

ISSN 0386-586X

**TECHNICAL NOTE OF
PUBLIC WORKS RESEARCH INSTITUTE**

VOLUME 39

**STUDY OF GROUND STRAINS FROM STRONG
MOTION ARRAY DATA FOR LIFELINE APPLICATION**

BY

**LEON RU-LIUNG WANG
KAZUHIKO KAWASHIMA
YAW-HUEI YEH**

AND

KOH AIZAWA

DECEMBER 1981

**PUBLIC WORKS RESEARCH INSTITUTE
MINISTRY OF CONSTRUCTION**

Tsukuba Science City, Ibaraki-Prefecture 305, Japan

Copyright © 1981 Fiscal year by P.W.R.I.

All rights reserved. No part of this book may be reproduced by any means, nor transmitted, nor translated into a machine language without the written permission of the Director of P.W.R.I.

この報告書は、土木研究所長の承認を得て刊行したものである。したがって、本報告書の全部又は一部の転載、複写は土木研究所長の承認を得ずしてこれを行なってはならない。

**STUDY OF GROUND STRAINS
FROM STRONG MOTION ARRAY
DATA FOR LIFELINE APPLICATION**

BY

**LEON RU-LIUNG WANG
KAZUHIKO KAWASHIMA
YAW-HUEI YEH**

AND

KOH AIZAWA

**PUBLIC WORKS RESEARCH INSTITUTE
MINISTRY OF CONSTRUCTION**

TABLE OF CONTENTS

Abstract	1
Introduction	2
Background Data	2
(A) PWRI Site	2
(B) Ashitaka Site	2
Calculation of Ground Velocities and Ground Displacements	3
Analysis of Ground Strains	4
(A) Finite Element Strains at PWRI Site	4
(B) Normal Surface Strains at Ashitaka Site	6
Discussions	7
Acknowledgement	7
References	8
Appendix A PWRI Site	21
1. Acceleration Time Histories	21
2. Velocity Time Histories	24
3. Displacement Time Histories	27
4. Ground Strain Time Histories	30
Appendix B Ashitaka Site	38
1. Acceleration Time Histories	38
2. Velocity Time Histories	39
3. Displacement Time Histories	40
4. Ground Strain Time Histories	41

Study of Ground Strains from Strong Motion Array Data for Lifeline Application

Leon Ru-Liang Wang*
Kazuhiko Kawashima**
Yaw-Huei Yeh***
Koh Aizawa****

ABSTRACT

The seismic behavior of lifeline systems is predominately controlled by the ground displacement/strain characteristics. This study investigates the ground displacements and ground strains from the latest strong-motion arrays data recorded at PWRI and Ashitaka sites.

At PWRI site, which have both horizontal and vertical arrays, separated by approximate 50m, it is found that the ground displacements seem to be dominated by the shear wave. Depth effects on the amplification of ground displacements have been observed.

At Ashitaka site, which has only surface arrays, the strains calculated with a distance ranged from 400m to 1300m could not represent the peak ground strain condition. Note that the original purpose of the strong motion array deployment at Ashitaka site was to study the wave propagation characteristics. To be useful to lifeline application, more strong motion accelerographs apart no more than 50 meters must be installed.

-
- * Professor of Civil Engineering, University of Oklahoma, Norman, Oklahoma; Visiting Researcher at Public Works Research Institute, Ministry of Construction during summer 1981 under the Japanese Government Research Awards for Foreign Specialists
 - ** Chief Research Engineer, Ground Vibration Division, Earthquake Disaster Prevention Department, Public Works Research Institute, Ministry of Construction, Japan
 - *** Graduate Student in Civil Engineering, University of Oklahoma, Norman, Oklahoma, U. S. A.
 - **** Assistant Research Engineer, Ground Vibration Division, Earthquake Disaster Prevention Department, Public Works Research Institute, Ministry of Construction, Japan

INTRODUCTION

The seismic behavior of lifeline systems, such as water, sewer, oil or gas pipelines etc. is predominantly controlled by the ground displacement or ground strain characteristics. In application, the free field motion on the surface of the ground would be sufficient to represent the ground motion input, because even for buried lifelines, the buried depth in general is rather shallow, say 1m to 2m deep as compared to subsurface soil layer.

Although it is quite important, the direct measurement of ground strains is very difficult, if not impossible. However, with the installation of strong motion dense arrays, it is now possible to calculate the ground strains from the earthquake records with some degree of accuracy.

Recently, the Public Works Research Institute has deployed a local laboratory array consisting of 20 accelerometers at PWRI site and a simple extended array consisting of 5 accelerographs at Ashitaka area in Shizuoka Prefecture. Since their installations, there have been a number of earthquake data recorded from these sites. Preliminary results on subsurface strains calculated by using some earlier data have been reported.(4)

To supplement the earlier report(4), this study is to investigate the surface ground strains from the latest data recorded at PWRI and Ashitaka sites for future application to lifelines. Also the subsurface ground strains from PWRI site, where data from vertical arrays are available, were investigated in order to determine the depth effects.

BACKGROUND DATA

(A) PWRI Site

The strong motion arrays, designated as A, B and C Fields, at PWRI are shown in Fig. 1. The geological profile at the site is shown in Fig. 2. One can see from figure 2 that the geological condition around the institute is more or less uniform. Shear wave velocities of the upper and lower diluvial deposits are approximately 250m/sec and 400m/sec, respectively.

Fig. 3 shows instrumentations at A, B, and C Fields. The number of accelerometers and the number of channels of strong-motion arrays at these fields are given in Table 1. The details of the triggering, recording and processing of the array systems can be found in the earlier reports (3, 4, 5) and thus will not be repeated.

