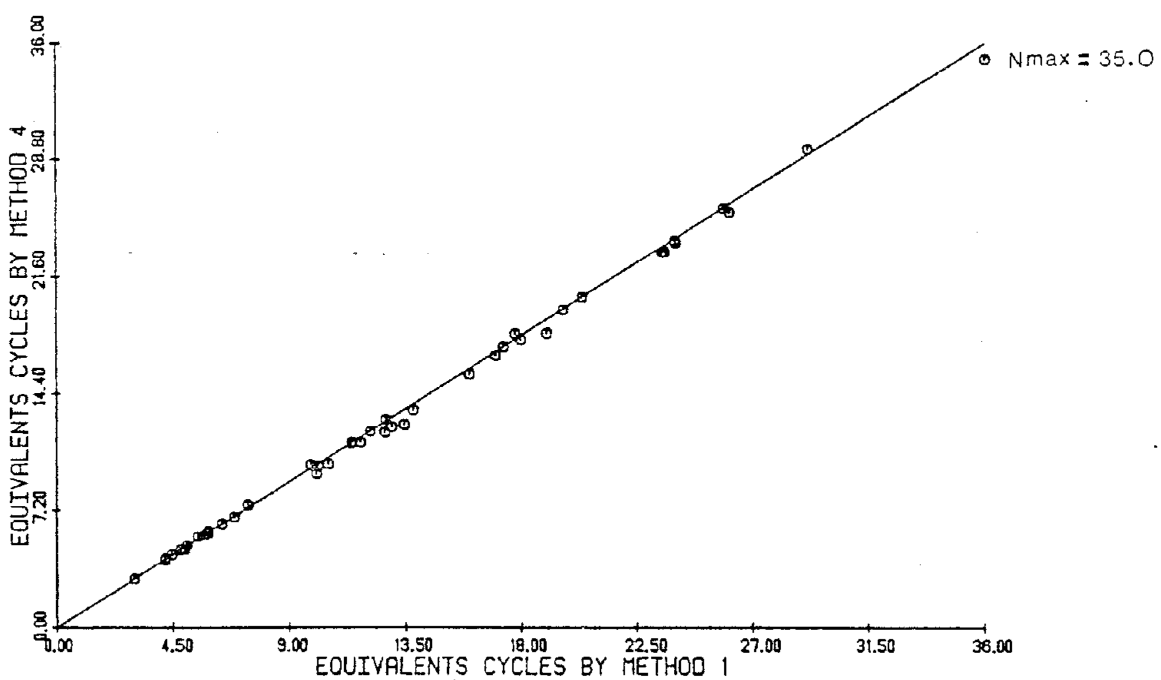
METHOD 1 VS METHOD 4 WITH SAFETY FACTOR = 1.50

FIGURE 18



METHOD 1 VS METHOD 4 WITH SAFETY FACTOR = 1.75

FIGURE 19



METHOD 1 VS METHOD 4 WITH SAFETY FACTOR = 2.00

FIGURE 20

is usually much smaller than N for Method 1.

This discrepancy is clearly due to the fact that in Method 1 the analysis of the entire accelerogram is always done, while in Method 4 the analysis is stopped, and N is computed when condition of initial liquefaction (Ru=1.00) is reached. As a consequence, N for Method 4 is always equal or smaller than N for Method 1.

It is very clear from an inspection of Figs. 17 through 20, that there is an upper limit for the values of N computed by Method 4, while no such limit exists for Method 1. This upper limit depends on the factor of safety, and is clearly related to the constraint imposed in Method 4 that $Ru \leq 1.00$. It is not difficult to demostrate that this upper limit, (N)max, must exist, and that (N)max is identical to N1 obtained from Fig. 3, for the curve corresponding to the given F.S., and for ap/(ap)max = 0.65. The corresponding values of (N)max obtained are plotted in Fig. 21. The reason for the behavior shown in Figs. 17 through 20 becomes now clear, and can be formulated as follows:

$(N)4 = (N)1 < (N)max$ if $(N)1 < (N)max$

$(N)4 = (N)max$ if $(N)1 > (N)max$

where (N)4, (N)1 are the values of N obtained for the same accelerogram with Methods 1 and 4, respectively, and

(N)max is the value listed in Fig. 21 for the corresponding F.S. The only reason why (N)4 = (N)1 for all the accelerograms in Fig. 20, is that, for F.S.= 2.0, in no accelerogram (N)1> (N)max = 35 cycles. Obviously, the chance of having (N)1 > (N)max for any particular accelerogram decreases as the value of F.S. increases.

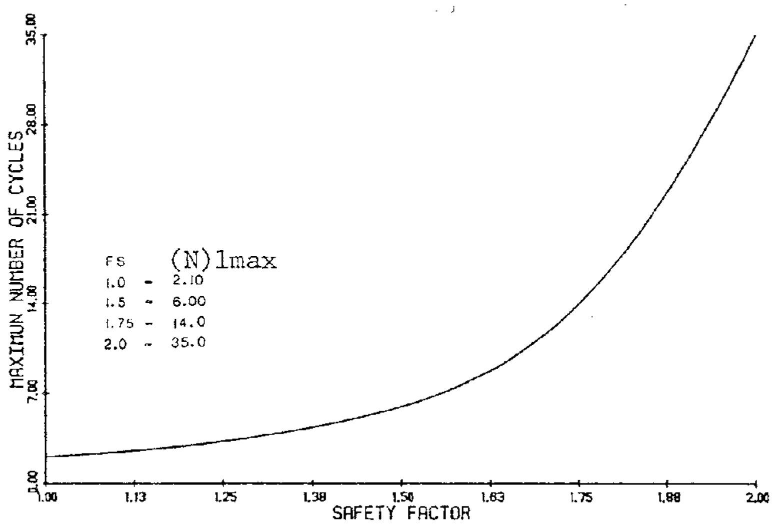


FIG.21 Safety Factor vs. Maximum Number of Equivalent Cycles for Method 4.

5.3 Correlation Between N and the Earthquake Parameters.

The equivalent number of cycles, N, computed using Method 1, was plotted for the three accelerogram sets used in this work, versus the distance to the epicenter, azimuth and magnitude. Some additional plots were also generated using Method 4. Appendices D and E include plots of N versus epicentral distance and azimuth for the records of

of this work from set 1, for F.S.= 1.5 and also for the figures.

The N values for accelerograms set 2, which contains rock sites accelerograms from several western U.S. earthquakes, were also plotted versus magnitude in Fig. 24, again using Method 1, F.S.= 1.5 and for the strongest components. The upper and lower bound curves from Fig. 22 have been superimposed with data points in Fig. 24, with good agreement.

The N values from Methods 1 and 4, obtained from the San Fernando earthquake (magnitude 6.6), are plotted versus epicentral distance and azimuth in Appendices D and E. An inspection of these plots show that there is considerable scatter in the data, and that there is no significant influence of distance or azimuth on the value of N. On the other hand, comparisons between corresponding plots of Appendices D and E suggest a significant influence of site condition N. For example, Fig. D-1, obtained with Method 1, F.S.= 1.5 and all components, shown that N range between about 4 cycles and 20 cycles, irrespective of epicentral distance. On the other hand, Fig. E-1, obtained in the same way but for the 14 rock sites only, indicates a range for N between about 4 cycles and 10 cycles, also irrespective of the distance. This suggests a greater range of variation for

N in soil sites than in rock sites, with the lower bound coinciding for both rock and soil sites but with some records obtained at soil sites having significantly larger number of cycles. This found for N (cycles) of records on rock and soil sites is similar to that obtained for records duration (seconds) by Dobry et al. (1978).

The values of N computed using Method 1 for F.S.= 1.5 and for the strongest components of the San Fernando earthquake, were retrieved for all soil sites from Table C-1 and their average and standard deviation was computed. The result was 9.2 ± 4.9 cycles. The same operation was performed with the 14 rock sites and the result was 6.3 ± 1.9 cycles. These mean and mean ± standard deviation range have been superimposed on Seed's curves in Fig. 25, for magnitude = 6.6 of that earthquake. The comparison in Fig. 25 shows that Seed's curves represent well the N values for rock sites during the San Fernando earthquake, but that a significant number of soil site records had N values above Seed's upper curve.

Although the correlation presented by Seed et al. (1975) in Fig. 22 was obtained originally with a F.S.= 1.5, it has been used in engineering practice for other values of

F.S. Therefore, it is of interest to verify the validity of Seed's curves for factors of safety different from 1.5. Figure 26 presents the corresponding plot for F.S.= 2.0. Figure 26 was obtained using the same data and procedure than Fig. 23, with the only difference between the two figures in the value of F.S.. The comparison in Fig. 26 indicates that Seed's correlation may underestimate significantly the value of N for factors of safety larger than 1.5

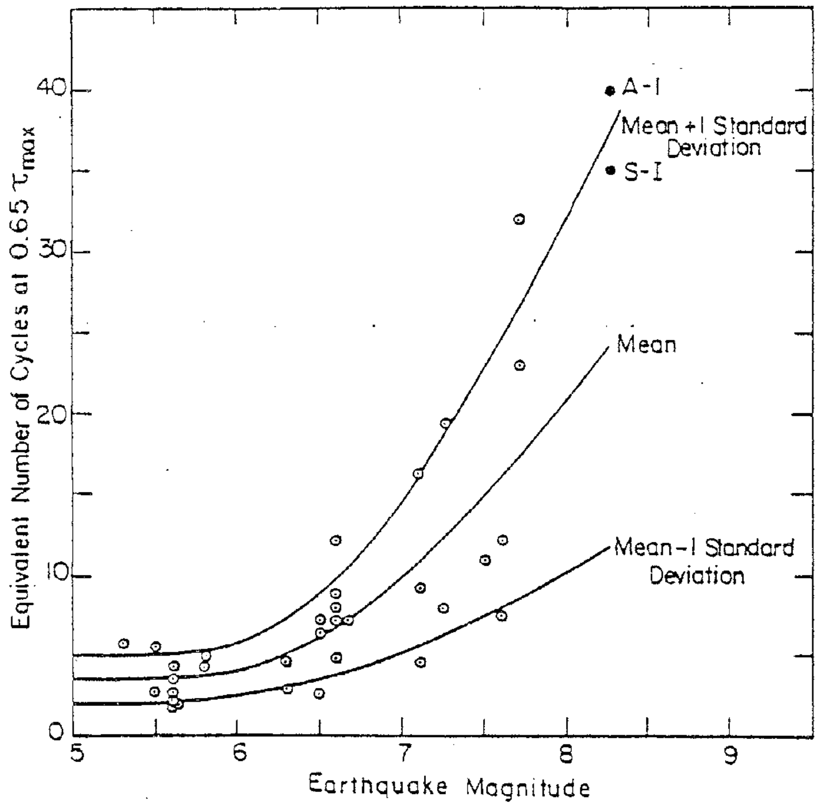


FIG. 22 Equivalent Numbers of Uniform Stress Cycles Based on Strong Componets of Ground Motion (Seed et al.,(1975) Method 1 (F.S.= 1.5)

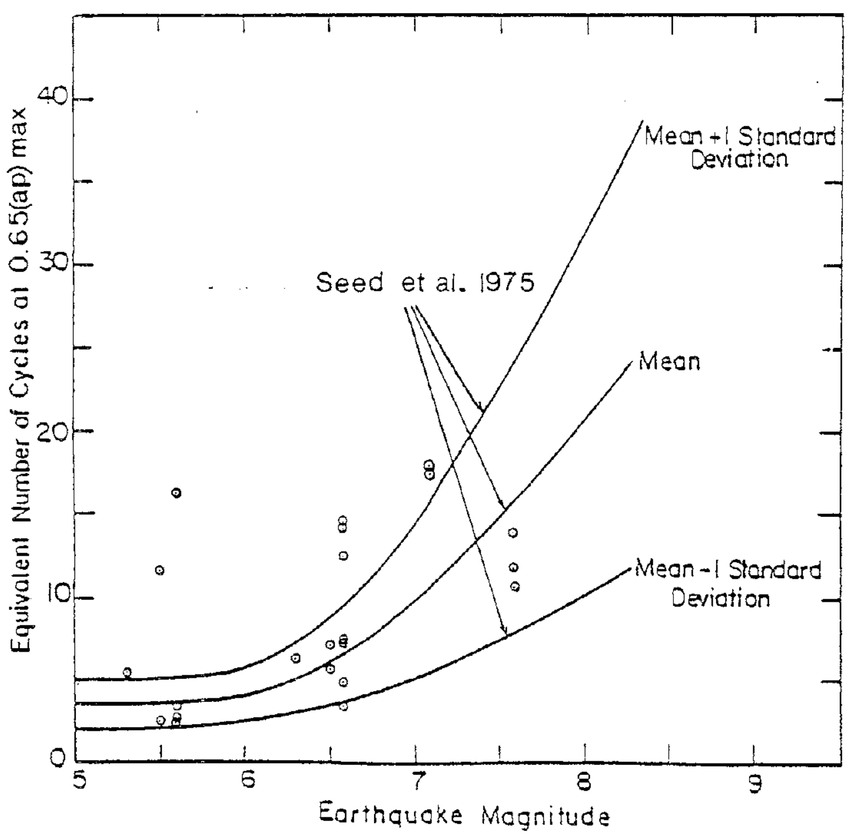


FIG. 23 Method 1 vs. Magnitude with F.S.= 1.5 Set 1 Strongest Component (Table B-2)

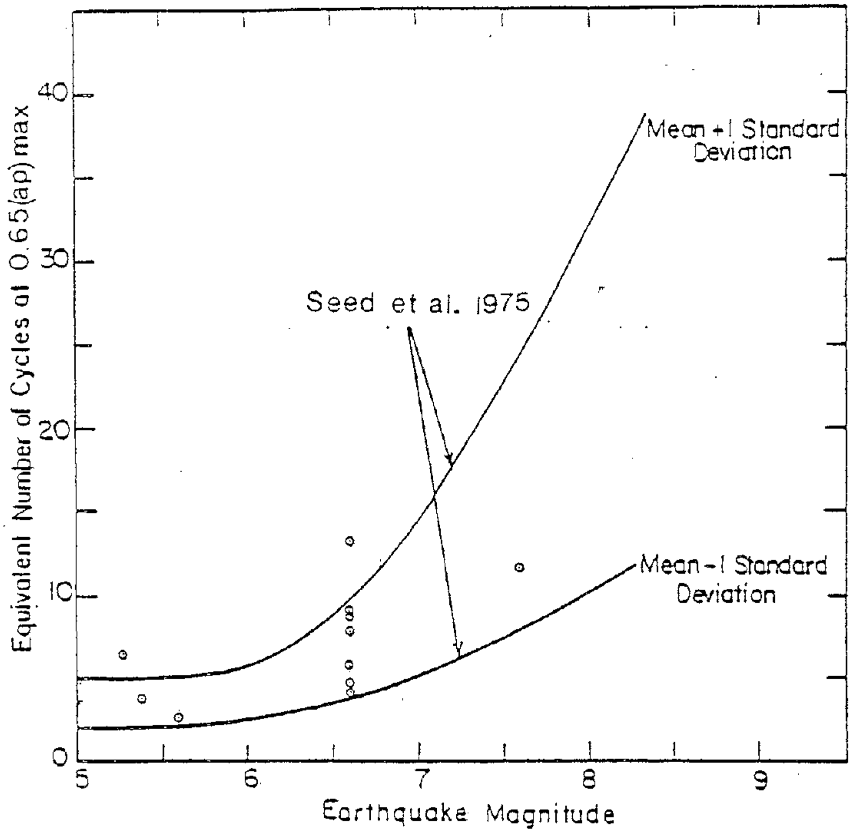


FIG. 24 Method 1 vs. Magnitude with F.S.= 1.5
Set 2 Strongest Component (Table B-5)

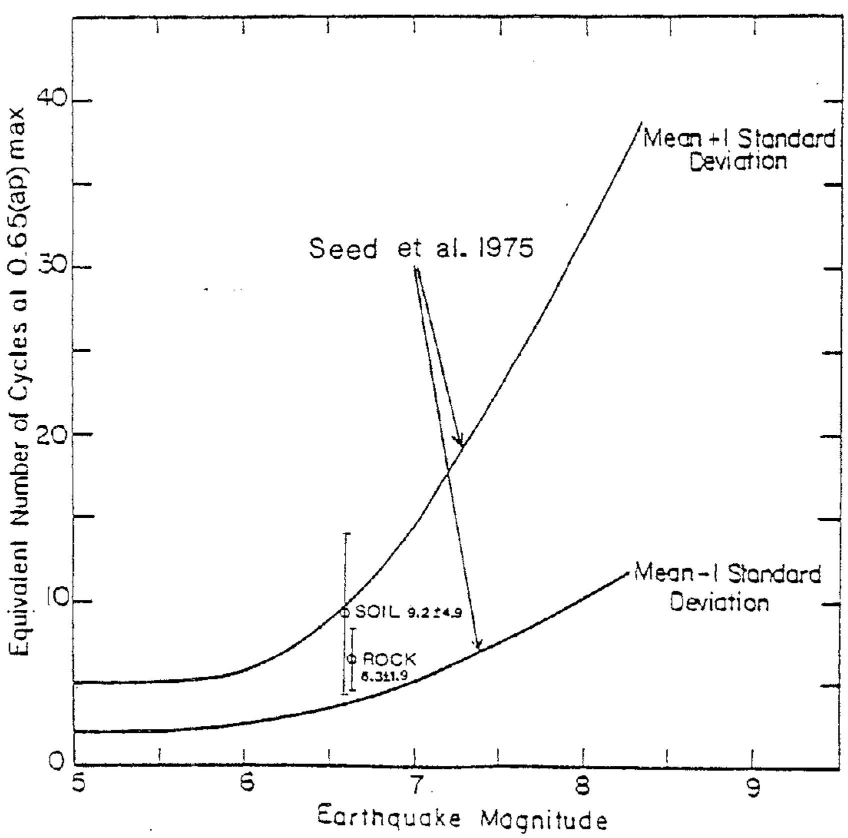


FIG. 25 Method 1 vs. Magnitude with F.S.= 1.5
Set 3 Strongest Component (Table C-1)

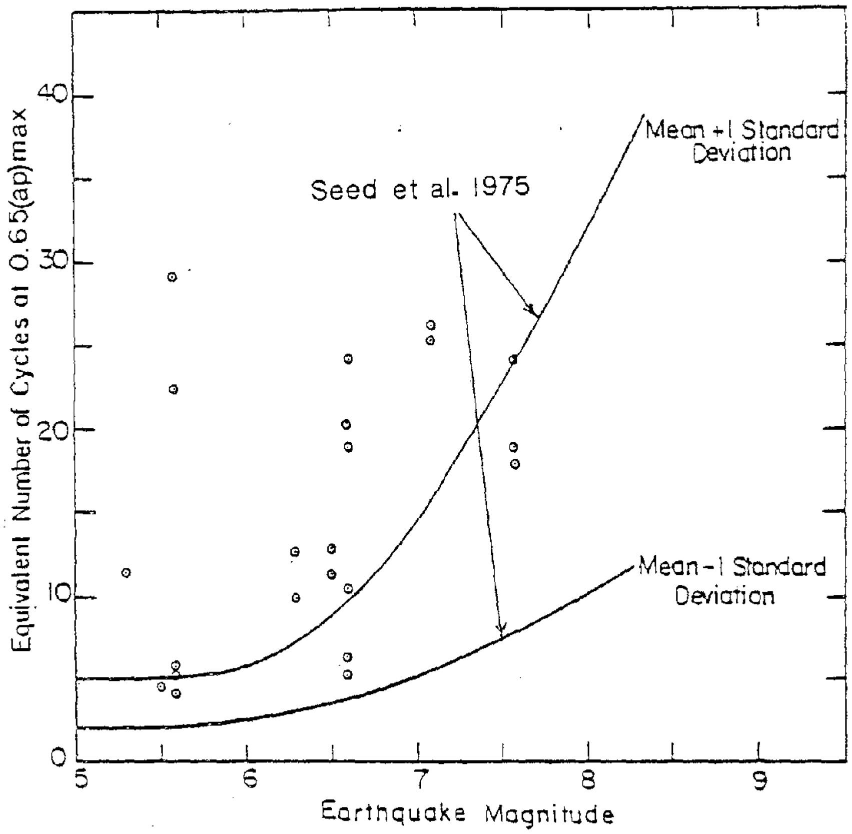


FIG. 26 Method 1 vs. Magnitude with F.S.= 2.0
Set 2 Strongest Component (Table B-5)

PART 6

DISCUSSION AND CONCLUSIONS

The importance of significant duration of motions produced by earthquakes is of concern to engineers because it has been identified as one of the basic parameters affecting soils failures due to liquefaction. In this investigation, four methods are presented for evaluating the equivalent number of cycles, N, at 0.65 (ap)max during earthquakes motions. All of these methods use the pore pressure ratio, Ru, built-up during the accelerogram as a basic parameters for the calculations, but they differ in assuming a linear or non-linear variation of Ru during stress-controlled tests, and in allowing or not the existence of values of Ru 1.0 (where Ru = 1.0 means initial liquefaction). The four methods were compared using actual accelerograms recorded in the western U.S., and it was concluded that:

1.- The value of N is not significantly affected by the assumption of linear versus non-linear variation of Ru.