Since last report after December 1980, three earthquakes, occurred in the middle of Chiba Prefecture, south-west of Ibaraki Prefecture and south-west of Ibaraki Prefecture, have been recorded at PWRI site. Denoted as EQ-13, 14 and 15, the epicenter locations, focus depths, and JMA magnitudes are given in Table 2. Fig. 4 shows the epicenters of these earthquakes.

Due to the fact that the magnitudes of EQ 14 and 15 are too small to give meaningful results, this study uses EQ 13 data only. Table 3 gives the maximum acceleration of the channels that were functioned properly during the earthquake. Appendix A1 shows the time histories of the corrected accelerations of those channels recorded.

(B) Ashitaka Site

The Ashitaka site is located between Numazu City and Fuji City in Shizuoka Prefecture facing Suruga Bay. Fig. 5 shows an aerial view of the array at the site. This is a simple extended array on the surface of the ground crossing Ukishimagahara in almost NS direction as shown in Fig. 5. The layout of strong motion accelerographs is shown in Fig. 6. Note from this figure that Point 4 had no data due to mal-function of the accelographs. Thus, there are only 3 segment routes, i. e., 1-2, 2-3 and 3-5, at the site.

The geological section along the simple extended array is shown in Fig. 7. Shear wave velocity

of subsurface ground is in the range between 70m/sec to 200m/sec. Tuff breccia exists at the depth of approximately 35m below the surface and has a shear wave velocity of approximately 650m/sec.

Due to the fact that the accelerographs, which are in NS and EW directions, do not coincide with the segment route directions of the array as shown in Fig. 6, a coordinate transformation is needed in order to calculate the ground strains along the route of the arrays. As shown in Fig. 8, the coordinate transformation is done by following equations:

$$\begin{aligned} X &= x_0 \cos \theta + y_0 \sin \theta \\ Y &= -x_0 \sin \theta + y_0 \cos \theta \end{aligned} \quad (1)$$

where X, Y are the coordinates along the segment route, x_0 and y_0 are EW and NS direction, and θ is the angle of rotation shown in Fig. 8.

After the coordinate transformation, the time histories of the corrected accelerations for 3 segments in Ashitaka site are given in Appendix B1. The maximum acceleration along three segment routes are given in Table 4.

CALCULATION OF GROUND VELOCITIES AND GROUND DISPLACEMENTS

The determination of ground velocity and ground displacement can be obtained by integrating the originally recorded acceleration data, $\tilde{a}(t)$, once and twice through Fourier transformations. The procedure first requires the transformation from time domain to frequency domain as

$$\tilde{F}(f) = \int_{-\infty}^{\infty} \tilde{a}(t) e^{-2\pi i f t} dt \quad (2)$$

To remove the undesirable errors (noise) in low and high frequency ranges, a band-pass filter must be applied to the acceleration records:

$$F(f) = F_c(f) \cdot \tilde{F}(f) \quad (3)$$

In this study, a trapezoid type filter shown in Fig. 9 is used. Mathematically, it is expressed as follows:

$$F_c(f) = \begin{cases} 0 & f \leq f_{l\ell\ell} \\ \frac{f - f_{l\ell\ell}}{f_{lu} - f_{l\ell\ell}} \cdot \frac{e^{i\phi(f)}}{R(f)} & f_{l\ell\ell} \leq f \leq f_{lu} \\ \frac{e^{i\phi(f)}}{R(f)} & f_{lu} \leq f \leq f_{u\ell} \\ \frac{f_{uu} - f}{f_{uu} - f_{u\ell}} \cdot \frac{e^{i\phi(f)}}{R(f)} & f_{u\ell} \leq f \leq f_{uu} \\ 0 & f \geq f_{uu} \end{cases} \quad (4)$$

in which $R(f)$ and $\phi(f)$ represent amplification and phase of sensors, respectively.

For broader applications, three different filters, called F1, F2 and F3, with different low frequency limits are suggested and shown in Table 5.

After the filtering operation, the modified or corrected acceleration $a(t)$ can be obtained as:

$$a(t) = \int_{-\infty}^{\infty} F(f) e^{2\pi i f t} df \quad (5)$$

and the velocity $v(t)$ and displacement $d(t)$ associated with $a(t)$ are calculated in the forms:

$$v(t) = \int_{-\infty}^{\infty} \frac{F(f)}{2\pi i f} e^{2\pi i f t} df \quad (6)$$

$$d(t) = \int_{-\infty}^{\infty} \frac{F(f)}{-4\pi^2 f^2} e^{2\pi i f t} df \quad (7)$$

Based on the characteristics of sensors used at the PWRI site, the amplification $R(f)$ and phase $\phi(f)$ in Eq. (4) were taken as

$$R(f) = \frac{1}{\sqrt{\left(\frac{1 - (f/f_0)^2}{2hf/f_0}\right)^2 + 1}} \quad (8)$$

$$\phi(f) = \tan^{-1}\left(\frac{2hf/f_0}{1 - (f/f_0)^2}\right)$$

in which f_0 and h , representing natural frequency and damping ratio of sensors in a type of velocity feed-back servo accelerometer, are taken as the values shown in Table 6.

By applying this procedure with F3 filter to the strong motion data at PWRI site, the time histories of velocity and displacement for PWRI site are obtained and shown in Appendices A2 and A3, respectively. Note that at the beginning of this study, all three filters have been used in the analysis, but it was found that F3 was most satisfactory.

Similarly using F3 filter, the time histories of velocity and displacement for Ashitaka site were calculated and shown in Appendices B2 and B3. In this case, the amplification $R(f)$ and phase $\phi(f)$ were taken as unity and zero, respectively, because the sensors used at the site are displacement feed back servo accelerometers having a flat sensitivity between DC and 50Hz.

After integrations, the maximum values of velocities and displacements for PWRI site and Ashitaka site are given in Tables 3 and 4, respectively.