2.- The value of N can be affected by the limitation of Ru to values $\leq$ 1.0. This is not significant for a factor of safety, F.S.= 2.0, against liquefaction in the first cycle, but is very important for F.S.= 1.0 and 1.5. This is associated with the fact that many earthquakes cause initial liquefaction when F.S. is low, Ru< 1.0 at all times when F.S. is high.

3.- If the limitation Ru < 1.0 is imposed, N can not be larger than Nmax, where Nmax is a function of F.S. and of the cyclic strength weighting curve of the soil. For the strength curve used in this work, Nmax = 6.0 cycles for F.S.= 1.5 and Nmax = 35 cycles for F.S.= 2.0.

4.- The four methods were used to compute N of 129 accelerograms recorded in the western U.S., including 96 accelerograms on rock sites and soil sites obtained during 1971 San Fernando earthquake. The values of N were tabulated, correlated and plotted versus epicentral distance and azimuth, for the case of the San Fernando earthquake. From these plots and correlations, obtained mostly with Method 1 and allowing Ru to be larger than 1.0, it is possible to conclude:

a- For the 1971 San Fernando earthquake, and for F.S.= 1.5, N ranged between about 4 and 10 cycles for the rock sites and between about 7 and 20 cycles for the soil sites, with little influence on N of epicentral distance and azimuth.

b- The values of N obtained from the strongest components of the wester U.S. records analyzed and correlated for F.S.= 1.5, are generally consistent with the correlation between N and magnitude, M, suggested by Seed et al. (1975), except for some soil records obtained during the San Fernando earthquake, which give significantly higher values.

c- Increasing the values of F.S. tends to icrease the values of N. As a consequence, some values of N computed using a F.S.= 2.0, are significantly higher than those predicted using Seed et al. (1975) correlation between N and M, and which was originally developed for F.S.= 1.5.

PART 7

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APPENDIX A
WEIGHTING CURVE

APPENDIX A

A-1 Selection of Weighting Curve

The development of some simple way to determine the series of uniform stress cycles, which are equivalent in its effects to the irregular stress patterns resulting from the earthquake motion, is clearly an essential feature for all the different methods presented in this work.

A representative cyclic strength curve for soils is used by Seed et al., (1975) in conjunction with a weighting procedure. This curve which is presented as a solid line in Fig. A-3, and as a curve of ap/(ap)max versus number of cycles to liquefaction, is also reproduced in the text as Fig. 2. This curve has been adopted for the development of the different methods studied in this work. The rest of the dicussion in this Appendix, is a summary of a similar presentation included in Seed et al., (1975).

A-2 Procedure for the Development of the Weighting Curve

In the study of the equivalent uniform stress series, the required weighting curve for evaluating the effects of an irregular sequence of stress cycles is provided directly by the results of experimental measurements during cyclic stress controlled tests. The result of such a series of tests performed using cyclic stress levels of different magnitudes, but constants in any one test, are shown in Figure A-1. It is readily apparent that a condition of liquefaction can be induced in the same test specimen by varius combinations of cyclic stress levels and number of cycles. For the data shown in Fig. A-1, the same condition of liquefaction is produced by:

- 2 uniform cycles at a stress level of 0.22 Kg/cm
- 5 uniform cycles at a stress level of 0.17 Kg/cm
- 10 uniform cycles at a stress level of 0.14 Kg/cm
- 40 uniform cycles at a stress level of 0.22 Kg/cm

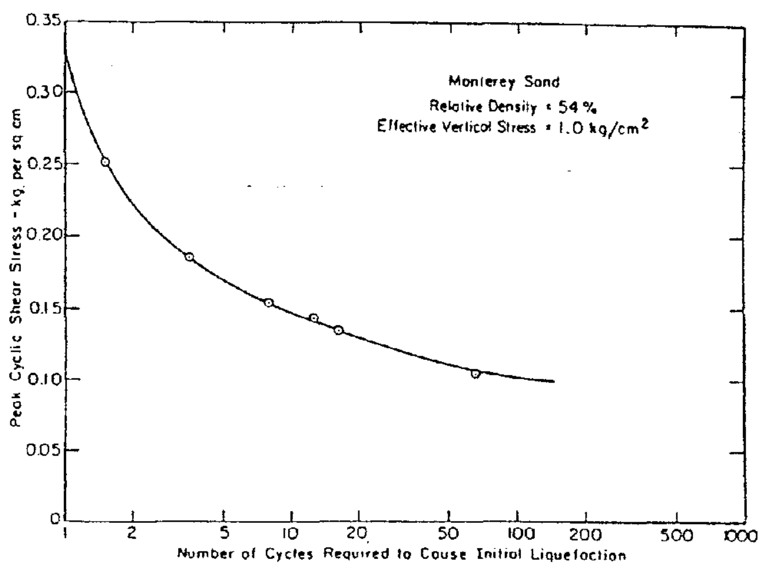


FIG.A-1 Relationship Between Cyclic Shear Stress and Number of Cycles Required to Cause Liquefaction

Therefore, a given number of cycles at any of these stress levels can be expressed as being equivalent to some other number of cycles at one of the other stress levels, and since the curve can provide results for any selected stress level, it can be used for the determination of the equivalent number of equivalent cycles at any other stress level.

It is apparent from the above discussion that the shape of the particular curve used to determine equivalencies of different stress series is a critical part of the conversion from irregular to equivalent uniform stress series. Ideally, the curve would be obtained by means of a series of simple shear tests on the particular soil under investigation. Data from other simple shear investigations, have similar shapes, and it appears reasonable to adopt such test data as a representative curve for determining equivalent effects of different stress levels and number of cycles.

This average curve, as proposed by Seed et al., (1975), is reproduced in Figure A-2, and it will be assumed herein that the shape of this curve is representative of the shear stress versus number of cycles relationship for any sand at any confining pressure.

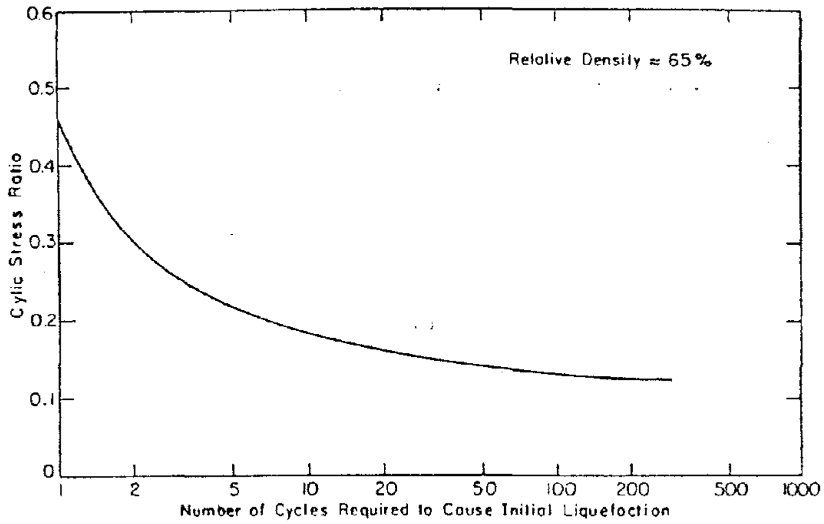


FIG.A-2 Representative Curve for Relationship Between Cyclic Stress Ratio and Number of Cycles to Liquefaction

Fig. A-2 plots the stress ratio, τ_p/σ_o' , versus number of cycles required for initial liquefaction. Following Seed et al., (1975), it is convenient to replot the same information by dividing all stress ratios by $(\tau_p)_1/\sigma_o'$, where $(\tau_p)_1/\sigma_o'$ is the stress ratio required to cause liquefaction in one cycle. For Fig. A-2, $(\tau_p)_1/\sigma_o' = 0.45$. In this way a plot of $\tau_p/(\tau_p)_1$ versus the number of cycles to liquefaction was obtained, which is ploted in Fig. A-3. Due to the proportionality in the field between seismic shear stress and surface accelerations, dicussed in the text, Fig. A-3 can be considered either a plot of $\tau_p/(\tau_p)_1$ or of $ap/(ap)_1$ versus number of cycles, where (ap) = amplitude of uniform acceleration series, and

$(ap)_1$ = amplitude of acceleration causing liquefaction in one cycle.

Fig. A-3 has also been reproduced in Fig. 2 in the text. Selected points of this curve were digitized and are included in the first two columns of Table A-1. (For example, $ap/(ap)_1 = 0.50$ corresponds to 4.00 cycles to liquefaction). As discussed in the text, it is convenient to transform Fig. A-3 once more into curves of ap/(ap)max versus number of cycles to liquefaction, where (ap)max = maximum peak acceleration of the accelerogram being considered. For this transformation, a factor of safety, F.S. = $(ap)_1/(ap)max$ is defined for the accelerogram, and:

$(ap)/(ap)max = F.S.(ap/(ap)_1)$

This expresion was used to transform the curve in Fig. A-3, into a family of curves of ap/(ap)max versus number of cycles to liquefaction, for F.S. = 1.0, 1.5, 1.75 and 2.00. This family of curves is included in Fig. 3 of the text, while the corresponding digitized values have been included in the first two columns of Tables A-1 through A-4. Only in Table A-1, for F.S.= 1.0, is $(ap)max = (ap)_1$; in Tables A-2, A-3 and A-4, $(ap)max \neq (ap)_1$.

In Tables A-1 through A-4, in addition to ap/(ap)max versus number of cycles to liquefaction, other pertinent information is also included, necessary to applied Method 1. For example, in Table A-2 and F.S. =1.50, for ap/(ap)max = 0.50, the number of cycles to initial liquefaction is 28. For this F.S. = 1.50, for ap/(ap)max = 0.65, the number of cycles to initial liquefaction is 6.00. Therefore, in Method 1 the conversion factor = 6/28 = 0.2, and 1 cycle of 0.50 (ap)max is equivalent to 0.20 cycles of 0.65 (ap)max.

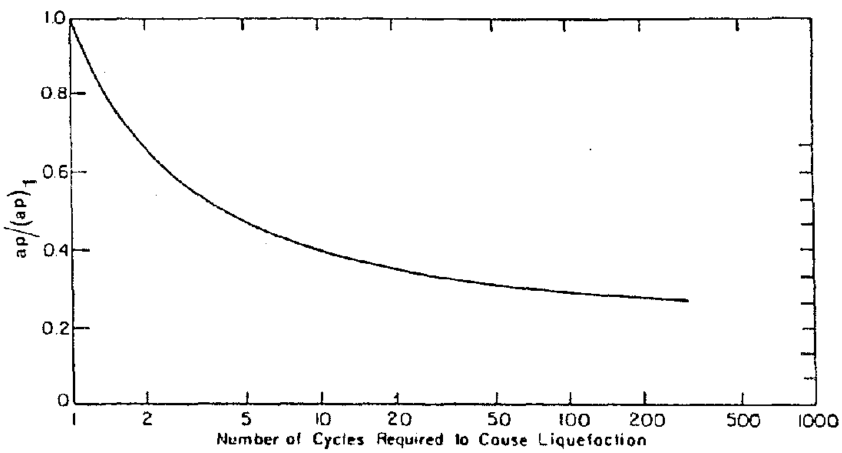


FIG.A-3 Representative Relationship Between $ap/(ap)_1$ and the Number of Cycles Required to Cause Liquefaction

TABLE A-1 EQUIVALENT STRESS LEVELS (FROM FIG. A-3)
SAFETY FACTOR = 1.00

1.00 Cycles @ 1.00(ap)max	= 2.1 Cycles @ 0.65(ap) max	1 Cycle @ 1.00 (ap)max	= 2.10 Cycles @ 0.65 (ap) max
1.10 Cycles @ 0.95	= 2.1 Cycles @ 0.65	1 Cycle @ 0.95	= 1.90 Cycles @ 0.65
1.20 Cycles @ 0.90	= 2.1 Cycles @ 0.65	1 Cycle @ 0.90	= 1.80 Cycles @ 0.65
1.40 Cycles @ 0.85	= 2.1 Cycles @ 0.65	1 Cycle @ 0.85	= 1.50 Cycles @ 0.65
1.75 Cycles @ 0.80	= 2.1 Cycles @ 0.65	1 Cycle @ 0.80	= 1.20 Cycles @ 0.65
1.80 Cycles @ 0.75	= 2.1 Cycles @ 0.65	1 Cycle @ 0.75	= 1.20 Cycles @ 0.65
1.90 Cycles @ 0.70	= 2.1 Cycles @ 0.65	1 Cycle @ 0.70	= 1.10 Cycles @ 0.65
2.10 Cycles @ 0.65	= 2.1 Cycles @ 0.65	1 Cycle @ 0.65	= 1.00 Cycles @ 0.65
2.50 Cycles @ 0.60	= 2.1 Cycles @ 0.65	1 Cycle @ 0.60	= 0.80 Cycles @ 0.65
3.00 Cycles @ 0.55	= 2.1 Cycles @ 0.65	1 Cycle @ 0.55	= 0.70 Cycles @ 0.65
4.00 Cycles @ 0.50	= 2.1 Cycles @ 0.65	1 Cycle @ 0.50	= 0.50 Cycles @ 0.65
7.00 Cycles @ 0.45	= 2.1 Cycles @ 0.65	1 Cycle @ 0.45	= 0.30 Cycles @ 0.65
10.00 Cycles @ 0.40	= 2.1 Cycles @ 0.65	1 Cycle @ 0.40	= 0.20 Cycles @ 0.65
20.00 Cycles @ 0.35	= 2.1 Cycles @ 0.65	1 Cycle @ 0.35	= 0.10 Cycles @ 0.65

TABLE A-2 EQUIVALENT STRESS LEVELS (FROM FIG. A-3)
SAFETY FACTOR = 1.50

2.00 Cycles @ 1.00(ap)max	= 6.0 Cycles @ 0.65(ap)max	1 Cycle @ 1.00(ap)max	= 3.00 Cycles @ 0.65(ap)max
2.20 Cycles @ 0.95	= 6.0 Cycles @ 0.65	1 Cycle @ 0.95	= 2.70 Cycles @ 0.65
2.50 Cycles @ 0.90	= 6.0 Cycles @ 0.65	1 Cycle @ 0.90	= 2.40 Cycles @ 0.65
2.90 Cycles @ 0.85	= 6.0 Cycles @ 0.65	1 Cycle @ 0.85	= 2.05 Cycles @ 0.65
3.50 Cycles @ 0.80	= 6.0 Cycles @ 0.65	1 Cycle @ 0.80	= 1.70 Cycles @ 0.65
4.20 Cycles @ 0.75	= 6.0 Cycles @ 0.65	1 Cycle @ 0.75	= 1.40 Cycles @ 0.65
5.00 Cycles @ 0.70	= 6.0 Cycles @ 0.65	1 Cycle @ 0.70	= 1.20 Cycles @ 0.65
6.00 Cycles @ 0.65	= 6.0 Cycles @ 0.65	1 Cycle @ 0.65	= 1.00 Cycles @ 0.65
8.80 Cycles @ 0.60	= 6.0 Cycles @ 0.65	1 Cycle @ 0.60	= 0.70 Cycles @ 0.65
16.00 Cycles @ 0.55	= 6.0 Cycles @ 0.65	1 Cycle @ 0.55	= 0.40 Cycles @ 0.65
28.00 Cycles @ 0.50	= 6.0 Cycles @ 0.65	1 Cycle @ 0.50	= 0.20 Cycles @ 0.65
58.00 Cycles @ 0.45	= 6.0 Cycles @ 0.65	1 Cycle @ 0.45	= 0.10 Cycles @ 0.65
100.00 Cycles @ 0.40	= 6.0 Cycles @ 0.65	1 Cycle @ 0.40	= 0.04 Cycles @ 0.65
320.00 Cycles @ 0.35	= 6.0 Cycles @ 0.65	1 Cycle @ 0.35	= 0.02 Cycles @ 0.65

TABLE A-3 EQUIVALENT STRESS LEVELS (FROM FIG. A-3)
SAFETY FACTOR = 1.75

3.10 Cycles @ 1.00(ap)max	= 14 Cycles @ 0.65(ap)max	1 Cycle @ 1.00(ap)max	= 4.52 Cycles @ 0.65(ap)max
3.60 Cycles @ 0.95	= 14 Cycles @ 0.65	1 Cycle @ 0.95	= 3.89 Cycles @ 0.65
4.20 Cycles @ 0.90	= 14 Cycles @ 0.65	1 Cycle @ 0.90	= 3.33 Cycles @ 0.65
4.80 Cycles @ 0.85	= 14 Cycles @ 0.65	1 Cycle @ 0.85	= 2.92 Cycles @ 0.65
5.20 Cycles @ 0.80	= 14 Cycles @ 0.65	1 Cycle @ 0.80	= 2.69 Cycles @ 0.65
5.50 Cycles @ 0.75	= 14 Cycles @ 0.65	1 Cycle @ 0.75	= 2.55 Cycles @ 0.65
10.00 Cycles @ 0.70	= 14 Cycles @ 0.65	1 Cycle @ 0.70	= 1.40 Cycles @ 0.65
14.00 Cycles @ 0.65	= 14 Cycles @ 0.65	1 Cycle @ 0.65	= 1.00 Cycles @ 0.65
24.00 Cycles @ 0.60	= 14 Cycles @ 0.65	1 Cycle @ 0.60	= 0.58 Cycles @ 0.65
44.00 Cycles @ 0.55	= 14 Cycles @ 0.65	1 Cycle @ 0.55	= 0.32 Cycles @ 0.65
120.00 Cycles @ 0.50	= 14 Cycles @ 0.65	1 Cycle @ 0.50	= 0.12 Cycles @ 0.65
1000.00 Cycles @ 0.45	= 14 Cycles @ 0.65	1 Cycle @ 0.45	= 0.01 Cycles @ 0.65
1000.00 Cycles @ 0.40	= 14 Cycles @ 0.65	1 Cycle @ 0.40	= 0.00 Cycles @ 0.65
1000.00 Cycles @ 0.35	= 14 Cycles @ 0.65	1 Cycle @ 0.35 τmax	= 0.00 Cycles @ 0.65

TABLE A-4 EQUIVALENT STRESS LEVELS (FROM FIG. A-3)
SAFETY FACTOR = 2.00

4.25 Cycles @ 1.00(ap)max	= 35 Cycles @ 0.65(ap)max	1 Cycle @ 1.00(ap)max	= 8.24 Cycles @ 0.65(ap)max
5.00 Cycles @ 0.95	= 35 Cycles @ 0.65	1 Cycle @ 0.95	= 7.00 Cycles @ 0.65
6.25 Cycles @ 0.90	= 35 Cycles @ 0.65	1 Cycle @ 0.90	= 5.60 Cycles @ 0.65
8.13 Cycles @ 0.85	= 35 Cycles @ 0.65	1 Cycle @ 0.85	= 4.31 Cycles @ 0.65
10.00 Cycles @ 0.80	= 35 Cycles @ 0.65	1 Cycle @ 0.80	= 3.50 Cycles @ 0.65
14.00 Cycles @ 0.75	= 35 Cycles @ 0.65	1 Cycle @ 0.75	= 2.50 Cycles @ 0.65
19.00 Cycles @ 0.70	= 35 Cycles @ 0.65	1 Cycle @ 0.70	= 1.84 Cycles @ 0.65
35.00 Cycles @ 0.65	= 35 Cycles @ 0.65	1 Cycle @ 0.65	= 1.00 Cycles @ 0.65
68.75 Cycles @ 0.60	= 35 Cycles @ 0.65	1 Cycle @ 0.60	= 0.51 Cycles @ 0.65
200.00 Cycles @ 0.55	= 35 Cycles @ 0.65	1 Cycle @ 0.55	= 0.18 Cycles @ 0.65
1000.00 Cycles @ 0.50	= 35 Cycles @ 0.65	1 Cycle @ 0.50	= 0.00 Cycles @ 0.65
1000.00 Cycles @ 0.45	= 35 Cycles @ 0.65	1 Cycle @ 0.45	= 0.00 Cycles @ 0.65
1000.00 Cycles @ 0.40	= 35 Cycles @ 0.65	1 Cycle @ 0.40	= 0.00 Cycles @ 0.65
1000.00 Cycles @ 0.35	= 35 Cycles @ 0.65	1 Cycle @ 0.35	= 0.00 Cycles @ 0.65