ANALYSIS OF GROUND STRAINS

(A) Finite Element Strains at PWRI Site

Because PWRI site consists both vertical and horizontal arrays, it is possible to construct a tetrahedron, shown in Fig. 10, for strain analysis. At each nodal point, the displacements $u(t)$, $v(t)$ and $w(t)$ in the tetrahedron are assumed to be linear in x-, y- and z-direction. Mathematically, they can be expressed as:

$$\begin{aligned} u &= \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 z \\ v &= \beta_1 + \beta_2 x + \beta_3 y + \beta_4 z \\ w &= q_1 + q_2 x + q_3 y + q_4 z \end{aligned} \quad (9)$$

where the coefficients α_i , β_i , and q_i can be determined by prescribing the nodal coordinates. Following Ref. 2, Eq. (9) is rewritten in matrix form as:

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \frac{1}{6V} \begin{bmatrix} u_i & u_j & u_m & u_p \\ v_i & v_j & v_m & v_p \\ w_i & w_j & w_m & w_p \end{bmatrix} \begin{Bmatrix} a_i + b_i x + c_i y + d_i z \\ a_j + b_j x + c_j y + d_j z \\ a_m + b_m x + c_m y + d_m z \\ a_p + b_p x + c_p y + d_p z \end{Bmatrix} \quad (10)$$

where

$$a_i = \det \begin{vmatrix} x_i & y_i & z_i \\ x_m & y_m & z_m \\ x_p & y_p & z_p \end{vmatrix}; \quad b_i = -\det \begin{vmatrix} 1 & y_i & z_i \\ 1 & y_m & z_m \\ 1 & y_p & z_p \end{vmatrix} \quad (11)$$

$$c_i = -\det \begin{vmatrix} x_i & 1 & z_i \\ x_m & 1 & z_m \\ x_p & 1 & z_p \end{vmatrix}; \quad d_i = -\det \begin{vmatrix} x_i & y_i & 1 \\ x_m & y_m & 1 \\ x_p & y_p & 1 \end{vmatrix}$$

$$6V = \det \begin{vmatrix} 1 & x_i & y_i & z_i \\ 1 & x_j & y_j & z_j \\ 1 & x_m & y_m & z_m \\ 1 & x_p & y_p & z_p \end{vmatrix} \quad (12)$$

and x_k , y_k , z_k are coordinates of point k ($k = i, j, m, p$) and other constants, a_k , b_k , c_k and d_k ($k = j, m, p$) can be obtained in the same way by changing the subscript in the order of j, m and p .

The determination of strains ϵ of a ground element surface, $\{ \epsilon \}$, can be done as:

$$\{ \epsilon \} = \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial w}{\partial z} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \\ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \end{Bmatrix} \quad (13)$$

By substituting Eq. (9) into Eq. (12), $\{\epsilon\}$ can be written in the form:

$$\{\epsilon\} = [B] \{\delta\} = [B_i \ B_j \ B_m \ B_p] \{\delta\} \quad (14)$$

where

$$[B_k] = \frac{1}{6V} \begin{bmatrix} b_k & 0 & 0 \\ 0 & c_k & 0 \\ 0 & c_k & d_k \\ c_k & b_k & 0 \\ 0 & d_k & c_k \\ d_k & 0 & b_k \end{bmatrix}, \quad (k = i, j, m, p) \quad (15)$$

$$\{\delta\} = \{\delta_i \ \delta_j \ \delta_m \ \delta_p\}^T \quad (16)$$

$$\{\delta_k\} = \{u_k \ v_k \ w_k\}^T \quad (17)$$

According to the above procedure, a computer program 4) has been written and is used in this study.

In consideration to evaluate the depth effects on ground strains, 10 observation stations at PWRI were selected to form 8 different tetrahedrons as shown in Fig. 11 for the strain analysis.

For lifeline applications, the principal strains, which dominate the system response behavior, must be determined. Since most lifeline systems are constructed in a horizontal plane (i. e. x-y plane) with respect to the ground, only ϵ_x , ϵ_y and γ_{xy} are necessary to calculate the principal strains in x-y plane. Thus, the principal strains⁴⁾ in x-y plane are:

$$\begin{aligned} \epsilon_{p1} &= \frac{\epsilon_x + \epsilon_y}{2} + \sqrt{\left(\frac{\epsilon_x - \epsilon_y}{2}\right)^2 + \frac{1}{4} \gamma_{xy}^2} \\ \epsilon_{p2} &= \frac{\epsilon_x + \epsilon_y}{2} - \sqrt{\left(\frac{\epsilon_x - \epsilon_y}{2}\right)^2 + \frac{1}{4} \gamma_{xy}^2} \end{aligned} \quad (18)$$

and the principal angle is

$$\tan 2\theta = \frac{\gamma_{xy}}{\epsilon_x - \epsilon_y} \quad (19)$$

Based on above described procedure, the ground strains, ϵ_x , ϵ_y , γ_{xy} as well as the principal strains and principal angle for the xy plane of the 8 tetrahedrons, 4 for surface or upper level strains and 4 for below ground or lower level (50m deep) strains, are presented in Appendix A4. The maximum strains are listed in Table 7.

(B) Nomal Surface Strains at Ashitaka Site

Due to the fact that Ashitaka site has accelerographs on the ground surface only, it is not possible to obtain the finite element strains described earlier. Upon transformation of coordinates, the normal ground strain, ϵ_{ij} , along the array segment route can easily be determined as:

$$\epsilon_{ij} = \frac{u_x^i - u_x^j}{L_{ij}} \quad (19)$$

where ϵ_{ij} represents the average strain between nodes i and j , and u_x^i and u_x^j are ground displacements in i - j direction at node i and j , respectively; L_{ij} is the distance between i and j . Based on above procedure, the strain time histories for the Ashitaka site are shown in Appendix B4. The maximum strains at Ashitaka site are given in Table 8.