APPENDIX B

ACCELERATION TIME HISTORIES RECORDED DURING EARTHQUAKES IN WESTERN U.S. (SETS 1 AND 2)

TABLE B-1
EQUIVALENT UNIFORM CYCLIC STRESS SERIES FOR DIFFERENTS EARTHQUAKES
APPLICATION OF METHOD 1, 2 AND 3 WITH SAFETY FACTOR = 1.00
(SET 1; FROM SEED ET AL. 1975)

CALTECH NUMBER	EARTHQUAKE	MAGNITUDE	RECORDING STATION	COMPONENT	NUMBER OF EQUIVALENT CYCLES AT τmax METHOD #1	METHOD #2 & 4	METHOD #3
001	Imperial Valley (1940)	6.6	El Centro	S00E S90W	8.85 15.60	2.10 2.10	8.24 14.10
007	Kern Country (1952)	7.6	Pasadena	S00E S90W	10.25 13.65	2.10 2.10	8.74 12.95
010	Kern Country (1952)	7.6	Taft	S69E N21E	13.55 9.85	2.10 2.10	12.66 8.87
013	Kern Country (1952)	7.6	Santa Barbara	S48E N42E	10.30 3.35	2.10 2.10	10.00 3.30
022	Eureka (1954)	6.5	Fed.Bldg.	N79E N11W	6.80 6.20	2.10 2.10	6.62 5.98
025	Eureka (1954)	6.5	Ferndale	N46W N44E	4.85 2.25	2.10 2.10	4.52 2.20
046	San Francisco (1957)	5.3	State Bldg.	S09E S81W	5.45 8.50	2.10 2.10	5.07 8.03
052	Hollister (1961)	5.6	Hollister	N89W S01W	16.75 2.80	2.10 2.10	15.82 2.68
061	Long Beach (1933)	6.3	Vernon	N82W S08W	6.60 3.00	2.10 2.10	6.28 2.39
076	N.W. California (1938)	5.5	Ferndale	N00E S00E	2.75 6.25	2.10 2.10	2.67 5.56
082	Wester Washington (1949)	7.1	Seattle	S02W N88W	19.35 12.10	2.10 2.10	17.93 10.92
085	Wester, Washington (1949)	7.1	Olympia	S86W S04E	20.95 7.15	2.10 2.10	19.76 5.55
088	Norther, California (1952)	5.5	Ferndale	S46E N44E	10.10 5.25	2.10 2.10	9.86 5.01
100	Park Field (1966)	5.6	#5	N85E N05W	2.40 2.35	2.10 2.10	2.01 2.18
103	Park Field (1966)	5.6	#8	N40W N50E	3.60 3.25	2.10 2.10	3.40 2.75
142	San Fernando (1971)	6.6	Orion Blvd.	N00W E00W	9.80 19.30	2.10 2.10	8.78 18.39
169	San Fernando (1971)	6.6	Hollywood Bsmt	N90E N00W	13.05 8.65	2.10 2.10	12.33 8.29
172	San Fernando (1971)	6.6	Hollywood P.Lot.	E00W N00S	14.45 12.20	2.10 2.10	13.67 11.79
322	San Fernando (1971)	6.6	Millikan Library	N00S E00W	5.80 4.30	2.10 2.10	5.55 3.76
124	San Fernando (1971)	6.6	Ventura Blvd	N11E N79W	13.20 15.15	2.10 2.10	12.80 14.05
190	San Fernando (1971)	6.6	Wilshire Blvd	N00S E00W	11.60 5.55	2.10 2.10	10.91 5.19
361	Ferndale (1967)	5.6	Ferndale	S44W N46W	2.05 1.20	1.97 1.05	1.97 1.05

TABLE B-2
EQUIVALENT UNIFORM CYCLIC STRESS SERIES FOR DIFFERENTS EARTHQUAKES
APPLICATION OF METHOD 1, 2 AND 3 WITH SAFETY FACTOR = 1.50
(SET 1; FROM SEED ET AL. 1975)

CALTECH NUMBER	EARTHQUAKE	MAGNITUDE	RECORDING STATION	COMPONENT	NUMBER OF EQUIVALENT CYCLES AT τmax METHOD #1	METHOD #2 & 4	METHOD #3
001	Imperial Valley (1940)	6.6	El Centro	S00E	7.30	6.00	7.01
				S90W	12.37	6.00	11.75
007	Kern Country (1952)	7.6	Pasadena	S00E	8.43	6.00	7.73
				S90W	13.74	6.00	13.42
010	Kern Country (1952)	7.6	Taft	S69E	11.72	6.00	11.32
				N21E	7.64	6.00	7.07
013	Kern Country (1952)	7.6	Santa Barbara	S48E	10.25	6.00	10.11
				N42E	2.55	2.47	2.47
022	Eureka (1954)	6.5	Fed.Bldg.	N79E	7.28	6.00	7.04
				N11W	7.23	6.00	7.10
025	Eureka (1954)	6.5	Ferndale	N46W	5.28	5.21	5.21
				N44E	2.50	2.53	2.53
046	San Francisco (1957)	5.3	State Bldg.	S09E	5.57	5.55	5.55
				S81W	8.92	6.00	8.59
052	Hollister (1961)	5.6	Hollister	N89W	16.74	6.00	16.56
				S01W	2.70	2.58	2.58
061	Long Beach (1933)	6.3	Vernon	N82W	6.51	6.00	6.48
				S08W	2.92	2.84	2.84
076	N.W. California (1938)	5.5	Ferndale	N00E	2.57	2.54	2.54
				S00E	6.02	5.77	5.77
082	Wester Washington (1949)	7.1	Seattle	S02W	17.21	6.00	16.82
				N88W	9.88	6.00	9.40
085	Wester, Washington (1949)	7.1	Olympia	S86W	17.93	6.00	17.54
				S04E	4.51	4.06	4.06
088	Norther, California (1952)	5.5	Ferndale	S46E	11.87	6.00	11.77
				N44E	5.56	5.45	5.45
100	Park Field (1966)	5.6	#5	N85E	2.57	2.47	2.47
				N05W	1.95	1.89	1.89
103	Park Field (1966)	5.6	#8	N40W	3.04	2.93	2.93
				N50E	3.47	3.33	3.33
142	San Fernando (1971)	6.6	Orion Blvd.	N00W	7.89	6.00	7.39
				E00W	19.76	6.00	19.10
169	San Fernando (1971)	6.6	Hollywood Bsmt	N90E	12.76	6.00	12.51
				N00W	8.13	6.00	7.63
172	San Fernando (1971)	6.6	Hollywood P.Lot.	E00W	14.40	6.00	14.04
				N00S	13.15	6.00	12.99
322	San Fernando (1971)	6.6	Millikan Library	N00S	4.72	4.69	4.69
				E00W	3.12	2.90	2.90
124	San Fernando (1971)	6.6	Ventura Blvd	N11E	14.44	6.00	14.33
				N79W	13.53	6.00	13.41
190	San Fernando (1971)	6.6	Wilshire Blvd	N00S	11.27	6.00	10.96
				E00W	4.87	4.77	4.77
361	Ferndale (1967)	5.6	Ferndale	S44W	2.57	2.50	2.50
				N46W	1.53	1.50	1.50

TABLE B-3
EQUIVALENT UNIFORM CYCLIC STRESS SERIES FOR DIFFERENTS EARTHQUAKES
APPLICATION OF METHOD 1, 2 AND 3 WITH SAFETY FACTOR = 1.75
(SET 1; FROM SEED ET AL. 1975)

CALTECH NUMBER	EARTHQUAKE	MAGNITUDE	RECORDING STATION	COMPONENT	NUMBER OF EQUIVALENT CYCLES AT τmax METHOD #1	METHOD #2 & 4	METHOD #3
001	Imperial Valley (1940)	6.6	El Centro	S00E	8.00	8.05	8.05
				S90W	14.31	13.71	13.71
007	Kern Country (1952)	7.6	Pasadena	S00E	9.71	9.22	9.22
				S90W	17.71	14.00	17.31
010	Kern Country (1952)	7.6	Taft	S69E	14.16	13.51	13.51
				N21E	7.88	7.45	7.45
013	Kern Country (1952)	7.6	Santa Barbara	S48E	12.76	12.90	12.90
				N42E	2.89	2.84	2.84
022	Eureka (1954)	6.5	Fed.Bldg.	N79E	9.52	8.91	8.91
				N11W	10.25	10.06	10.06
025	Eureka (1954)	6.5	Ferndale	N46W	6.98	7.00	7.00
				N44E	3.75	3.70	3.70
046	San Francisco (1957)	5.3	State Bldg.	S09E	7.27	7.27	7.27
				S81W	11.27	10.95	10.95
052	Hollister (1961)	5.6	Hollister	N89W	22.52	14.00	22.52
				S01W	3.27	3.16	3.16
061	Long Beach (1933)	6.3	Vernon	N82W	7.95	8.04	8.04
				S08W	4.09	4.08	4.08
076	N.W. California (1938)	5.5	Ferndale	N00E	3.14	3.11	3.11
				S00E	7.70	7.36	7.36
082	Wester Washington (1949)	7.1	Seattle	S02W	22.05	14.00	21.60
				N88W	11.35	10.64	10.64
085	Wester, Washington (1949)	7.1	Olympia	S86W	20.33	14.00	20.21
				S04E	4.24	4.11	4.11
088	Norther, California (1952)	5.5	Ferndale	S46E	16.64	14.00	16.28
				N44E	7.31	7.05	7.05
100	Park Field (1966)	5.6	#5	N85E	3.67	3.63	3.63
				N05W	2.42	2.42	2.42
103	Park Field (1966)	5.6	#8	N40W	3.37	3.34	3.34
				N50E	4.60	4.55	4.55
142	San Fernando (1971)	6.6	Orion Blvd.	N00W	8.73	8.12	8.12
				E00W	25.99	14.00	24.96
169	San Fernando (1971)	6.6	Hollywood Bsmt	N90E	16.35	14.00	16.06
				N00W	9.77	8.96	8.96
172	San Fernando (1971)	6.6	Hollywood P.Lot.	E00W	18.72	14.00	18.63
				N00S	17.94	14.00	17.75
322	San Fernando (1971)	6.6	Millikan Library	N00S	3.22	3.18	3.18
				E00W	3.12	2.90	2.90
124	San Fernando (1971)	6.6	Ventura Blvd	N11E	19.42	14.00	19.11
				N79W	16.70	14.00	16.73
190	San Fernando (1971)	6.6	Wilshire Blvd	N00S	14.52	14.00	14.08
				E00W	5.71	5.77	5.77
361	Ferndale (1967)	5.6	Ferndale	S44W	3.72	3.68	3.68
				N46W	2.66	2.66	

TABLE B – 4
EQUIVALENT UNIFORM CYCLIC STRESS SERIES FOR DIFFERENTS EARTHQUAKES
APPLICATION OF METHOD 1, 2 AND 3 WITH SAFETY FACTOR = 2.00
(SET 1; FROM SEED ET AL. 1975)

CALTECH NUMBER	EARTHQUAKE	MAGNITUDE	RECORDING STATION	COMPONENT	NUMBER OF EQUIVALENT CYCLES AT τ_{max} METHOD #1	METHOD #2&4	METHOD #3
001	Imperial Valley (1940)	6.6	El Centro	S00E	9.84	10.01	10.01
				S90W	17.98	17.71	17.71
007	Kern Country (1952)	7.6	Pasadena	S00E	12.96	12.36	12.36
				S90W	23.98	23.67	23.67
010	Kern Country (1952)	7.6	Taft	S69E	18.97	18.11	18.11
				N21E	10.06	9.48	9.47
013	Kern Country (1952)	7.6	Santa Barbara	S48E	17.75	18.08	18.08
				N42E	4.46	4.50	4.50
022	Eureka (1954)	6.5	Fed.Bldg.	N79E	12.70	12.03	12.03
				N11W	15.98	15.60	15.60
025	Eureka (1954)	6.5	Ferndale	N46W	11.39	11.37	11.37
				N44E	5.46	5.58	5.58
046	San Francisco (1957)	5.3	State Bldg.	S09E	11.42	11.42	11.42
				S81W	16.99	16.74	16.74
052	Hollister (1961)	5.6	Hollister	N89W	29.12	29.44	29.44
				S01W	4.96	4.82	4.82
061	Long Beach (1933)	6.3	Vernon	N82W	12.72	12.82	12.82
				S08W	5.87	5.95	5.95
076	N.W. California (1938)	5.5	Ferndale	N00E	4.80	4.77	4.77
				S00E	11.75	11.41	11.41
082	Wester Washington (1949)	7.1	Seattle	S02W	26.09	25.53	25.53
				N88W	13.79	13.38	13.38
085	Wester, Washington (1949)	7.1	Olympia	S86W	25.85	25.79	25.79
				S04E	5.75	5.71	5.71
088	Norther, California (1952)	5.5	Ferndale	S46E	23.57	23.13	23.13
				N44E	10.12	9.96	9.96
100	Park Field (1966)	5.6	#5	N85E	5.87	5.80	5.80
				N05W	4.21	4.27	4.27
103	Park Field (1966)	5.6	#8	N40W	5.05	5.08	5.08
				N50E	6.87	6.81	6.81
142	San Fernando (1971)	6.6	Orion Blvd.	N00W	10.51	10.06	10.06
				E00W	36.01	35.00	35.00
169	San Fernando (1971)	6.6	Hollywood Bsmt	N90E	20.36	20.31	20.31
				N00W	13.45	12.51	12.51
172	San Fernando (1971)	6.6	Hollywood P.Lot.	E00W	23.95	23.83	23.83
				N00S	23.46	23.11	23.11
322	San Fernando (1971)	6.6	Millikan Library	N00S	7.39	7.56	7.56
				E00W	4.81	4.85	4.85
124	San Fernando (1971)	6.6	Ventura Blvd	N11E	19.60	19.55	19.55
				N79W	17.30	17.30	17.30
190	San Fernando (1971)	6.6	Wilshire Blvd	N00S	12.13	12.10	12.10
				E00W	6.40	6.40	6.40
361	Ferndale (1967)	5.6	Ferndale	S44W	4.20	4.15	4.15
				N46W	3.00	3.00	3.00

TABLE B-5
EQUIVALENT NUMBER OF CYCLES AT 0.65 (ap)max
ROCK SITES
(SET 2; FROM DOBRY ET AL. 1978)

CALTECH NUMBER	EARTHQUAKE	MAGNITUDE	RECORDING STATION	COMPONENT	NUMBER OF EQUIVALENT CYCLES METHOD 1			
					SF=1.0,	SF=1.5,	SF=1.75,	SF=2.0
043	San Francisco	5.3	Golden Gate	N108	4.25	4.74	6.33	9.84
				S80E	5.95	6.54	8.67	12.93
427	Lytle Creek	5.4	Wringhtwood	S65E	6.00	5.74	7.08	8.91
				S25W	3.45	3.86	5.05	8.37
109	Parkfield	5.6	Temblor	N65W	2.85	3.18	4.28	6.77
				S25W	2.40	2.50	3.06	4.87
073	Helena	6.0	Helena	E00W	4.70	4.79	6.99	8.56
				N005	5.00	5.89	8.85	13.07
457	San Fernando	6.6	Lankershim	S90W	4.30	4.80	6.89	10.17
				N00E	9.90	8.54	9.48	11.98
055	San Fernando	6.6	Griffith	S90W	6.65	5.54	6.33	8.88
				S00W	4.80	4.12	5.05	6.71
160	San Fernando	6.6	445 Figueroa	N52W	7.85	7.63	8.51	10.96
				S38W	17.25	15.71	17.54	23.52
232	San Fernando	6.6	Water Buld.	N50W	4.15	2.84	3.06	4.71
				S40W	9.45	8.93	11.23	16.83
076	San Fernando	6.6	Fairmont	N56E	5.95	5.21	6.05	9.32
				N34W	14.10	13.20	16.79	20.81
304	San Fernando	6.6	Ft Tejon	N90E	7.65	7.32	9.06	13.32
				N00E	4.40	4.15	5.12	8.22
010	Kern Country	7.6	Taft	S69E	13.55	11.72	14.16	18.97
				N21E	9.85	7.64	7.88	10.06

APPENDIX C

ACCELERATION TIME HISTORIES RECORDED DURING 1971 SAN FERNANDO EARTHQUAKE (SET 3)

TABLE C-1
EQUIVALENT NUMBER OF CYCLES AT 0.65 (ap) max
SAN FERNANDO EARTHQUAKE 1971
SAFETY FACTOR = 1.50

(SET 3; FROM BOND, 1980)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65 (ap)max METHOD #1	METHOD #2 & 4	METHOD #3
142	21.09	199.36	2500	N00W	7.89	6.00	7.39
			1317	S90W	19.76	6.00	19.10
151	41.40	159.94	1227	N54W	6.40	6.00	6.10
			978	N36E	13.73	6.00	13.22
160	40.59	161.75	1471	N52W	4.80	4.63	4.61
			1170	S38W	8.54	6.00	8.38
166	29.54	305.70	3094	N21E	3.35	3.10	3.08
			2654	N69W	6.33	5.96	5.95
169	35.67	170.86	1482	N90E	8.13	6.00	7.63
			1038	S00W	12.76	6.00	12.51
172	35.67	170.86	2070	S90E	13.15	6.00	12.99
			1673	S00W	14.40	6.00	14.04
175	38.54	182.88	1471	S44W	9.69	6.00	9.34
			1338	N46W	6.56	6.00	6.34
184	41.33	156.16	1303	S52W	15.03	6.00	14.83
			1180	N38W	10.24	6.00	9.88
193	38.49	167.82	1557	S90W	7.48	6.00	7.14
			1467	S00W	3.55	3.42	3.39
202	33.50	171.91	980	N90E	7.04	6.00	6.77
			812	N00E	12.69	6.00	12.58
211	87.35	321.89	265	S00W	7.38	6.00	7.13
			253	N90E	8.12	6.00	7.79
214	38.11	171.10	1150	N15E	8.91	6.00	8.73
			822	N75W	11.48	6.00	11.19
223	38.70	166.88	1338	N00E	9.92	6.00	9.85
			1118	S90W	10.41	6.00	9.93
232*	41.14	161.10	1692	N50W	4.12	3.95	3.93
			1265	S40W	5.54	5.36	5.36

TABLE C-1 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2 & 4	METHOD #3
241*	33.32	281.82	2130	S08E	5.23	4.98	4.96
			1983	S82W	8.29	6.00	8.00
247	38.63	166.27	1619	N90E	9.68	6.00	9.41
			1582	S00W	13.50	6.00	13.14
256	47.96	158.04	1046	N83W	5.47	5.44	5.36
			805	S07W	8.90	6.00	8.56
259	87.13	146.05	282	S86W	17.48	6.00	17.65
			268	S04E	15.12	6.00	14.26
262	32.61	155.40	2657	S70E	6.48	6.00	6.40
			2091	S20W	8.37	6.00	8.04
265	42.67	161.90	1390	S37W	5.12	5.04	4.99
			1319	S53E	10.29	6.00	10.16
274*	41.67	155.14	791	S28W	7.69	6.00	7.36
			642	S62E	10.28	6.00	9.99
283	36.10	178.21	962	S88E	6.32	6.00	6.14
			839	S02W	12.85	6.00	12.93
292	41.32	161.70	2364	S53E	3.34	3.07	3.03
			1920	S37W	6.12	5.84	5.81
301	106.48	110.83	375	S00W	16.46	6.00	15.90
			300	N90E	10.21	6.00	10.02
304*	69.70	318.23	246	N00E	7.63	6.00	7.44
			206	N90E	15.71	6.00	14.96
307	45.04	74.49	1205	N90W	14.56	6.00	14.38
			915	N00E	16.06	6.00	15.24
310	53.51	326.52	1031	N90W	2.34	2.26	2.26
			852	N00E	4.95	4.73	4.71
313	37.41	187.77	831	S00W	12.04	6.00	11.50
			776	N90E	8.73	6.00	8.82
316*	34.72	143.62	1886	S90W	6.04	6.00	6.02
			875	S00W	12.01	6.00	11.84
319	38.41	139.11	1073	N90E	8.36	6.00	8.28
			935	N00E	9.30	6.00	9.04

TABLE C-1 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
322	38.38	139.73	1980	N00E	4.72	4.69	4.65
			1816	N90E	3.12	2.90	2.86
328	30.11	137.52	2078	S82E	4.44	4.48	4.45
			1390	S08W	5.60	5.56	5.49
334	41.10	161.67	1019	N38E	7.91	6.00	7.61
			785	N52W	12.18	6.00	11.68
340	32.58	52.64	1362	S30W	6.69	6.00	6.27
			1108	S60E	19.04	6.00	18.52
343	28.09	193.03	2206	N11E	8.76	6.00	8.43
			1460	N79W	13.51	6.00	13.16
352	48.98	182.54	337	S45E	18.83	6.00	18.50
			327	S45W	14.91	6.00	14.19
361	41.70	147.14	1194	S90W	8.39	6.00	8.35
			1123	S00W	13.82	6.00	13.60
370	74.90	140.87	349	S90W	7.88	6.00	6.99
			345	S00W	13.81	6.00	13.01
379	35.83	179.35	916	S90W	4.81	4.79	4.74
			609	N00E	15.06	6.00	14.67
388	36.86	181.59	1843	N50E	6.23	6.00	6.05
			1606	N40W	6.10	5.69	5.69
397	37.54	182.73	979	N54E	10.98	6.00	10.89
			823	S36E	11.58	6.00	11.19
406	27.81	196.32	1402	S81E	7.07	6.00	6.62
			1290	S09W	12.63	6.00	12.09
415	30.86	352.33	1455	N21E	4.10	3.93	3.92
			1089	S69E	5.28	5.12	5.03
418*	27.98	343.83	1682	S69E	6.79	6.00	6.49
			1435	S21W	8.47	6.00	8.27
421*	27.75	326.61	1193	N21E	7.14	6.00	7.12
			1094	N69W	10.27	6.00	10.02
424*	24.35	321.61	3462	N21E	5.55	5.42	5.42
			2779	N69W	9.96	6.00	9.75

TABLE C-1 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
427	33.46	132.94	1139	S00W	16.16	6.00	15.98
			1034	S90W	19.50	6.00	19.40
436	38.56	166.75	1120	S90W	15.12	6.00	14.53
			1076	N00E	12.77	6.00	12.43
445	41.09	161.29	1683	S53E	3.27	3.30	3.26
			1161	S37W	6.22	6.00	6.16
457*	29.36	173.86	1642	N00E	2.84	2.78	2.74
			1476	S90W	8.93	6.00	8.80
472	138.56	145.96	159	N57W	7.59	6.00	7.33
			120	N33E	18.03	6.00	17.28
487	41.46	162.50	1160	S53E	4.99	4.85	4.78
			834	N37E	13.43	6.00	13.07
496*	72.02	326.76	467	N90E	9.96	6.00	9.88
			208	S00W	5.64	5.31	5.23
1	82.96	146.10	299	S90W	11.02	6.00	10.29
			239	S00W	22.22	6.00	21.98
10	70.09	93.54	557	N25E	6.62	6.00	6.24
			424	N65W	10.42	6.00	10.03
13	70.09	93.54	572	S25W	7.16	6.00	6.61
			431	S65E	10.79	6.00	10.32
16	74.28	136.62	673	S50E	13.36	6.00	12.48
			673	S40W	18.13	6.00	18.13
19	52.69	143.32	967	S53W	13.92	6.00	13.45
			957	S37E	7.54	6.00	7.03
22	71.05	112.33	759	N75W	14.31	6.00	14.34
			557	N15E	11.81	6.00	11.43
25	37.06	182.65	1265	N36W	19.22	6.00	18.71
			1144	N54E	6.14	6.00	5.99
34	66.66	179.36	401	S25E	4.34	4.15	4.11
			247	N65E	19.16	6.00	18.53
37	39.30	164.35	989	N61W	12.41	6.00	12.06
			967	N29E	12.21	6.00	11.55

TABLE C-1 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
46	121.32	146.58	409	N33E	10.35	6.00	10.03
			310	N57W	17.10	6.00	16.71
49	74.06	159.44	350	N76W	23.58	6.00	22.73
			312	S14W	22.70	6.00	22.47
52	184.42	120.61	354	N45W	9.29	6.00	8.89
			256	N45E	6.96	6.00	6.53
55*	32.53	164.34	1769	S00W	5.21	5.06	5.02
			1674	S90W	13.20	6.00	13.00
58	40.54	164.06	2388	N62W	4.14	4.26	4.17
			1379	N28E	10.03	6.00	9.73
67	72.53	165.18	260	N00E	11.64	6.00	11.39
			208	N90E	24.27	6.00	23.11
70	72.36	167.50	284	N21W	12.09	6.00	11.67
			281	N69E	20.85	6.00	19.92
73	107.19	107.79	439	N90E	4.23	4.03	4.03
			374	N00E	9.66	6.00	7.19
76*	34.04	355.07	971	N34W	4.15	4.13	4.13
			647	N56E	7.32	6.00	7.19
79	133.50	270.60	170	S48E	22.22	6.00	21.70
			165	N42E	14.12	6.00	13.85
82	150.22	119.75	384	S45W	12.21	6.00	11.99
			349	S45E	8.06	6.00	8.03
88	34.81	164.48	1563	S01E	12.90	6.00	12.82
			1541	S89W	10.32	6.00	10.11
97	38.63	166.27	1083	S00W	8.77	6.00	8.37
			882	N90E	9.13	6.00	8.88
106	94.52	152.81	343	N90E	10.97	6.00	10.55
			242	S00W	13.83	6.00	13.13
109*	42.06	124.64	1658	N87W	9.37	6.00	9.14
			1377	N03E	12.07	6.00	11.81
112	79.02	249.40	259	S00W	22.56	6.00	22.06
			252	S90W	14.75	6.00	14.01

TABLE C-1 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
115*	63.72	122.95	697	N55E	6.51	6.00	6.15
			533	N35W	10.59	6.00	10.07
118	50.48	179.04	413	N00E	8.03	6.00	7.65
			378	S90W	12.12	6.00	12.08
124	28.10	191.36	2433	S12W	14.42	6.00	14.33
			1970	N78W	13.51	6.00	13.41
133	33.45	171.13	1673	S00E	8.67	6.00	8.34
			1224	N90E	9.35	6.00	9.29
142	37.07	179.22	1618	N90E	4.76	4.47	4.43
			1192	S00E	16.10	6.00	16.11
148	40.36	160.80	1380	N53W	3.29	3.17	3.13
			868	N37E	20.35	6.00	19.95
157	40.38	160.84	1494	N53W	2.94	2.91	2.86
			1268	S37W	6.41	6.00	6.08
163	34.18	170.11	1160	S00E	7.65	6.00	7.63
			1070	N90E	15.13	6.00	14.88
172	37.89	182.86	842	S46E	12.67	6.00	12.39
			799	N44E	14.74	6.00	14.57
178	40.35	161.67	1956	N37E	6.19	5.96	5.09
			1883	S53E	3.60	3.45	3.45
184	40.65	161.92	2420	N30W	3.77	3.62	3.62
			2207	S60W	4.45	4.28	4.28
190	37.59	175.36	1284	N82W	4.85	4.79	4.79
			1238	N08E	11.27	6.00	10.96
199	43.19	166.22	834	S61E	5.51	5.15	5.15
			564	N29E	14.64	6.00	14.48
208	38.27	180.04	1077	N31W	5.92	6.00	5.95
			978	N59E	11.25	6.00	11.03
211	37.68	174.87	937	S07W	5.71	5.44	5.44
			684	N38W	11.00	6.00	11.03
220	38.55	166.79	1252	N90W	8.19	6.00	7.92
			1042	S00W	12.27	6.00	12.15

TABLE C-1 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
223	38.59	167.15	1536	N00W	7.59	6.00	7.33
			1297	S90W	10.06	6.00	9.76
226	50.64	177.60	615	S90E	8.23	6.00	7.79
			555	N00E	11.55	6.00	10.99

* ROCK SITE

TABLE C-2
EQUIBALENT NUMBER OF CYCLES AT 0.65 (ap)max
SAN FERNANDO EARTHQUAKE 1971
SAFETY FACTOR = 2.00
(SET 3; FROM BOND, 1980)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
142	21.09	199.36	2500	N00W	10.51	10.06	10.06
			1317	S90W	36.91	35.00	35.00
151	41.40	159.94	1227	N54W	8.65	8.47	8.47
			978	N36E	21.81	20.96	20.96
160	40.59	161.75	1471	N52W	10.17	9.90	9.90
			1170	S38W	11.98	11.94	11.94
166	29.54	305.70	3094	N21E	5.31	5.19	5.19
			2654	N69W	11.77	11.37	11.37
169	35.67	170.86	1482	N90E	13.45	12.51	12.51
			1038	S00W	20.36	20.31	20.31
172	35.67	170.86	2070	S90E	23.46	23.11	23.11
			1673	S00W	23.95	23.83	23.83
175	38.54	182.88	1471	S44W	16.04	15.46	15.46
			1338	N46W	11.03	10.73	10.73
184	41.33	156.16	1303	S52W	28.18	28.20	28.20
			1180	N38W	19.13	18.11	18.11
193	38.49	167.82	1557	S90W	11.81	11.30	11.30
			1467	S00W	6.38	6.37	6.37
202	33.50	171.91	980	N90E	11.88	11.52	11.52
			812	N00E	24.01	23.88	23.88
211	87.35	321.89	265	S00W	12.81	12.43	12.43
			255	N90E	14.13	13.95	13.95
214	38.11	171.10	1150	N15E	15.54	15.95	15.95
			822	N75W	21.62	21.07	21.07
223	38.70	166.88	1338	N00E	17.04	16.94	16.94
			1118	S90W	17.67	17.18	17.18
232*	41.14	161.10	1692	N50W	6.71	6.76	6.76
			1265	S40W	8.88	8.88	8.88

TABLE C-2 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
241*	33.32	281.82	2130	S08E	8.89	8.40	8.40
			1983	S82W	11.81	11.55	11.54
247	38.63	166.27	1619	N90E	16.08	15.87	15.87
			1582	S00W	25.50	24.98	24.98
256	47.96	158.04	1046	N83W	8.40	8.48	8.48
			805	S07W	12.71	12.88	12.88
259	87.13	146.05	282	S86W	26.64	27.87	27.87
			268	S04E	19.68	19.53	19.53
262	32.61	155.40	2657	S70E	11.13	11.15	11.15
			2091	S20W	12.24	11.92	11.92
265	42.67	161.90	1390	S37W	7.47	7.70	7.70
			1319	S53E	21.12	20.78	20.78
274*	41.67	155.14	791	S28W	12.44	12.40	12.40
			642	S62E	20.51	19.80	19.80
283	36.10	178.21	962	S88E	10.15	9.94	9.94
			839	S02W	23.13	23.83	23.83
292	41.32	161.70	2364	S53E	5.29	5.42	5.42
			1920	S37W	8.72	8.58	8.58
301	106.48	110.83	375	S00W	25.82	24.84	24.84
			300	N90E	15.84	16.65	16.65
304*	69.70	318.23	246	N00E	10.96	11.24	11.24
			206	N90E	23.52	22.58	22.58
307	45.04	74.49	1205	N90W	18.42	18.58	18.58
			915	N00E	20.51	19.74	19.74
310	53.51	326.52	1031	N90W	4.71	4.77	4.77
			852	N00E	8.31	8.14	8.14
313	37.41	187.77	831	S00W	18.30	17.50	17.50
			776	N90E	12.23	12.70	12.70
316*	34.72	143.62	1886	S90W	11.43	11.91	11.91
			875	S00W	19.36	19.53	19.53
319	38.41	139.11	1073	N90E	13.07	13.11	13.11
			935	N00E	14.21	14.17	14.17

TABLE C-2 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65 (ap)max METHOD #1	METHOD #2&4	METHOD #3
332	38.38	139.73	1980	N00E	7.39	7.56	7.56
			1816	N90E	4.81	4.85	4.85
328	30.11	137.52	2078	S82E	8.04	8.22	8.22
			1390	S08W	7.16	7.40	7.40
334	41.10	161.67	1019	N38E	14.34	14.06	14.06
			785	N52W	18.60	17.88	17.88
340	32.58	52.64	1362	S30W	9.54	9.26	9.26
			1108	S60E	32.27	31.52	31.52
343	28.09	193.03	2206	N11E	12.09	12.05	12.05
			1460	N79W	22.15	21.90	21.90
352	48.98	182.54	337	S45E	27.02	26.93	26.93
			327	S45W	24.77	23.44	23.44
361	41.70	147.14	1194	S90W	13.40	13.65	13.65
			1123	S00W	22.91	22.54	22.54
370	74.90	140.87	349	S90W	8.20	7.59	7.59
			345	S00W	22.06	20.78	20.78
379	35.83	179.35	916	S90W	6.97	7.20	7.20
			609	N00E	22.93	22.68	22.68
388	36.86	181.59	1843	N50E	8.24	8.37	8.37
			1606	N40W	10.44	9.97	9.97
397	37.54	182.73	979	N54E	19.81	19.58	19.58
			823	S36E	17.15	16.66	16.66
406	27.81	196.32	1402	S81E	11.08	11.00	11.00
			1290	S09W	18.58	18.10	18.10
415	30.86	352.33	1455	N21E	7.30	7.02	7.02
			1089	S69E	8.64	8.54	8.54
418*	27.98	343.83	1682	S69E	9.00	8.84	8.84
			1435	S21W	17.32	17.29	17.29
421*	27.75	326.61	1193	N21E	10.77	11.10	11.10
			1094	N69W	17.57	17.36	17.36
424*	24.35	321.61	3462	N21E	10.17	10.25	10.25
			2779	N69W	19.42	18.63	18.63

TABLE C-2 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65(ap)max METHOD #1	METHOD #2&4	METHOD #3
427	33.46	132.94	1139	1139	29.65	29.71	29.71
			1034	1034	37.31	35.00	37.05
436	38.56	166.75	1120	1120	24.42	23.44	23.44
			1076	1076	22.17	21.87	21.87
445	41.09	161.29	1683	1683	6.92	7.30	7.30
			1161	1161	10.30	10.47	10.47
457*	29.36	173.86	1642	1642	4.45	4.71	4.71
			1476	1476	16.70	16.83	16.83
472	138.56	145.96	159	159	12.44	12.46	12.46
			120	120	26.16	25.00	25.00
487	41.46	162.50	1160	1160	7.46	7.40	7.40
			834	834	21.28	21.02	21.02
496*	72.02	326.76	467	467	17.33	17.32	17.32
			208	208	7.09	7.02	7.02
1	82.96	146.10	299	299	14.40	14.24	14.24
			239	239	36.97	35.00	35.00
10	70.09	93.54	557	557	7.99	7.88	7.88
			424	424	14.92	14.82	14.82
13	70.09	93.54	572	572	9.07	8.66	8.66
			431	431	15.55	15.36	15.36
16	74.28	136.62	673	673	28.11	28.98	28.98
			673	673	17.25	16.57	16.57
19	52.69	143.32	967	967	23.52	23.10	23.10
			957	957	11.57	11.40	11.40
22	71.05	112.33	759	759	22.82	23.52	23.52
			557	557	17.85	18.42	18.42
25	37.06	182.65	1265	1265	35.76	34.70	34.70
			1144	1144	8.64	8.93	8.93
34	66.66	179.36	401	401	6.30	6.37	6.37
			247	247	29.55	29.37	29.37
37	39.30	164.35	989	989	21.23	20.49	20.49
			967	967	20.21	18.91	18.91

TABLE C-2 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65 (ap)max METHOD #1	METHOD #2 &4	METHOD #3
46	121.32	146.58	409	N33E	14.30	14.72	14.72
			310	N57W	28.36	28.79	28.79
49	74.06	159.44	350	N76W	41.13	35.00	39.96
			312	S14W	41.09	35.00	40.98
52	184.42	120.61	354	N45W	15.13	14.93	14.93
			256	N45E	9.25	9.45	9.45
55*	32.53	164.34	1769	S00W	9.32	9.35	9.35
			1674	S90W	20.81	20.21	20.21
58	40.54	164.06	2388	N62W	6.71	7.04	7.04
			1379	N28E	16.37	16.18	16.18
67	72.53	165.18	260	N00E	15.15	15.88	15.88
			208	N90E	35.39	33.21	33.21
70	72.36	167.50	284	N21W	14.72	15.16	15.16
			281	N69E	27.47	26.76	26.76
73	107.19	107.79	439	N90E	5.90	5.69	5.69
			374	N00E	14.02	14.32	14.32
76*	34.04	355.07	971	N34W	8.22	8.37	8.37
			647	N56E	13.32	13.32	13.32
79	133.50	270.60	170	S48E	35.70	35.00	35.44
			165	N42E	21.98	22.22	22.22
82	150.22	119.75	384	S45W	21.57	21.43	21.43
			349	S45E	11.39	12.12	12.12
88	34.81	164.48	1563	S01E	20.81	20.93	20.93
			1541	S89W	17.65	18.00	18.00
97	38.63	166.27	1083	S00W	16.33	15.73	15.73
			882	N90E	15.93	15.27	15.27
106	94.52	152.81	343	N90E	18.83	18.40	18.40
			242	S00W	19.14	18.92	18.92
109*	42.06	124.64	1658	N87W	15.07	14.64	14.64
			1377	N03E	17.38	17.83	17.83
112	79.02	249.40	259	S00W	38.65	35.00	38.17
			252	S90W	21.69	21.28	21.28

TABLE C-2 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65 (ap)max METHOD #1	METHOD #2 &4	METHOD #3
115*	63.72	122.95	697	N55E	11.70	11.13	11.13
			533	N35W	16.07	15.37	15.37
118	50.48	179.04	413	N00E	11.14	10.94	10.94
			378	S90W	19.51	20.26	20.26
124	28.10	191.36	2433	S12W	29.30	29.33	29.33
			1970	N78W	21.26	21.73	21.73
133	33.45	171.13	1673	S00E	14.94	14.48	14.48
			1224	N90E	15.00	15.53	15.53
142	37.07	179.22	1618	N90E	6.48	6.31	6.31
			1192	S00E	27.56	27.85	27.85
148	40.36	160.80	1380	N53W	5.96	5.78	5.78
			868	N37E	37.65	35.00	37.62
157	40.38	160.84	1494	N53W	4.48	4.66	4.66
			1268	S37W	10.21	9.91	9.91
163	34.18	170.11	1160	S00E	11.63	12.32	12.32
			1070	N90E	23.41	23.78	23.78
172	37.89	182.86	842	S46E	21.19	20.63	20.65
			799	N44E	29.46	28.75	28.75
178	40.35	161.67	1956	N37E	8.34	8.02	8.02
			1883	S53E	7.84	7.76	7.76
184	40.65	161.92	2420	N30W	6.78	6.80	6.80
			2207	S60W	6.48	6.45	6.45
190	37.59	175.36	1284	N82W	8.28	8.39	8.39
			1238	N08E	20.84	20.51	20.51
199	43.19	166.22	834	S61E	9.89	9.39	9.39
			564	N29E	26.55	26.32	26.32
208	38.27	180.04	1077	N31W	9.80	10.06	10.06
			978	N59E	19.98	19.55	19.55
211	37.68	174.87	937	S07W	10.06	9.78	9.78
			684	N38W	20.54	20.48	20.48
220	38.55	166.79	1252	N90W	12.81	12.80	12.80
			1042	S00W	21.67	22.20	22.20