DISCUSSIONS

In examining the maximum ground displacements at PWRI site from Table 3, one can find that the displacements on the surface in general are larger than those underground as expected. It is interesting to note, however, that the amplification due to the depth effect in the EW direction is more than in the NS direction. Since the epicenter of EQ13 was located at 71km south of PWRI, such amplification in the direction normal to seismic wave propagation direction may be attributed to the shear wave.

The amplification on ground strains can be seen in Table 7 and similar conclusions are observed. To quantify the amplification due to depth effect, the magnification ratios, which is defined as the maximum upper level strain divided by the lower level strain, for PWRI site are given in Table 9. It is found that the amplification of axial strain in EW direction ranged between 3 to 4. For NS direction, however, there was little amplification (magnification ratio = 1.07 for Zone I and II) or even reversed amplification (0.82 for Zone III and IV). Such reversed amplification, perhaps, is due to the variation of local geology/soil conditions at the site. For future application to lifeline systems, earthquake input (acceleration and/or velocity) must be correlated ground strains along with site environments (geological and/or soil conditions). More data must be obtained.

For Ashitaka site, the strains, which were calculated over a distance ranged from 400m to 1275m, were too low to represent the peak ground strains for lifeline application. Note that the original purpose of the strong motion array deployment at Ashitaka site was to study the wave propagation characteristics. Thus, to be useful to lifeline application, more strong motion accelerographs apart no more than 50m must be installed.

ACKNOWLEDGEMENT

The writing of this report was during the period when the first author was working on an NSF project entitled "Developments for Seismic Performance Evaluation of Buried Lifelines" (NSF Grant No. CEE-8025172, Dr. S. C. Liu, Program Manager) and was a Visiting Researcher at Public Works Research Institute (Dr. T. Okubo, Director General) under the Japanese Government Research Awards for Foreign Specialists. The financial supports from the National Science Foundation and Japan Science and Technology Agency as well as the cooperations from Public Works Research Institute are greatly appreciated.

The authors wishes to thank Dr. E. Kuribayashi, Director of Earthquake Disaster Prevention Department, Dr. T. Iwasaki, Head of Ground Vibration Division and Mr. O. Ueda, Head of Earthquake Engineering Division for their cooperation and encouragement.

REFERENCE

- 1) International Association for Earthquake Engineering: Strong-Motion Earthquake Instrument Arrays, Proc. of the International Workshop on Strong-Motion Earthquake Instruments Arrays, Edited by Iwan, W. D., 1978, Honolulu, Hawaii, U. S. A.
- 2) Iwan, W. D.: The Deployment of Strong-Motion Earthquake Instrument Arrays, Earthquake Engineering and Structural Dynamics, Vol. 7, 1979.
- 3) Sakagami, Y., Okubo, T., Iwasaki, T. and Kawashima, K.: Dense Instrument Array Program of the Public Works Research Institute for Observing Strong Earthquake-Motion, 12th Joint Meeting, U. S. -Japan Panel on Wind and Seismic Effect, UJNR, Washington, D. C., U. S. A. 1980.
- 4) Okubo, T., Iwasaki, T. and Kawashima, K.: Dense Instrument Array Program in Public Works Research Institute for Observing Strong Earthquake Motion, Some Recent Earthquake Engineering Research and Practice in Japan, The Japanese National Committee of the International Association for Earthquake Engineering, 1980.
- 5) Okubo, T., Iwasaki, T. and Kawashima, K.: Dense Instrument Array Program of the Public Works Research Institute and Preliminary Analysis of Some Records, 13th Joint Meeting, U. S.-Japan Panel on Wind and Seismic Effect, UJNR, Tsukuba, Japan, 1981.
- 6) Iwasaki, T.: Free Field and Design Motions during Earthquakes, International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, U. S. A., 1981.
- 7) Zienkiewicz, O. C.: The Finite Element Method in Engineering Science, McGraw-Hill, 1971.

Table 1 Number of Accelerometer and Number of Channel of Strong-Motion Arrays at PWRI

FIELD	DEPTH	POINTS	CHANNELS
A-FIELD	GROUND SURFACE	7	21
	- 2m	1	3
	- 50m	5	15
B-FIELD	- 2m	1	3
	- 66m	4	12
	- 96m	1	3
C-FIELD	GROUND SURFACE	1	3
TOTAL		20	60

Table 2 Information on Earthquakes Recently Recorded at PWRI Site

EQ. No.	Date	Epicenter			Epicentral Distance [km]	JMA Magnitude	Depth [km]
		Region	Longitude	Latitude			
EQ-13	1980. 9. 25	Central Chiba Pref.	140°12'	35°30'	71	6.1	70
EQ-14	1981. 1. 28	South East of Ibaraki Pref.	139°48'	36°12'	32	< 4	60
EQ-15	1981. 3. 12	South East of Ibaraki Pref.	140°06'	36°00'	14	approximately 4	60

Table 3 Maximum Accelerations (gal), Maximum Velocities (cm/sec) and Maximum Displacements (cm) of EQ 13 at PWRI Site