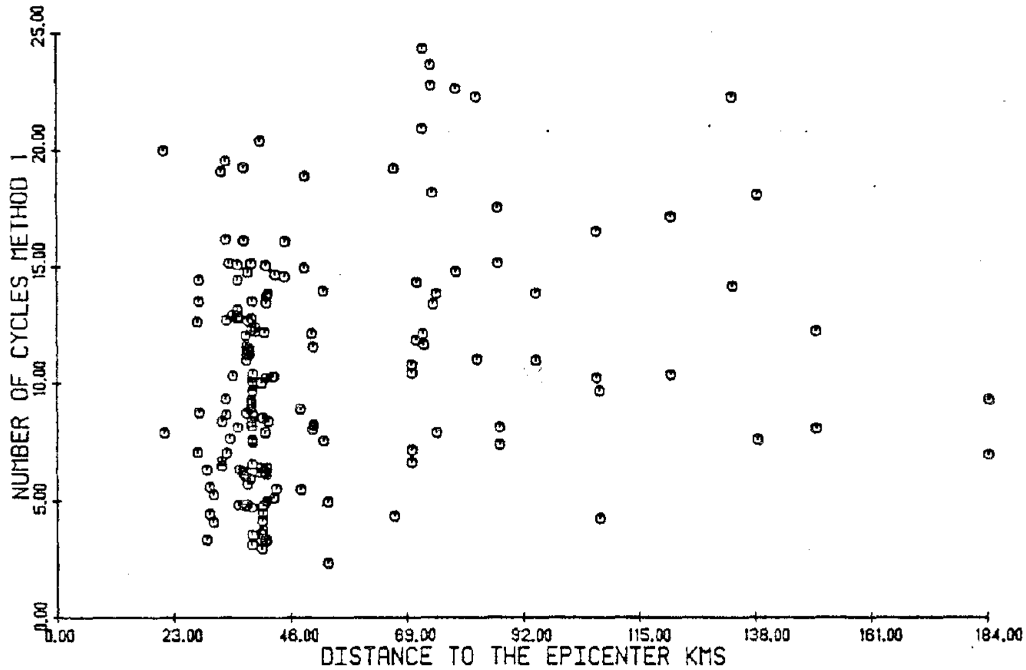
TABLE C-2 (continuation)

CALTECH NUMBER	DISTANCE TO EPICENTER km	AZIMUT	PEAK ACCELERATION mm/sec^2	COMPONENT	NUMBER OF CYCLES AT 0.65 (ap)max METHOD #1	METHOD #2 &4	METHOD #3
233	38.59	166.79	1536	N00W	13.07	12.90	12.90
			1297	S90W	15.23	14.50	14.50
226	50.64	177.60	615	S90E	13.50	13.35	13.35
			555	N00E	17.84	17.14	17.14

* ROCK SITE

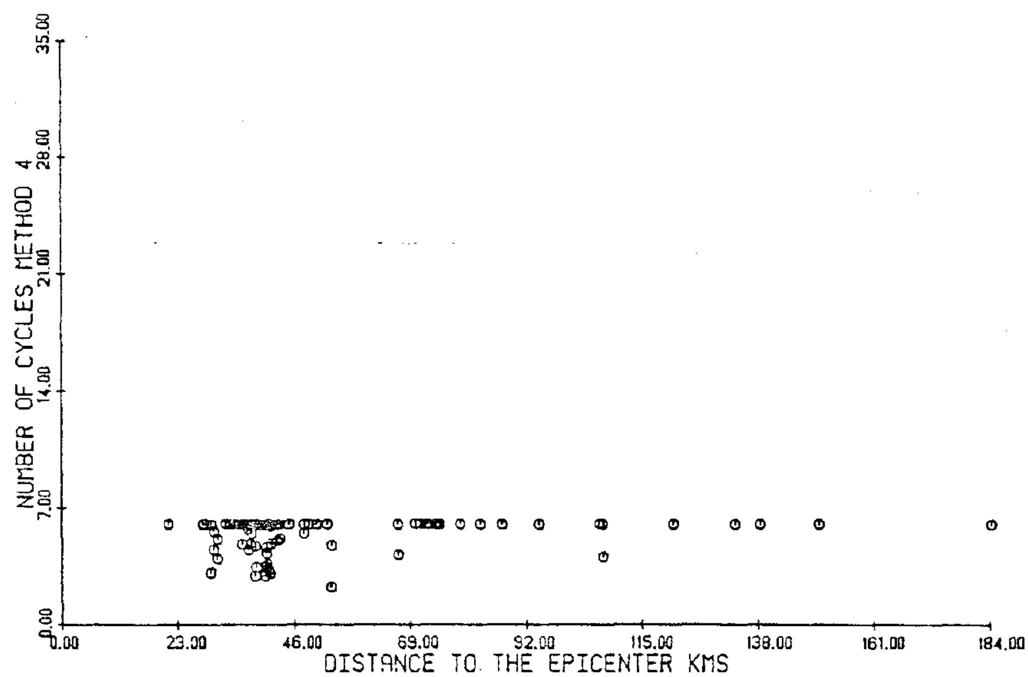
APPENDIX D

PLOTS OF N VERSUS EPICENTRAL DISTANCE AND AZIMUTH
FOR ACCELEROGRAMS RECORDED DURING 1971
SAN FERNANDO EARTHQUAKE (SET 3)
" SOIL SITES "



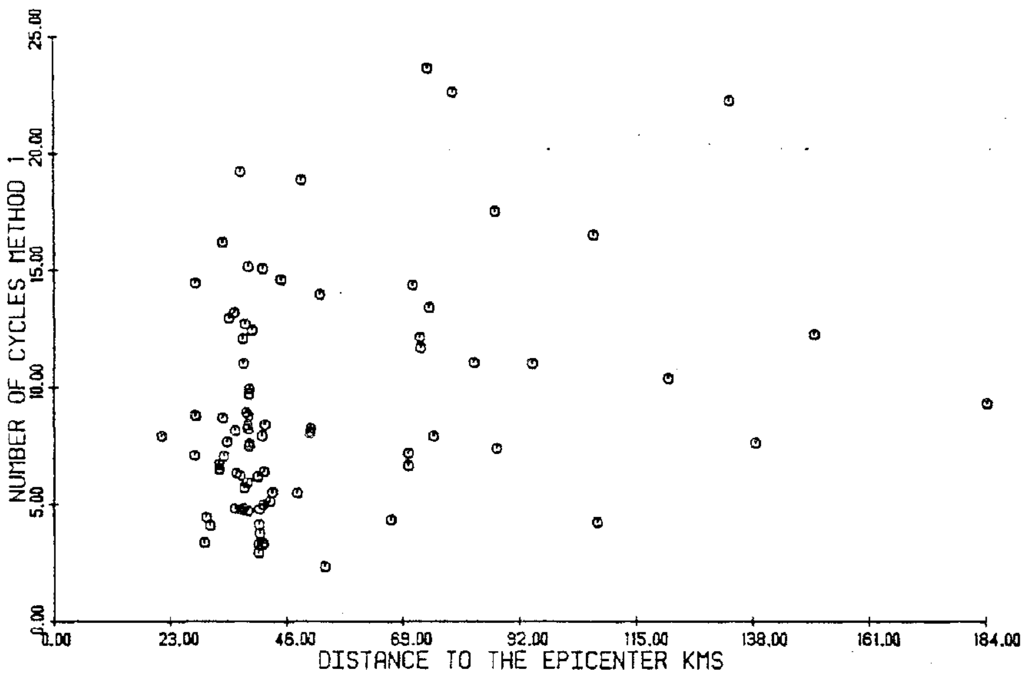
DISTANCE VS METHOD 1 (S.F. =1.50)

FIGURE D-1



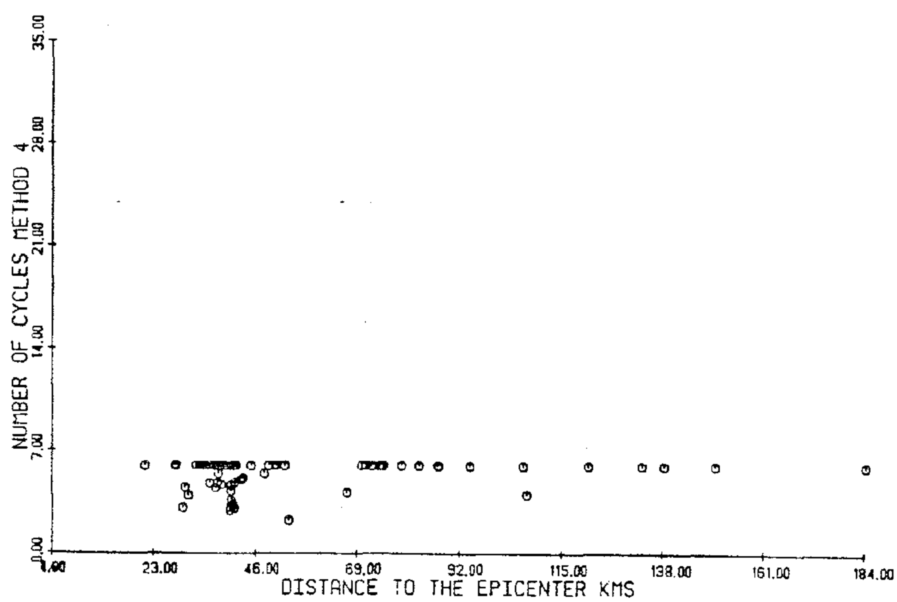
DISTANCE VS METHOD 4 (S.F. =1.50)

FIGURE D-2



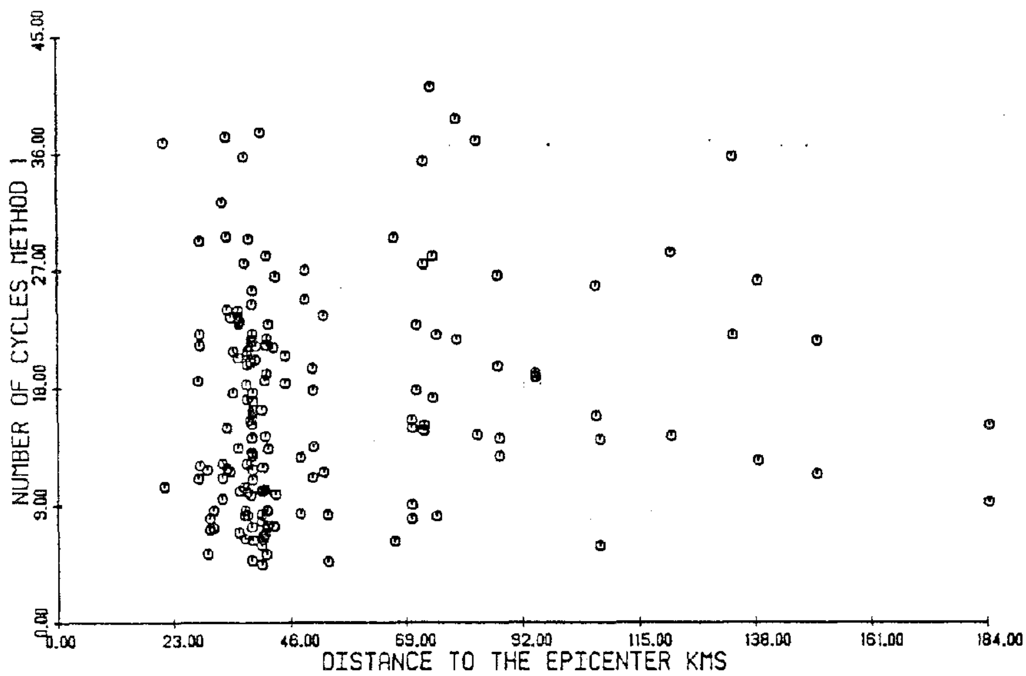
DISTANCE VS METHOD 1 STRONG COMPONENT (S.F. =1.50)

FIGURE D-3



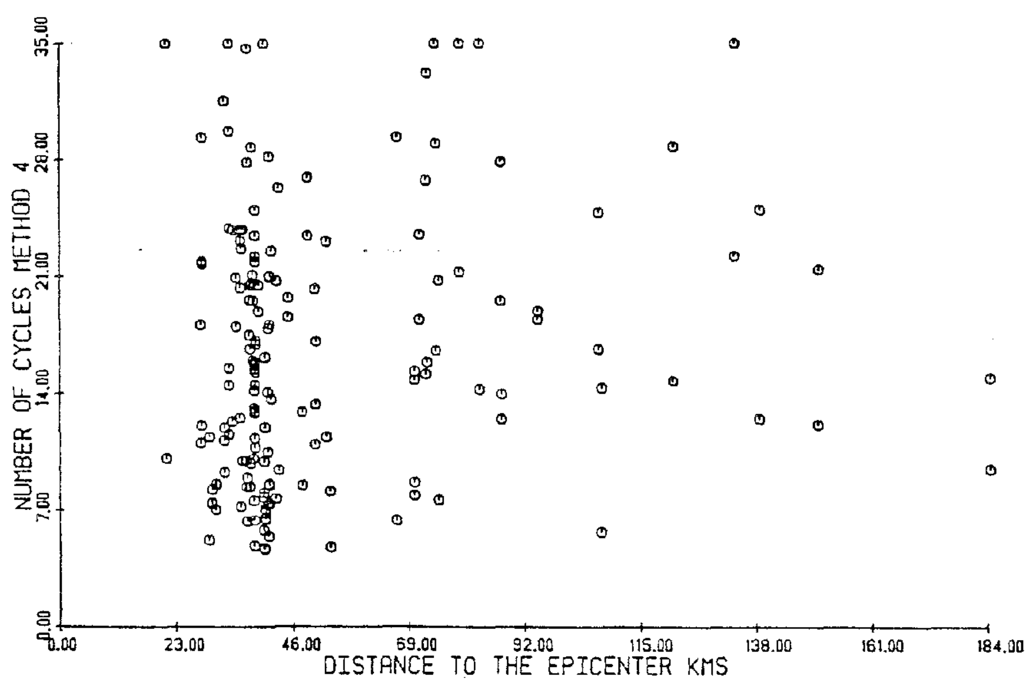
DISTANCE VS METHOD 4 STRONG COMPONENT (S.F. =1.50)

FIGURE D-4



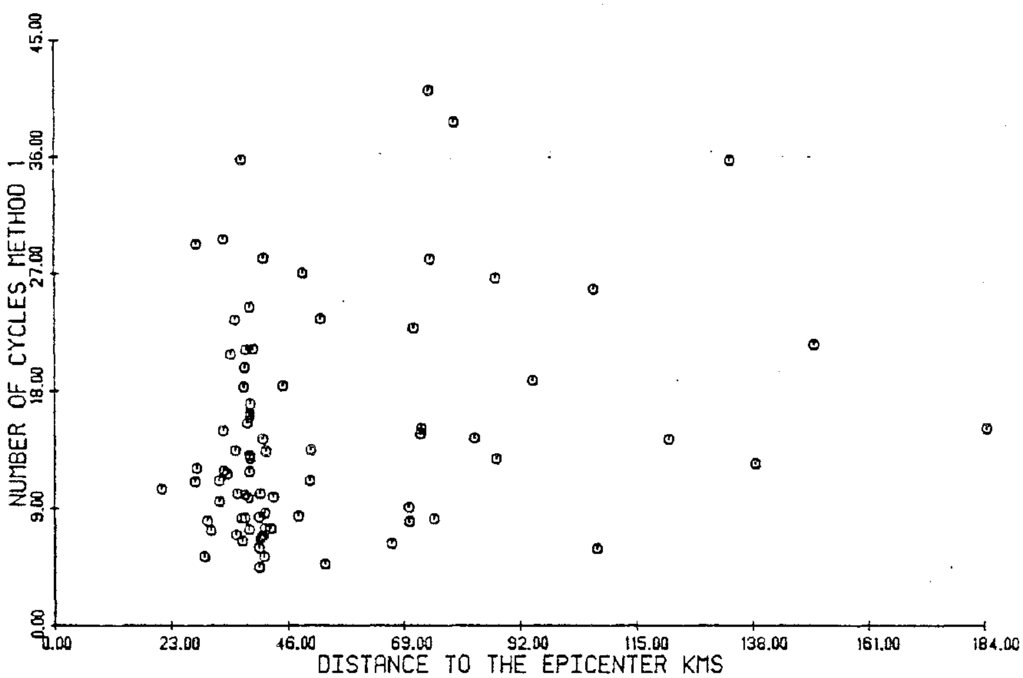
DISTANCE VS METHOD 1 (S.F. =2.00)

FIGURE D-5



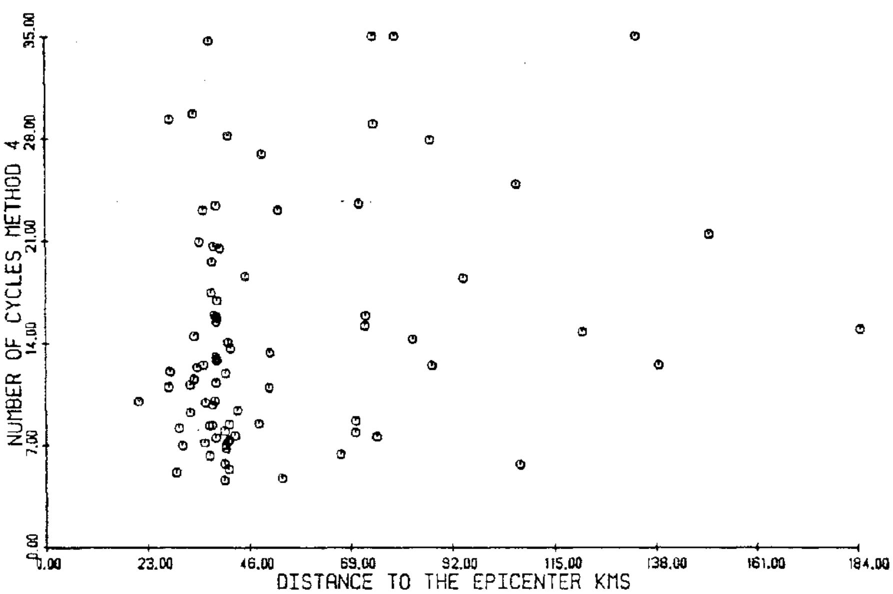
DISTANCE VS METHOD 4 (S.F. =2.00)

FIGURE D-6



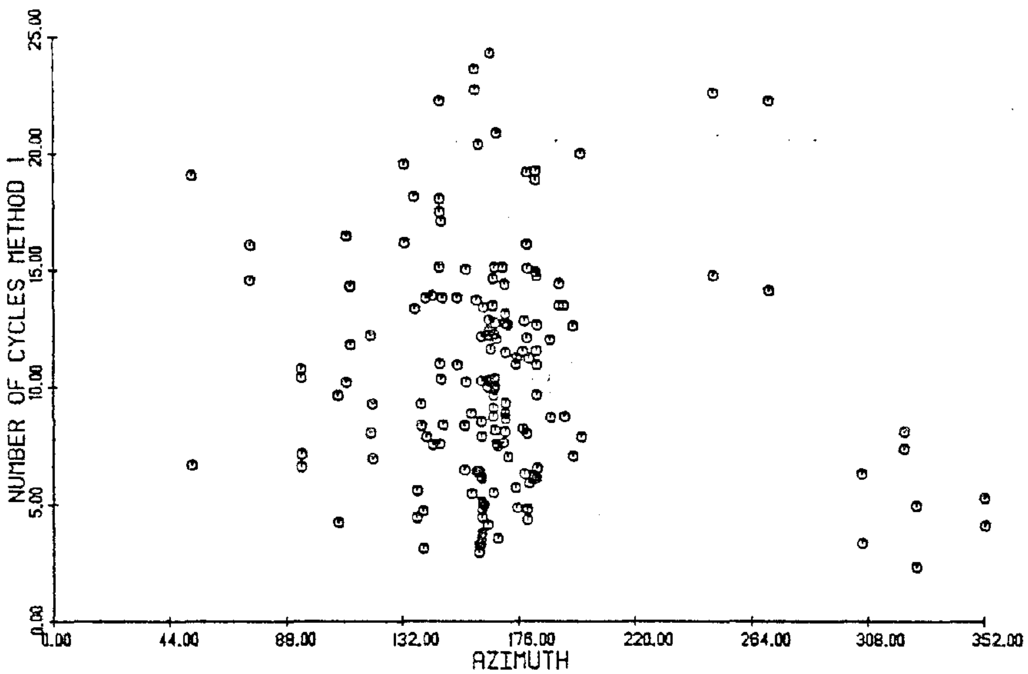
DISTANCE VS METHOD 1 STRONG COMPONENT (S.F. =2.00)

FIGURE D-7



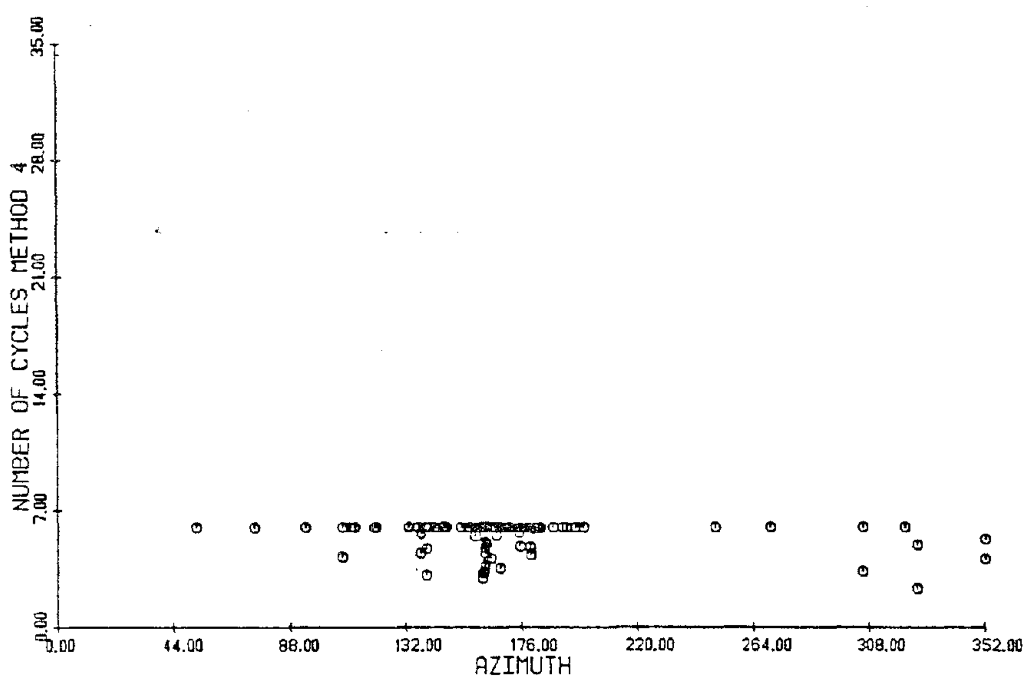
DISTANCE VS METHOD 4 STRONG COMPONENT (S.F. =2.00)

FIGURE D-8



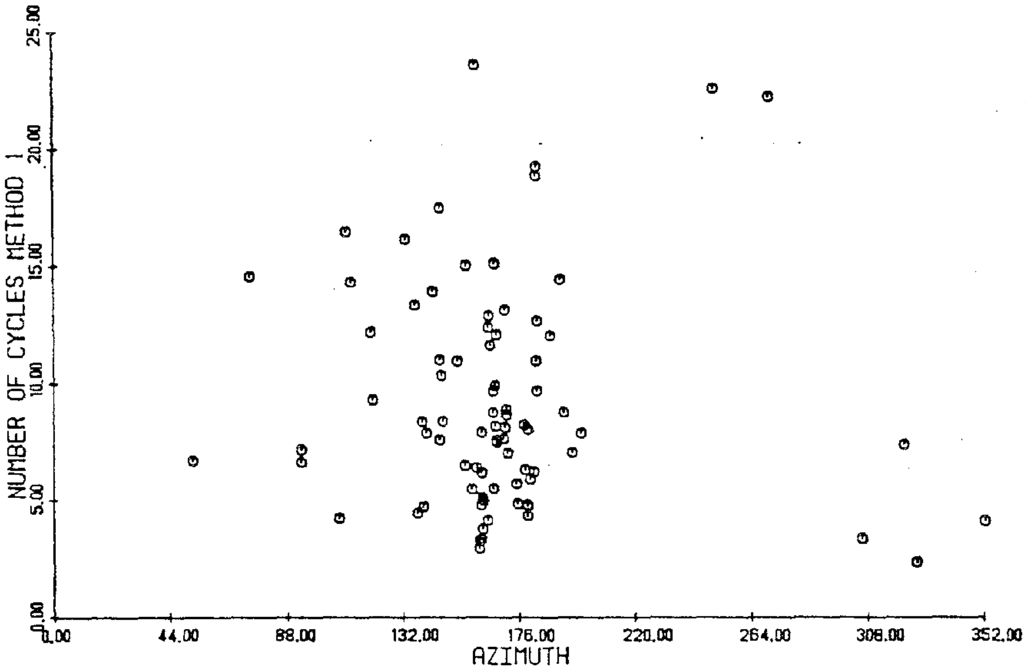
AZIMUTH VS METHOD 1 (S.F. =1.50)

FIGURE D-9



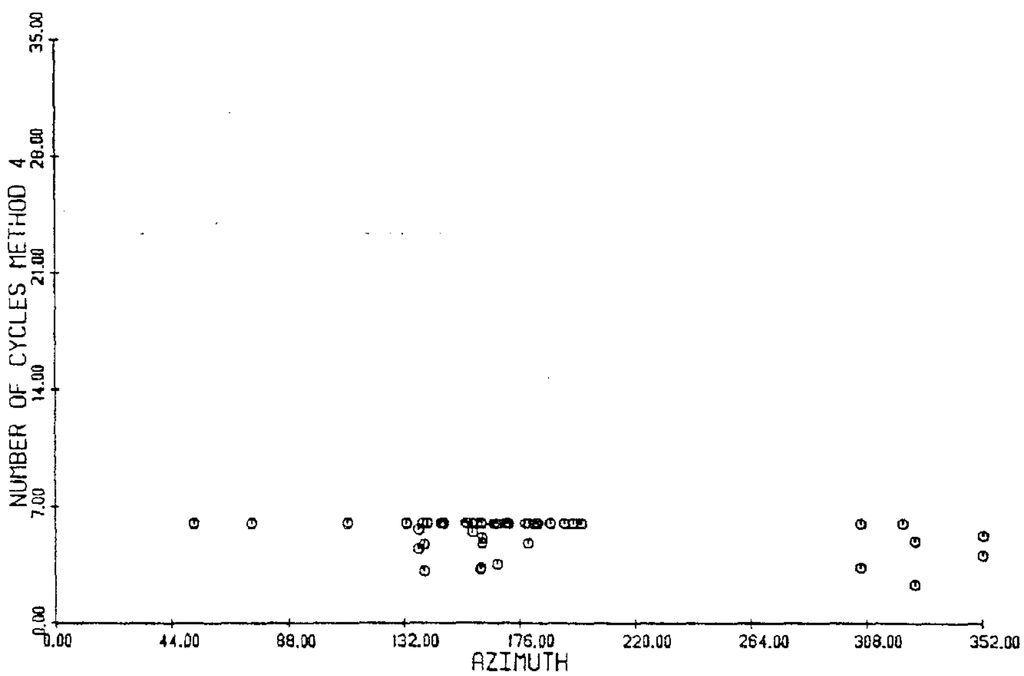
AZIMUTH VS METHOD 4 (S.F. =1.50)

FIGURE D-10



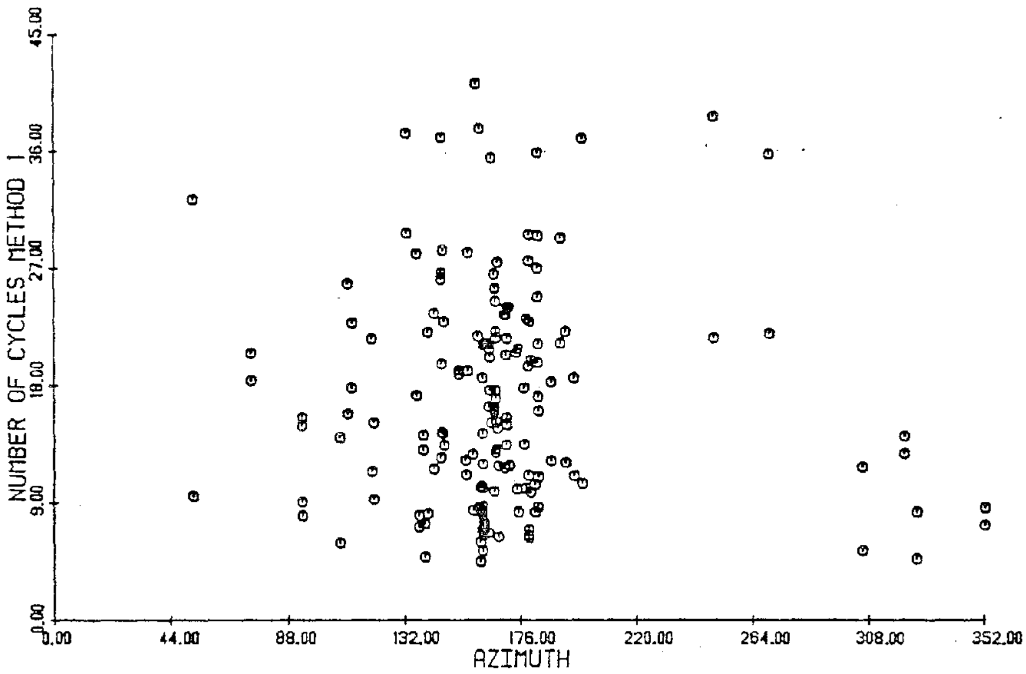
AZIMUTH VS METHOD 1 STRONG COMPONENT (S.F. =1.50)

FIGURE D-11



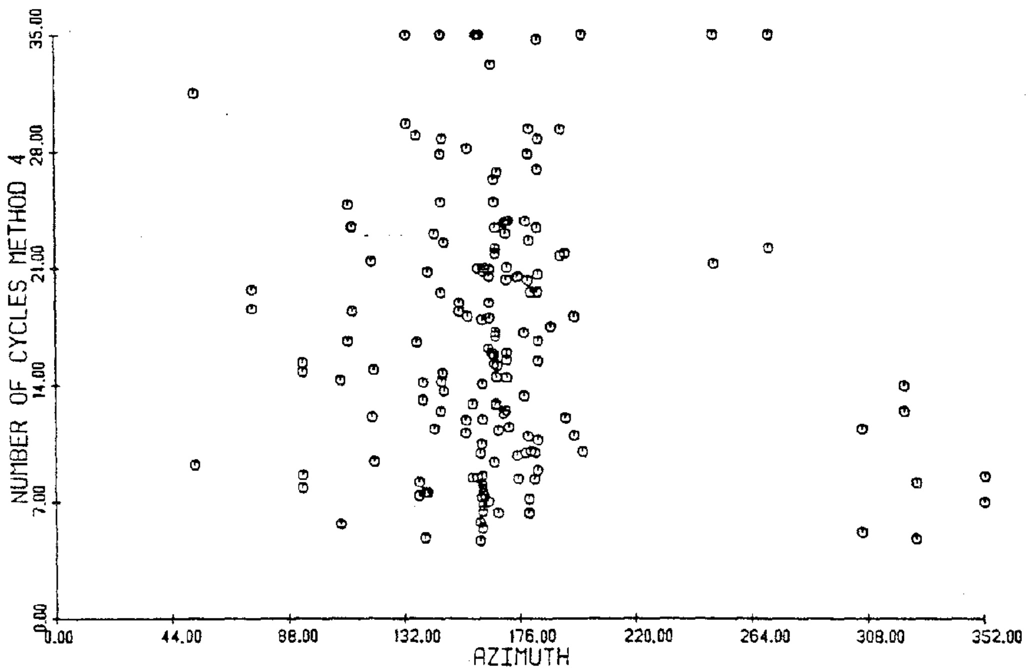
AZIMUTH VS METHOD 4 STRONG COMPONENT (S.F. =1.50)

FIGURE D-12



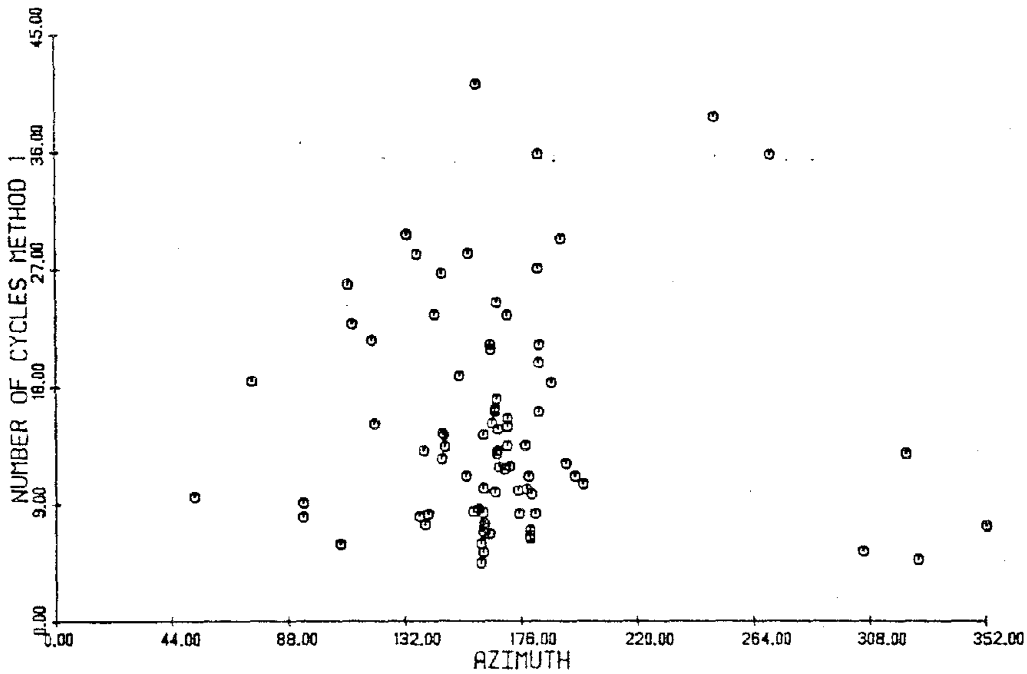
AZIMUTH VS METHOD 1 (S.F. =2.00)

FIGURE D-13



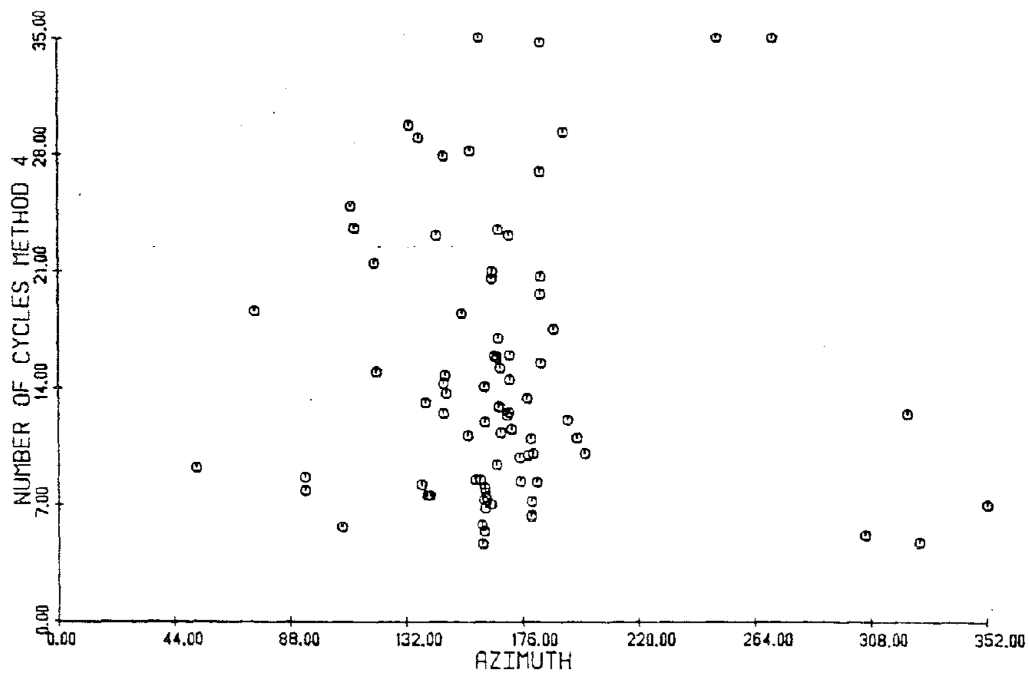
AZIMUTH VS METHOD 4 (S.F. =2.00)

FIGURE D-14



AZIMUTH VS METHOD 1 STRONG COMPONENT (S.F. =2.00)

FIGURE D-15

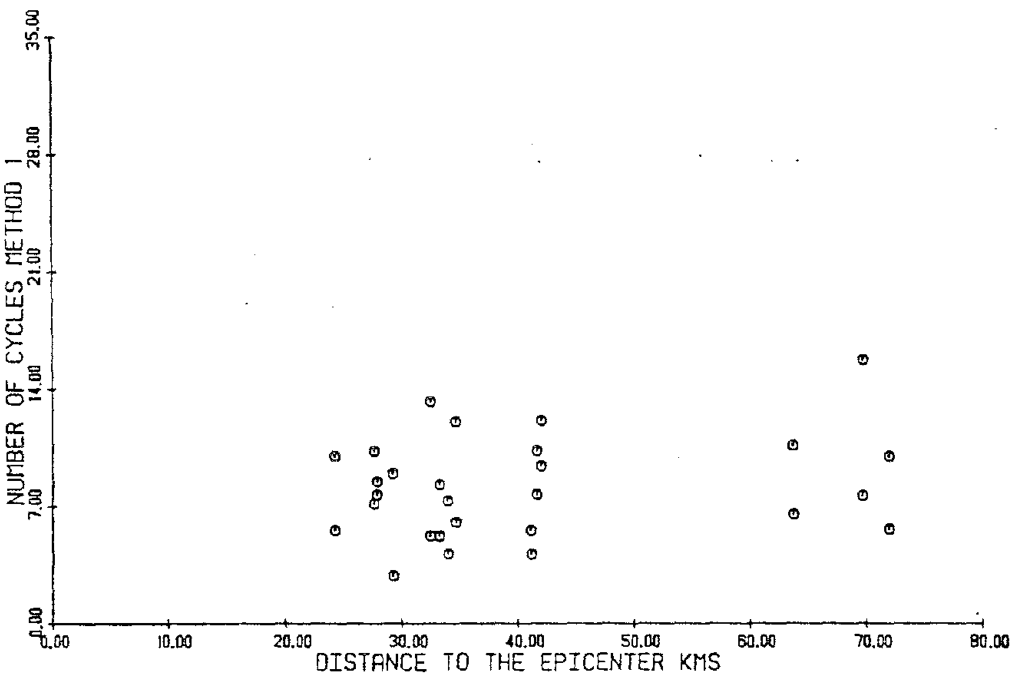


AZIMUTH VS METHOD 4 STRONG COMPONENT (S.F. =2.00)

FIGURE D-16

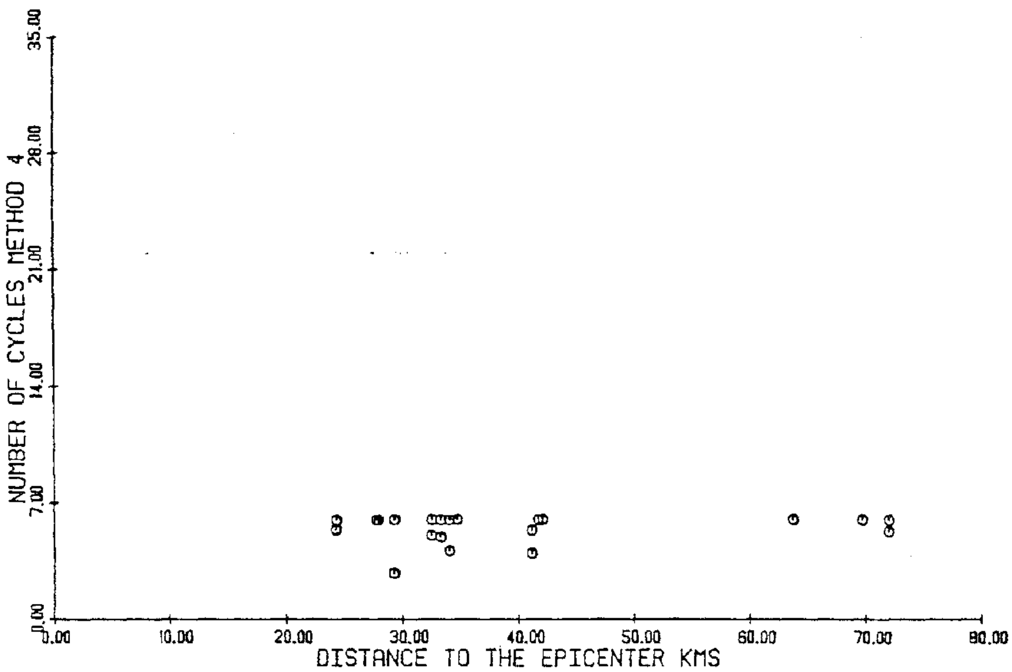
APPENDIX E

PLOTS OF N VERSUS EPICENTRAL DISTANCE AND AZIMUTH
FOR ACCELEROGRAMS RECORDED DURING 1971
SAN FERNANDO EARTHQUAKE (SET 3)
" ROCK SITES "