Point	Comp.	Max. Accel.	Max. Vel.	Max. disp.
1	NS	39.47	2.40	-0.299
	EW	40.08	-2.48	0.342
	UD	-12.64	-0.79	-0.112
2	NS	13.05	-1.19	0.242
	EW	-14.94	1.03	0.189
	UD	-5.94	0.54	-0.081
3	NS	15.20	-1.22	0.233
	EW	-13.95	1.00	0.180
	UD	-	-	-
4	NS	12.61	-0.99	-0.212
	EW	14.48	1.29	0.208
	UD	-5.86	0.56	0.085
5	NS	11.81	-1.04	-0.206
	EW	14.59	1.32	0.224
	UD	-	-	-
6	NS	-14.41	-1.03	-0.243
	EW	-13.58	-1.11	-0.206
	UD	6.81	0.46	-0.074
7	NS	43.04	-2.43	-0.282
	EW	44.15	3.52	0.473
	UD	-11.61	-0.77	0.102
8	NS	25.29	-1.54	-0.202
	EW	23.76	1.57	0.247
	UD	7.35	-0.40	0.061
9	NS	32.58	2.24	0.328
	EW	35.49	2.78	0.446
	UD	-	-	-
13	NS	-22.51	-1.20	0.152
	EW	28.00	-1.81	0.242
	UD	-6.75	-0.43	-0.052

* No data due to mal-function of instrument

Table 4 Max. Acc. (gal), Max.Vel.(cm/sec) and Max. Disp. (cm) at Ashitaka Site after Coordinate Transformation

Segment	Station	Comp.	Max. Acceleration [gal]	Max. Velocity [cm/sec]	Max. Displacement [cm]
1 ~ 2	1	NS	- 73.10	3.33	1.69
		EW	122.00	- 3.31	0.90
		UD	73.80	2.13	- 0.66
	2	NS	- 181.00	- 6.84	0.79
		EW	169.00	- 9.61	0.93
		UD	68.80	2.62	- 0.54
2 ~ 3	2	NS	- 192.00	- 7.11	0.80
		EW	156.00	- 9.49	- 0.86
		UD	68.80	2.62	- 0.55
	3	NS	- 163.00	- 7.48	0.92
		EW	- 120.00	- 9.12	- 0.74
		UD	- 36.8	- 1.82	- 0.57
3 ~ 5	3	NS	- 151.0	- 7.96	- 0.77
		EW	135.0	- 8.90	- 0.90
		UD	- 36.8	- 1.82	- 0.57
	5	NS	99.4	- 3.82	0.73
		EW	- 111.0	2.82	0.82
		UD	46	1.51	0.44

Table 5 Band-Pass Filter

Filter No.	$1/f_{\text{ql}}[\text{ sec }]$	$1/f_{\text{qu}}[\text{ sec }]$	$f_{\text{ul}}[\text{ Hz }]$	$f_{\text{uu}}[\text{ Hz }]$
F-1	11	10	20	21
F-2	8.5	7.5	20	21
F-3	6	5	20	21

Table 6 Characteristics of Sensors Used at PWRI Site

Point No.	Natural Frequency f_0 [Hz]	Damping Ratio h	
		Lower Frequency Range	High Frequency Range
1 ~ 9	5	100	50
13	5	50	50

Table 7 Maximum Ground Strains [$\times 10^{-6}$] at PWRI Site for EQ 13

Zone	Strain	Lower Level	Upper Level
I	ϵ_x	9.4	- 27.2
	ϵ_y	- 14.5	15.4
	ϵ_z	- 12.4	- 12.4
	γ_{xy}	- 13.4	- 46.4
	γ_{yz}	-	- 54.2
	γ_{zx}	59.7	68.2
II	ϵ_x	12.1	52.4
	ϵ_y	- 14.5	15.4
	ϵ_z	- 12.4	- 12.4
	γ_{xy}	15.8	66.4
	γ_{yz}	-	- 54.2
	γ_{zx}	60.4	47.3
III	ϵ_x	12.1	52.4
	ϵ_y	17.3	14.2
	ϵ_z	- 12.4	- 12.4
	γ_{xy}	20.1	81.4
	γ_{yz}	-	-
	γ_{zx}	60.4	47.3
IV	ϵ_x	9.4	- 27.2
	ϵ_y	17.3	14.2
	ϵ_z	- 12.4	- 12.4
	γ_{xy}	- 19.1	32.2
	γ_{yz}	-	-
	γ_{zx}	59.7	68.2

Table 8 Maximum Normal Ground Strains [$\times 10^{-6}$]
along the Route of Array at Ashitaka Area

Segment	Strain ϵ_x
1 ~ 2 ($\ell = 790\text{m}$)	- 7.6
2 ~ 3 ($\ell = 403\text{m}$)	- 22.4
3 ~ 5 ($\ell = 1275\text{m}$)	6.7

Table 9 Magnification Ratio (Max. Upper Level Strain/Max.
Lower Level Strain)

Zone	Strain	Magnification
I	ϵ_x	2.90
	ϵ_y	1.07
	ϵ_z	1.00
	γ_{xy}	3.47
	γ_{yz}	-
	γ_{zx}	1.14
II	ϵ_x	4.33
	ϵ_y	1.07
	ϵ_z	1.00
	γ_{xy}	4.19
	γ_{yz}	-
	γ_{zx}	0.78
III	ϵ_x	4.32
	ϵ_y	0.82
	ϵ_z	1.00
	γ_{xy}	4.05
	γ_{yz}	-
	γ_{zx}	0.78
IV	ϵ_x	2.90
	ϵ_y	0.82
	ϵ_z	1.00
	γ_{xy}	1.69
	γ_{yz}	-
	γ_{zx}	1.14

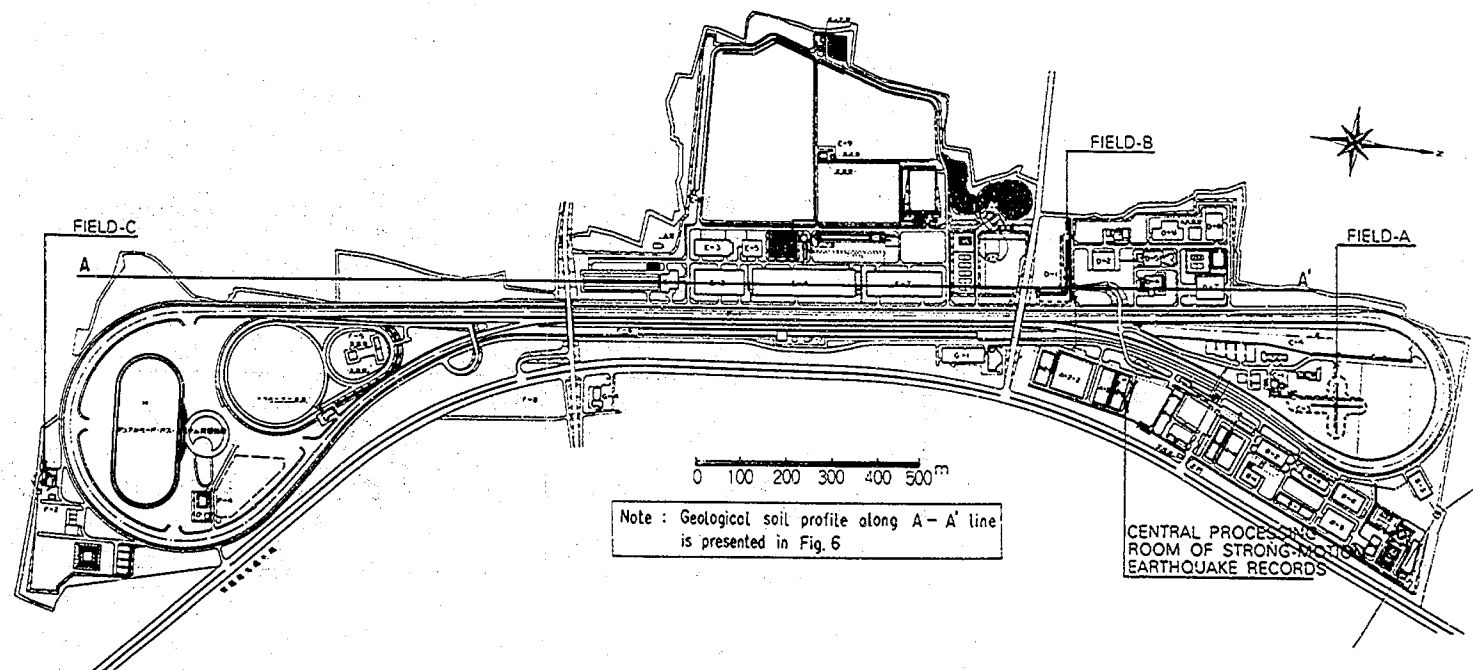


Fig. 1 Location of Local Laboratory Arrays at PWRI

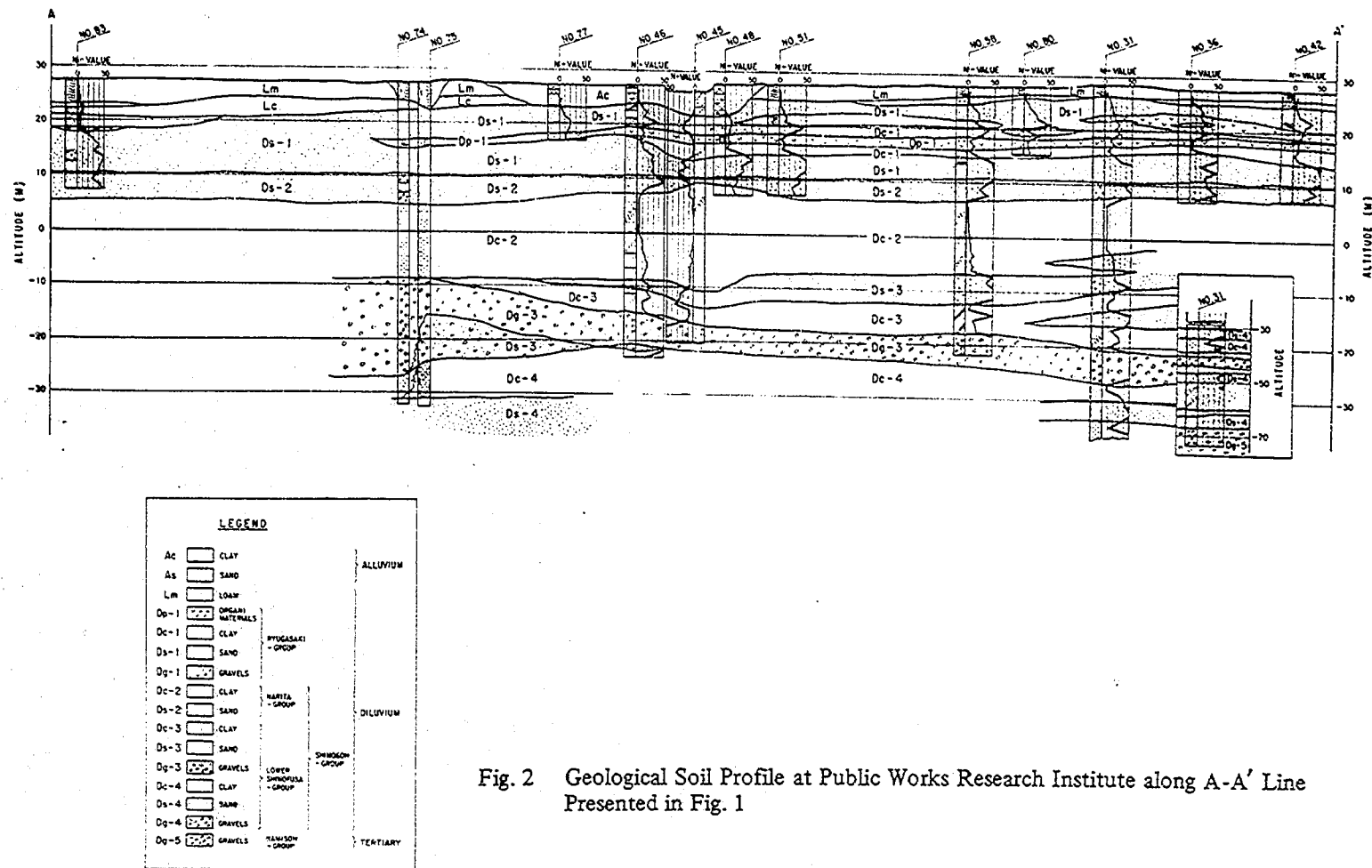


Fig. 2 Geological Soil Profile at Public Works Research Institute along A-A' Line Presented in Fig. 1