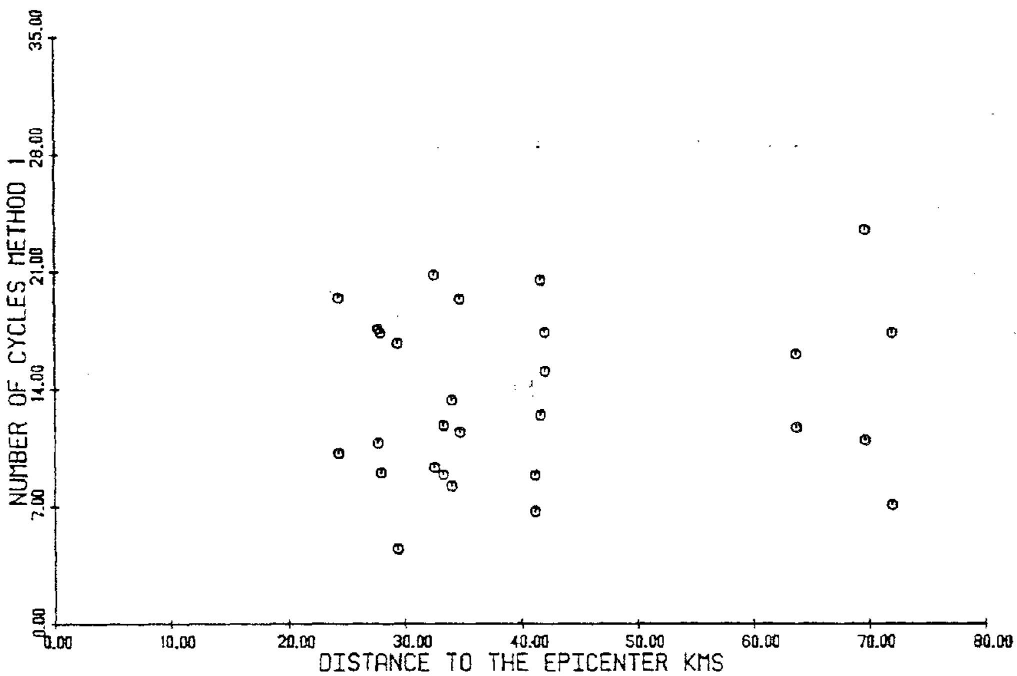
DISTANCE VS METHOD 1 ROCK SITE (S.F. =1.50)

FIGURE E-1



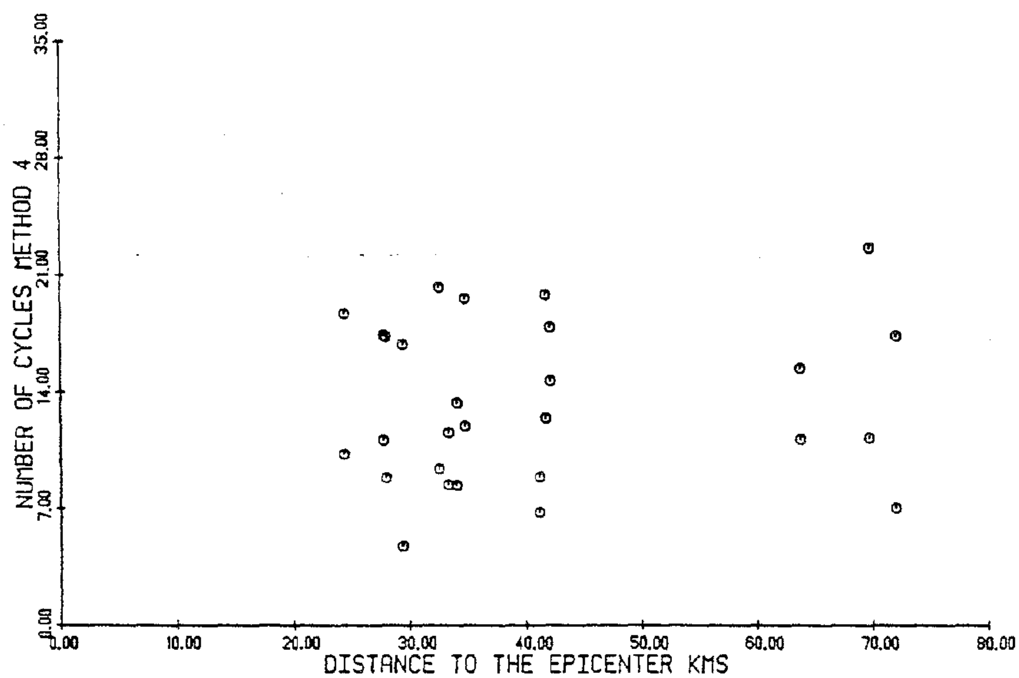
DISTANCE VS METHOD 4 ROCK SITE (S.F. =1.50)

FIGURE E-2



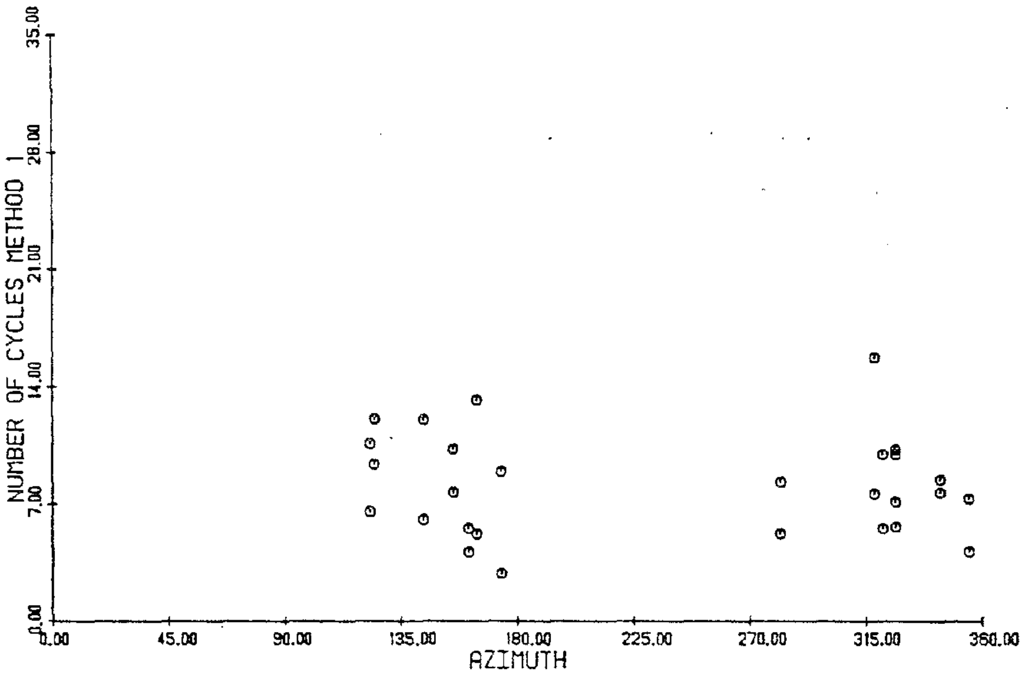
DISTANCE VS METHOD 1 ROCK SITE (S.F. =2.00)

FIGURE E-3



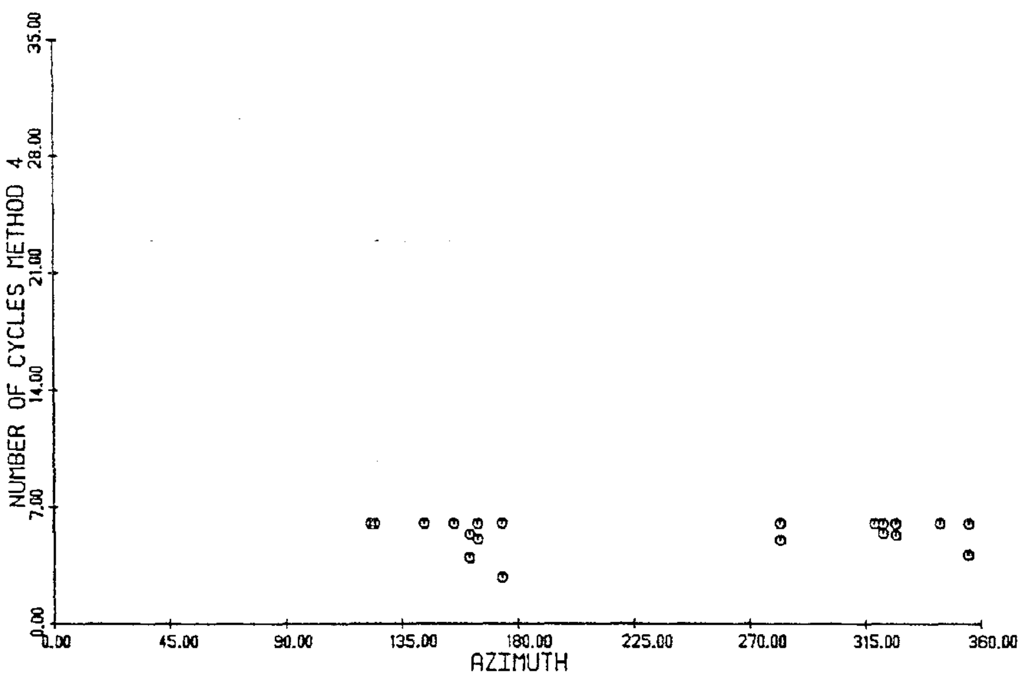
DISTANCE VS METHOD 4 ROCK SITE (S.F. =2.00)

FIGURE E-4



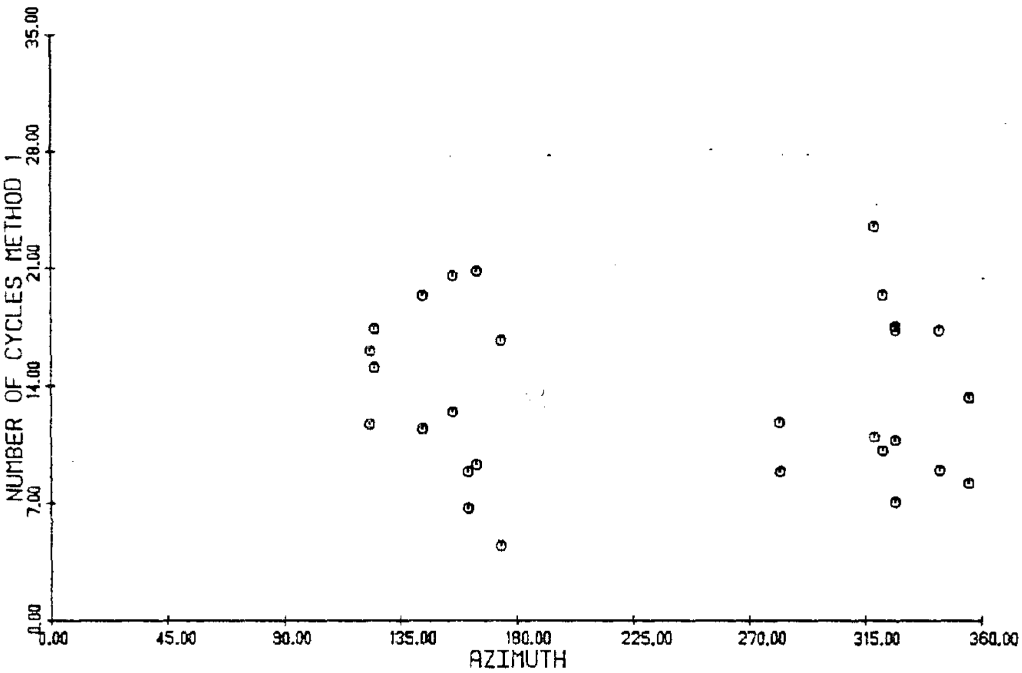
AZIMUTH VS METHOD 1 ROCK SITE (S.F. =1.50)

FIGURE E-5



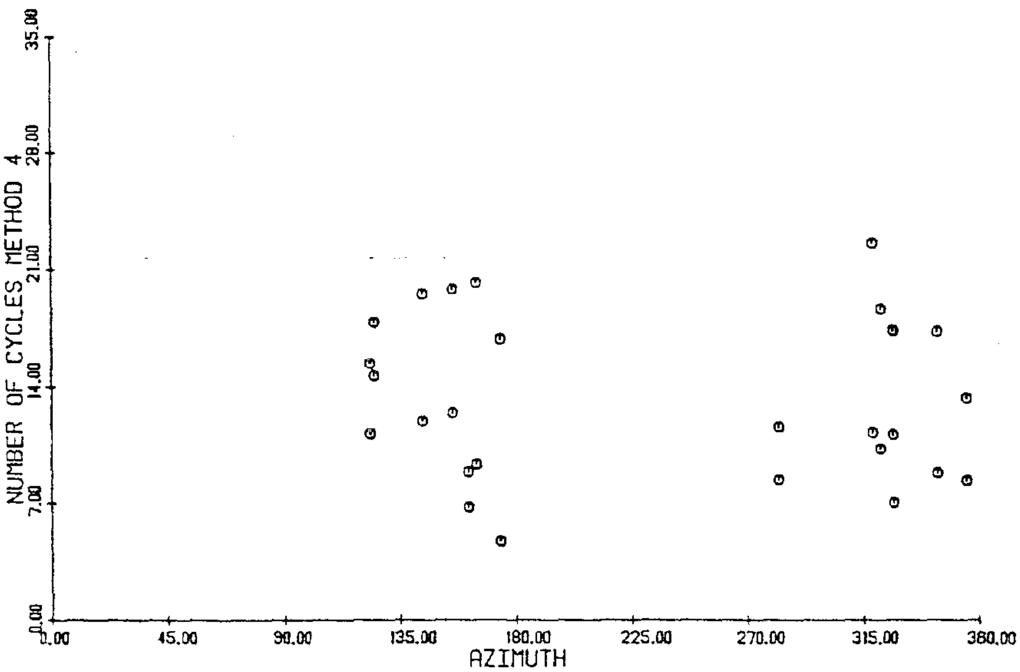
AZIMUTH VS METHOD 4 ROCK SITE (S.F. =1.50)

FIGURE E-6



AZIMUTH VS METHOD 1 ROCK SITE (S.F. =2.00)

FIGURE E-7



AZIMUTH VS METHOD 4 ROCK SITE (S.F. =2.00)