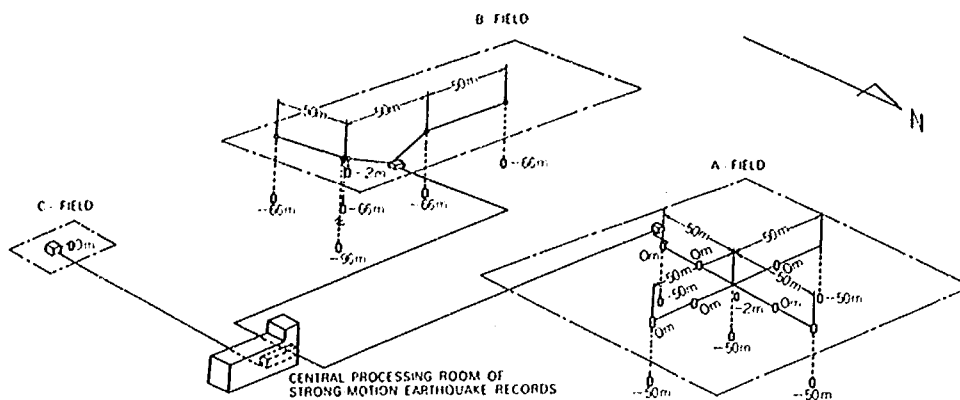


Fig. 3 Local Laboratory Arrays at PWRI

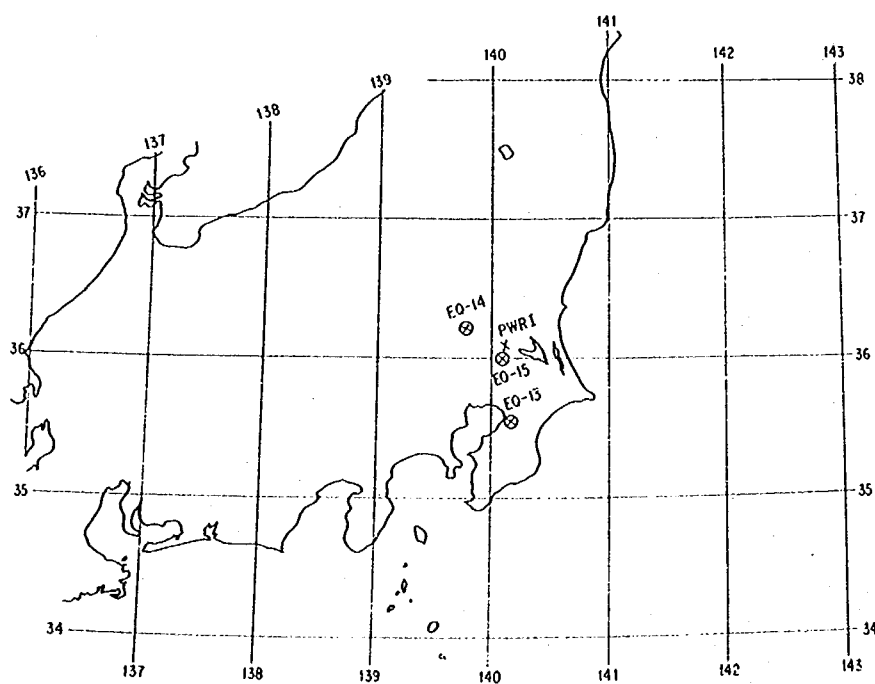


Fig. 4 Location of Epicenters and Observation Station (PWRI)

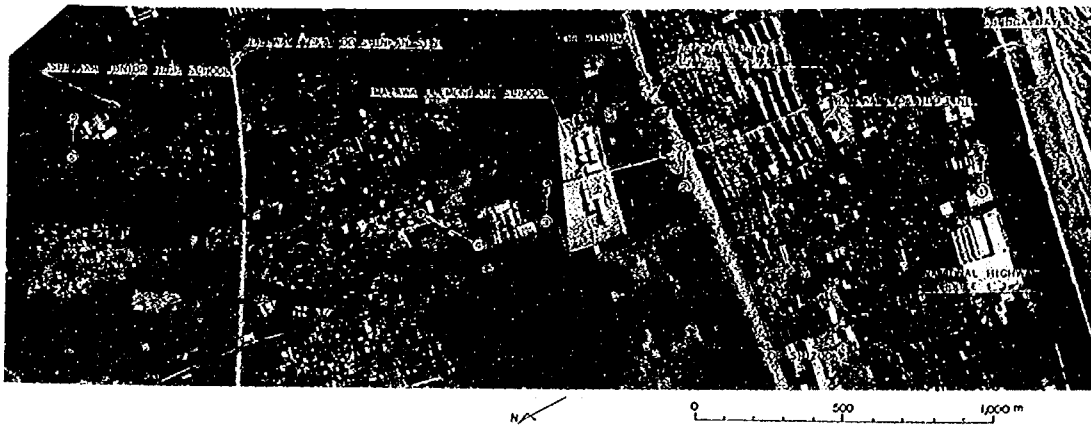


Fig. 5 Aerial View of Simple Extended Array at Ashitaka Area, Numazu, Shizuoka Prefecture