FIGURE E-8

APPENDIX F

COMPUTER PROGRAM

```
C       **************************************************
C
C       PROGRAM TO GET THE REPRESENTATION OF IRREGULAR STRESS
C       TIME HISTORIES BY EQUIVALENT UNIFORM STRESS SERIES IN
C       LIQUEFACTION ANALYSIS.-
C
C       **************************************************
C
C                 DEFINITION OF THE VARIABLES
C
C       CO        .= COMMAND TO CHOOSE THE OPERATION
C
C       READING SECTION:
C       NPTS       = THE NUMBER OF POINTS IN THE ACCELEROGRAM.
C       NFILE      = THE NUMBER OF IDENTIFICATION FOR THE FILE.
C       COMPON     = THE COMPONENT THAT IS GOING A CHECK
C
C       PEAK ACCELERATION:
C       AMAX       = THE PEAK ACCELERATION.
C       AMIN1      = LOWER BOUND ABOVE HORIZONTAL AXIS.
C       AMIN2     .= LOWER BOUND BELOW HORIZONTAL AXIS.
C
C       METHOD 1:
C       DT         = TIME BETWEEN EACH ACCELERATION.
C       TIME       = TIME WHEN EACH PEAK OCCURS.
C       NPTS       = THE NUMBER OF POINTS IN THE ACCEL.
C       NCNT       = THE NUMBER OF PEAKS IN THE ACCEL.
C       NCNT1      = NUMBER OF PEAKS ABOVE THE HORIZONTAL AXIS
C       NCNT2      = NUMBER OF PEAKS BELOW THE HORIZONTLA AXIS
C       PICK       = THE PEAK ACCELERATION.
C       PICK1      = THE PEAKS ABOVE THE HORIZONTAL AXIS.
C       PICK2      = THE PEAKS BELOW THE HORIZONTAL AXIS.
C       XNUM1      = NUMBER OF PEAKS ABOVE HORZ. AXIS EQV. .65TMAX
C       XNUM2      = NUMBER OF PEAKS BELOW HORZ. AXIS EQV. .65TMAX
C       SUM1       = TOTAL NUMBER OF PEAKS ABOVE HORZ. AXIS
C       SUM2       = TOTAL NUMBER OF PEAKS BELOW HORZ. AXIS
C       CYCLES     = THE EQUIVALENT NUMBER OF CYCLES
C
C       METHOD 2:
C       NPTS       = NUMBER OF POINTS
C       AP         = THE PEAK ACCELERATIONS
C       AP1        = THE NORMALIZED PEAKS ACCELERATION
C       AP2        = THE NORMALIZED PEAKS UP TO LOWER BOUND
C       K          = THE NUMBER OF ACCELERATIONS TO CHECK
C       UI         = INITIAL PORE PRESSURE
C       UF         = FINAL PORE PRESSURE AFTER HALF CYCLE
```

```
C     XN       = EQUIVALENT NUMBER OF CYCLES
C     XNL      = EQUIVALENT NUMBER OF CYCLES CAUSE LIQUEF.
C     TRAN     = TRANSFER NUMBER OF CYCLES TO .65TMAX
C     SUMA     = TOTAL NUMBER OF CYCLES OF .65TMAX
C
C                       DIMENSIONS:
C
C     METHOD 1
      DIMENSION PICK(5000),PICK1(3000),PICK2(3000),XNUM(14),
     +XNUM1(14),XNUM2(14),XNUM3(14),PICKS(5000)
C
C     METHOD 2
      DIMENSION AP(5000),AP1(5000),AP2(5000),UI(3000),UF(3000),
     +T(3000),TIME(3000),XN(3000),XN1(3000),XNL2(3000),EQV(3000),
     +TRAN(3000)
C
C     METHOD 3
      DIMENSION AP3(5000),UI1(3000),UI2(3000),UF1(3000),
     +UF2(3000),XN2(3000),XN3(3000),XN4(3000),XN5(3000),XNL3(3000),
     +T1(3000),T2(3000),TRAN1(3000),TRAN2(3000),EQV1(3000),
     +EQV2(3000),TIME1(3000),AP4(5000),AP5(5000)
C
      DIMENSION COMM(10),COMP(3)
C
      COMMON/A/FCOR(100),ACCEL(5000),ICOR(100)
      DATA COMP/'X','Y','Z'/
      DATA COMM/'READ','PEAK','MET1','MET2','MET3','DIST','QUIT'/
      DATA YES/'Y'/
C
      COMMON/HEAD/CORTIL(2000)
C
      INTEGER*2 LEN
      LOGICAL*1 CORTIL
C
      LEN=8
      WRITE(6,1)
    1 FORMAT('     PLEASE WAIT, GETTING THE TAPE READY')
C
      CALL CNTRL('POSN=#1#',LEN,1,RET)
      NPOS=1
    2 WRITE(6,3)
    3 FORMAT(/5X,'COMMANDS'/9X,'- READ RECORDS'/9X,
     +'- PEAK ACCELERATION'/9X,'- METHOD 1 -NUMBER OF CYCLES'/9X,
     +'- METHOD 2 -NUMBER OF CYCLES'/9X,
     +'- METHOD 3 -NUMBER OF CYCLES'/9X,
     +'- DISTANCE TO THE EPICENTER'/9X,
```

```
     +'- QUIT')
      I=0
      READ(5,4)CO
    4 FORMAT(A4)
    5 I=I+1
      IF(CO .EQ. COMM(I)) GO TO 8
      IF(I .GT. (7)) GO TO 6
      GO TO 5
    6 WRITE(6,7)
    7 FORMAT('***** UNRECOGNIZABLE COMMAND *****')
      GO TO 2
    8 GO TO(100,200,300,400,500,600,700),I
C
C     ************** READING SECTION ********************
C
  100 WRITE(6,107)
  107 FORMAT('  CHOOSE THE FILE NUMBER THAT YOU WANT TO CHECK')
  110 WRITE(6,113)
  113 FORMAT('  THE FILE NUMBER FORMAT (I3)')
      READ(5,115)NFILE
      WRITE(2,114)NFILE
  114 FORMAT(I3,'------------------------------------------------')
  115 FORMAT(I3)
  116 WRITE(6,117)
  117 FORMAT('  WHICH COMPONENT ? (X,Y,Z)')
      READ(5,103)COMPON
  103 FORMAT(A1)
      ICO=0
  119 ICO=ICO+1
      IF(COMP(ICO) .EQ. COMPON) GO TO 120
      IF(ICO .GT. 3) GO TO 116
      GO TO 119
  120 NFILE=NFILE+ICO-1
C
      CALL TAPECO(NFILE,NPOS)
C
      CALL TPREAD(NPTS,1)
C
      WRITE(6,122)(CORTIL(I),I=481,532),(CORTIL(J),J=561,569)
  122 FORMAT(1X,52A1/1X,9A1)
      WRITE(6,124)
  124 FORMAT('  DO YOU WANT THIS RECORD ? (Y,N)')
      READ(5,103)A1
      IF(A1 .NE. YES) GO TO 110
C
      CALL TPREAD(NPTS,2)
```

```
      GO TO 2
C
C     *************** PEAK ACCELERATION *********************
C
  200 WRITE(6,225)
  225 FORMAT(' ARE YOU GOING TO USE A DIFF. PEAK ACCELERATION (Y,N)')
      READ(5,103)A1
      IF (A1 .EQ. YES) GO TO 227
      AMAX=FCOR(66)
      AMAX=ABS(AMAX*10.)
      WRITE(2,226)AMAX
      WRITE(6,226)AMAX
  226 FORMAT(1X,'THE PEAK ACCELERATION=',F10.0)
      GO TO 230
C
  227 WRITE(6,228)
  228 FORMAT(' WHAT PEAK ACCELERATION ARE YOU GOING TO USE')
      READ(5,229)AMAX
  229 FORMAT(F10.0)
      WRITE(2,226)AMAX
      WRITE(6,226)AMAX
  230 GO TO 2
C
C     ********** METHOD 1 (NUMBER OF EQV. CYCLES) **********
C
  300 CONTINUE
      CALL MPEAK(NPTS,.02,PICK,NCNT,TIME)
C
  335 FORMAT(1X,F10.2)
C
      AMIN1=.325*AMAX
      AMIN2=-.325*AMAX
      I=1
      NCNT1=0
C
      DO 336 J=1,NCNT
       IF(PICK(J) .LT.   0.0) GO TO 336
       IF(PICK(J) .LT. AMIN1) GO TO 336
       PICK1(I)=PICK(J)
       NCNT1=NCNT1+1
       I=I+1
  336 CONTINUE
C
      I=1
      NCNT2=0
C
```

```
      DO 338 J=1,NCNT
       IF(PICK(J) .GT.   0.0) GO TO 338
       IF(PICK(J) .GT. AMIN2) GO TO 338
       PICK2(I)=PICK(J)
       NCNT2=NCNT2+1
       I=I+1
  338 CONTINUE
C
      CALL SELECT(AMAX,PICK1,NCNT1,XNUM1)
C
      CALL MUL(XNUM1)
C
      CALL SELECT(AMAX,PICK2,NCNT2,XNUM2)
C
      CALL MUL(XNUM2)
C
      SUM1=0.
      DO 350 I=1,14
       SUM1=SUM1+XNUM1(I)
 350  CONTINUE
C
      SUM2=0.
      DO 345 I=1,14
       SUM2=SUM2+XNUM2(I)
  345 CONTINUE
C
      CYCLES=(SUM1+SUM2)/2.
C
      WRITE(2,122) (CORTIL(I),I=481,532),(CORTIL(J),J=561,569)
      WRITE(2,347)CYCLES
      WRITE(6,347)CYCLES
  347 FORMAT(' THE NUMBER OF EQUIVALENT CYCLES BY METHOD 1  ',F10.2,
     +/' '/)
C
      GO TO 2
C
C     ********** METHOD 2 (NUMBER OF EQV. CYCLES) *********
C
  400 CALL MPEAK(NPTS,.02,AP,K,TIME)
C
      DO 410 J=1,K
       AP1(J)=ABS(AP(J)/AMAX)
  410 CONTINUE
      PHI=3.141592654
      UI(1)=0.0
      I=0
```

```
      DO 420 J=1,K
       IF(AP1(J) .LT. .4) GO TO 420
       I=I+1
       AP2(I)=AP1(J)
       T(I)=TIME(J)
       CALL GRAPH(AP2(I),XNL2(I))
       XN(I)=XNL2(I)*(.5*(1.0-COS(PHI*UI(I))))**.7
       XN1(I)=XN(I)+.5
       IF((XN1(I)/XNL2(I)) .GE. 1.0) GO TO 430
       UF(I)=.5+(1./PHI)*(ARSIN(2.*(XN1(I)/XNL2(I))**(1./.7)-1.0))
       UI(I+1)=UF(I)
  420 CONTINUE
C
C     TRANSFER THE NUMBER OF CYCLES REQUIRED TO .65TMAX
C
      GO TO 440
  430 CONTINUE
      ITOT=I
      XEQV=0.0
      XU=0.0
      XU=1.0
      XEQV=2.10*(.5*(1.0-COS(PHI*XU)))**.7
      GO TO 450
C
  440 CONTINUE
      ITOT=I
      XEQV=0.0
      XEQV=2.10*(.5*(1.0-COS(PHI*UF(I))))**.7
      WRITE(2,455)UF(ITOT)
      WRITE(6,455)UF(ITOT)
      GO TO 456
C
  450 CONTINUE
      WRITE(2,122) (CORTIL(I),I=481,532),(CORTIL(J),J=561,569)
      WRITE(2,455)XU
      WRITE(6,455)XU
  455 FORMAT(' THE PORE PRESSURE                                    ',F10.2,
     +/' '/)
  456 WRITE(2,460)XEQV
      WRITE(6,460)XEQV
  460 FORMAT(' THE NUMBER OF CYCLES AT .65 TMAX METHOD 2    ',F10.2,
     +/' '/)
      WRITE(2,470)T(ITOT)
      WRITE(6,470)T(ITOT)
  470 FORMAT(' TIME WHEN LIQUEFACTION OCCURS BY METHOD 2    ',F10.2,
     +/' '/)
```

```
C
      GO TO 2
C
C     ******** METHOD 3 AND COMPARATION WITH METHOD 2 *********
C
  500 CALL MPEAK(NPTS,.02,AP,K1,TIME1)
C
      DO 510 J=1,K1
        AP4(J)=ABS(AP(J)/AMAX)
  510 CONTINUE
      PHI=3.141592654
      UI1(1)=0.0
      I=0
      DO 515 J=1,K1
        IF(AP4(J) .LT. 0.40) GO TO 515
        I=I+1
        AP5(I)=AP4(J)
        T1(I)=TIME1(J)
        CALL GRAPH(AP5(I),XNL3(I))
        XN2(I)=XNL3(I)*UI1(I)
        XN3(I)=XN2(I)+0.5
        UF1(I)=XN3(I)/XNL3(I)
        UI1(I+1)=UF1(I)
  515 CONTINUE
C
C     TRANSFER THE NUMBER OF CYCLES REQUIRED TO .65TMAX
C
  520 CONTINUE
      ITOT1=I
      XEQV1=0.0
      XEQV1=2.10*UF1(ITOT1)
C
      WRITE(2,122) (CORTIL(I),I=481,532),(CORTIL(J),J=561,569)
      WRITE(2,525)UF1(ITOT1)
      WRITE(6,525)UF1(ITOT1)
  525 FORMAT(' THE PORE PRESSURE AT THE END OF THE E-QUAKE  ',F10.2,
     +/' '/)
      WRITE(2,535)XEQV1
      WRITE(6,535)XEQV1
  535 FORMAT(' THE NUMBER OF CYCLES AT .65 TMAX METH.1-A    ',F10.2,
     +/' '/)
      WRITE(2,540)T1(ITOT1)
      WRITE(6,540)T1(ITOT1)
  540 FORMAT(' TIME WHEN LIQUEFACTION OCCURS BY METH.1-A    ',F10.2,
     +/' '/)
C
```

```
      GO TO 2
C
C     *************** DISTANCE TO THE EPICENTER *****************
C
  600 CALL DISTAN(DIST,DIRC)
      WRITE(2,610)DIST
      WRITE(6,610)DIST
  610 FORMAT(' THE DISTANCE TO THE EPICENTER IS       ',F10.2,'KMS')
      WRITE(2,620)DIRC
      WRITE(6,620)DIRC
  620 FORMAT(' THE DIRECTION IS (THE AZIMUT)          ',F10.2)
C
      GO TO 2
C
C     ******************** QUIT SECTION ************************
C
  700 WRITE(6,710)
  710 FORMAT(' READY TO FINISH? (Y,N)')
      READ(5,103)A1
      IF(A1 .NE. YES) GO TO 2
      STOP
      END
C     =====================================================
C
      SUBROUTINE SELECT(AMAX,PICKS,NN1,XNUM)
      DIMENSION PICKS(1),XNUM(1)
C
      XK1=1.025*AMAX
      XK2=1.025*AMAX
C
      DO 65 I=1,14
       XK1=XK1-0.05*AMAX
       XNUM(I)=0.
       DO 55 J=1,NN1
        IF(ABS(PICKS(J)) .LT. XK1) GO TO 55
        IF(ABS(PICKS(J)) .GT. XK2) GO TO 55
        XNUM(I)= XNUM(I)+1.
   55  CONTINUE
       XK2=XK2-0.05*AMAX
   65 CONTINUE
C
      RETURN
      END
C     _____________________________________________________
C
      SUBROUTINE TAPECO(NREC,NPOS)
```

```
C
      NP=NREC-NPOS
      IF(NP .NE. 0) GO TO 15
      NP=1
      CALL SKIP(NP,0,1)
      NP=-1
      CALL SKIP(NP-1,1,1)
      GO TO 30
   15 IF(NP .LT. 0) GO TO 20
      CALL SKIP(NP,0,1)
      GO TO 30
   20 CALL SKIP(NP-1,1,1)
C
   30 NPOS=NREC
C
      RETURN
      END
C     _______________________________________________________
C
      SUBROUTINE TPREAD(NDATA,IR)
C
      LOGICAL*1 CORTIL,P
      COMMON /HEAD/CORTIL(2000)
      COMMON /A/FCOR(100),ACCEL(5000),ICOR(100)
C
      GO TO (100,200),IR
  100 READ(1,10,END=300)CORTIL
   10 FORMAT(80A1)
      RETURN
C
  200 READ(1,15)ICOR
      READ(1,20)FCOR
   15 FORMAT(20I4)
   20 FORMAT(8F10.3)
      NDATA=ICOR(53)
      READ(1,25)(ACCEL(I),I=1,NDATA)
   25 FORMAT(8F10.0)
  300 RETURN
      END
C     ---------------------------------------------------
C
      SUBROUTINE PEAK(NPTS,DIFF,PICK,NCNT)
C
      DIMENSION PICK(1),DIFF(5000)
      COMMON/A/FCOR(100),ACCEL(5000),ICOR(100)
C
```

```
      NDIFF=NPTS-1
      DO 10 I=1,NDIFF
       DIFF(I)=ACCEL(I+1)-ACCEL(I)
   10 CONTINUE
C
      J=1
      NCNT=0
      NN=NDIFF-1
      DO 20 I=1,NN
       IF(DIFF(I) .LE. 0.0 .AND. DIFF(I+1) .LE. 0.0) GO TO 20
       IF(DIFF(I) .GE. 0.0 .AND. DIFF(I+1) .GE. 0.0) GO TO 20
       IF(DIFF(I) .GE. 0.0 .AND. DIFF(I+1) .LE. 0.0) GO TO 15
       IF(ACCEL(I+1) .GT. 0.0 .AND. ACCEL(I) .GT. 0.0) GO TO 20
       PICK(J)=ACCEL(I+1)
       NCNT=NCNT+1
       J=J+1
       GO TO 20
   15  IF(ACCEL(I+1) .LT. 0.0 .AND. ACCEL(I) .LT. 0.0) GO TO 20
       PICK(J)=ACCEL(I+1)
       NCNT=NCNT+1
       J=J+1
   20 CONTINUE
C
      RETURN
      END
C     ----------------------------------------------------
C
      SUBROUTINE MPEAK(NPTS,DT,AP,K,TIME)
C
      DIMENSION TZERO(5000),AP(5000),TIME(3000)
      COMMON/A/FCOR(100),ACCEL(5000),ICOR(100)
C
C               VARIABLES DEFINITION:
C
C     K     = THE NUMBER OF AP(PEAKS ACCEL.)
C     NPTS  = THE NUMBER OF TOTAL ACCELERATIONS.
C     DT    = THE TIME BETWEEN EACH ACCEL.
C     AP    = THE PEAKS ACCELERATIONS.
C     TIME  = THE TIME WHEN EACH PEAK ACCURS.
C
      J=0
      NPTS1=NPTS-1
      DO 100 I=1,NPTS1
       IF(ACCEL(I+1) .EQ. 0.0) GO TO 100
       Q=ACCEL(I)/ACCEL(I+1)
       IF(Q .GT. 0.0) GO TO 100
```

```
        J=J+1
        TZERO(J)=((ABS(ACCEL(I))/ABS(ACCEL(I+1)-ACCEL(I)))+FLOAT(I-1))*DT
  100 CONTINUE
      K=0
      JMAX=J-1
      DO 110 I=1,JMAX
       I1=IFIX(TZERO(I)/DT)+2
       I2=IFIX(TZERO(I+1)/DT)+1
       APMAX=0.0
       DO 105 J=I1,I2
        IF(ABS(ACCEL(J)) .LT. APMAX) GO TO 105
        APMAX=ABS(ACCEL(J))
        IMAX=J
  105  CONTINUE
       K=K+1
       AP(K)=ACCEL(IMAX)
       TIME(K)=FLOAT(IMAX -1)*DT
  110 CONTINUE
      RETURN
      END
C     ---------------------------------------------------------
C
      SUBROUTINE GRAPH(APL1,XNL1)
      DATA N/0/
C
      DIMENSION VAL(14),VAL1(14),VAL2(14)
C
      IF(APL1.GT.1.0)APL1=1.0
      IF(N .GT. 0) GO TO 23
      N=1
      VAL1(1)=1.00
      VAL1(2)=1.10
      VAL1(3)=1.20
      VAL1(4)=1.40
      VAL1(5)=1.75
      VAL1(6)=1.80
      VAL1(7)=1.90
      VAL1(8)=2.10
      VAL1(9)=2.50
      VAL1(10)=3.00
      VAL1(11)=4.00
      VAL1(12)=7.00
      VAL1(13)=10.0
      VAL1(14)=20.0
C
      VAL(1)=1.
```

```
      DO 10 I=2,14
       VAL(I)=VAL(I-1)-.05
   10 CONTINUE
      DO 20 I=1,13
       VAL2(I)=VAL1(I)-VAL1(I+1)
   20 CONTINUE
   23 DO 30 I=1,13
       IF(ABS(APL1) .LT. VAL(I+1)) GO TO 30
       IF(ABS(APL1) .GT. VAL(I)  ) GO TO 30
       IF(ABS(APL1) .EQ. VAL(I+1)) GO TO 25
       IF(ABS(APL1) .EQ. VAL(I)  ) GO TO 26
       REST=ABS(APL1)-VAL(I+1)
       X=(VAL2(I)*REST)/.05
       XNL1=VAL1(I+1)+X
       GO TO 35
   25  APL1=VAL(I+1)
       XNL1=VAL1(I+1)
       GO TO 35
   26  APL1=VAL(I)
       XNL1=VAL1(I)
       GO TO 35
   30 CONTINUE
   35 CONTINUE
C
      RETURN
      END
C     ----------------------------------------------------------
C
      SUBROUTINE GRAPH2(APL1,XNL1)
      DATA N/0/
C
      DIMENSION VAL(14),VAL1(14),VAL2(14)
C
      IF(APL1 .GT. 1.0)APL1=1.0
      IF(N .GT. 0) GO TO 23
      N=1
      VAL1(1)=3.0
      VAL1(2)=2.7
      VAL1(3)=2.4
      VAL1(4)=2.05
      VAL1(5)=1.7
      VAL1(6)=1.4
      VAL1(7)=1.2
      VAL1(8)=1.0
      VAL1(9)=0.7
      VAL1(10)=0.4
```

```
      VAL1(11)=0.2
      VAL1(12)=0.1
      VAL1(13)=0.04
      VAL1(14)=0.02
C
      VAL(1)=1.
      DO 10 I=2,14
       VAL(I)=VAL(I-1)-.05
   10 CONTINUE
      DO 20 I=1,13
       VAL2(I)=VAL1(I)-VAL1(I+1)
   20 CONTINUE
   23 DO 30 I=1,13
       IF(ABS(APL1) .LT. VAL(I+1)) GO TO 30
       IF(ABS(APL1) .GT. VAL(I)  ) GO TO 30
       IF(ABS(APL1) .EQ. VAL(I+1)) GO TO 25
       IF(ABS(APL1) .EQ. VAL(I)  ) GO TO 26
       REST=ABS(APL1)-VAL(I+1)
       X=(VAL2(I)*REST)/.05
       XNL1=VAL1(I+1)+X
       GO TO 35
   25  APL1=VAL(I+1)
       XNL1=VAL1(I+1)
       GO TO 35
   26  APL1=VAL(I)
       XNL1=VAL1(I)
       GO TO 35
   30 CONTINUE
   35 CONTINUE
C
      RETURN
      END
C     -----------------------------------------------------------------
C
      SUBROUTINE MUL(XNUM3)
      DIMENSION XNUM3(1)
C
      XNUM3(1)=XNUM3(1)*2.10
      XNUM3(2)=XNUM3(2)*1.90
      XNUM3(3)=XNUM3(3)*1.80
      XNUM3(4)=XNUM3(4)*1.50
      XNUM3(5)=XNUM3(5)*1.20
      XNUM3(6)=XNUM3(6)*1.20
      XNUM3(7)=XNUM3(7)*1.10
      XNUM3(8)=XNUM3(8)*1.0
      XNUM3(9)=XNUM3(9)*0.80
```

```
      XNUM3(10)=XNUM3(10)*0.70
      XNUM3(11)=XNUM3(11)*0.50
      XNUM3(12)=XNUM3(12)*0.30
      XNUM3(13)=XNUM3(13)*0.20
      XNUM3(14)=XNUM3(14)*0.10
C
      RETURN
      END
C    -------------------------------------------------------
C
      SUBROUTINE DISTAN(DIST,DIRC)
C
C     CALCULATE DISTANCE AND DIRECTION FROM EPICENTER TO RECORD
C     *** FROM KUBO AND PENZIEN (1976)
C
      LOGICAL*1 CORTIL,P
      COMMON/HEAD/CORTIL(2000)
      COMMON/A/FCOR(100),ACCEL(5000),ICOR(100)
C
C     RADIUS OF EARTH (EQUIVALENT SPHERE)
C
      DATA RR/6371.2213/
      DATA PAIA,PAIB/1.745329252E-2,57.29577951/
C
      EPLAT=FLOAT(ICOR(16))+FLOAT(ICOR(17))/60.0+FLOAT(ICOR(18))/3600.0
      EPLON=ABS(FLOAT(ICOR(19)))+FLOAT(ICOR(20))/60.0+
     %FLOAT(ICOR(21))/3600.0
      OBLAT=FLOAT(ICOR(10))+FLOAT(ICOR(11))/60.0+FLOAT(ICOR(12))/3600.0
      OBLON=ABS(FLOAT(ICOR(13)))+FLOAT(ICOR(14))/60.0+
     %FLOAT(ICOR(15))/3600.0
C
      OBLAT=OBLAT*PAIA
      OBLON=OBLON*PAIA
      EPLAT=EPLAT*PAIA
      EPLON=EPLON*PAIA
C
      AA=OBLAT-EPLAT
      BB=0.5*(COS(EPLAT)+COS(OBLAT))*(OBLON-EPLON)
      DIRC=-ATAN2(BB,AA)*PAIB
      IF(DIRC)1100,1200,1200
 1100 DIRC=DIRC+360.0
 1200 DIST=RR*SQRT(AA*AA+BB*BB)
C
      RETURN
      END
END OF FILE
```