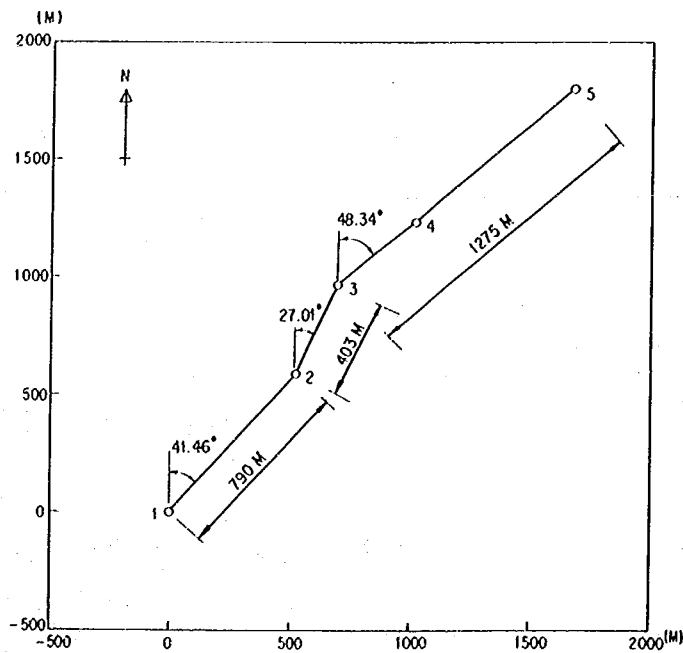


Fig. 6 Layout of Strong Motion Accelerographs Installed at Ashitaka Area, Japan

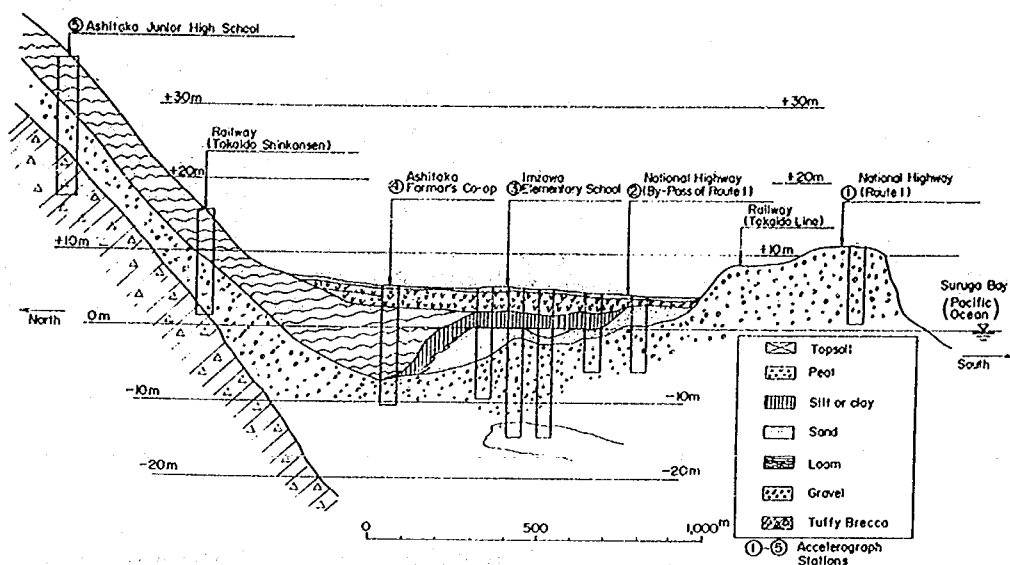


Fig. 7 Observing Stations at Simple Extended Array at Ashitaka Area, Numazu, Shizuoka Prefecture

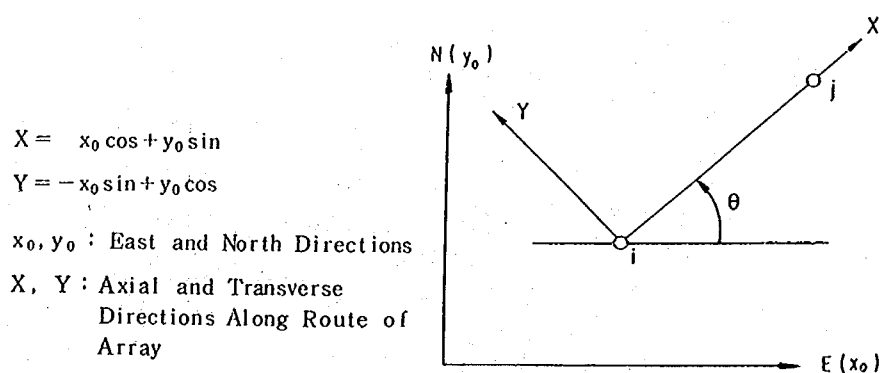


Fig. 8 Coordinate Transformation at Ashitaka Site

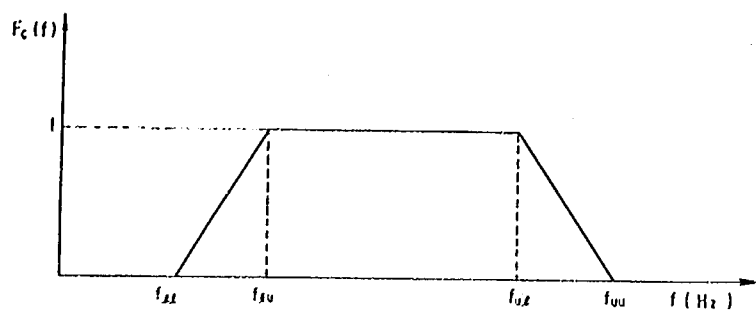


Fig. 9 Band-Pass Filter Used

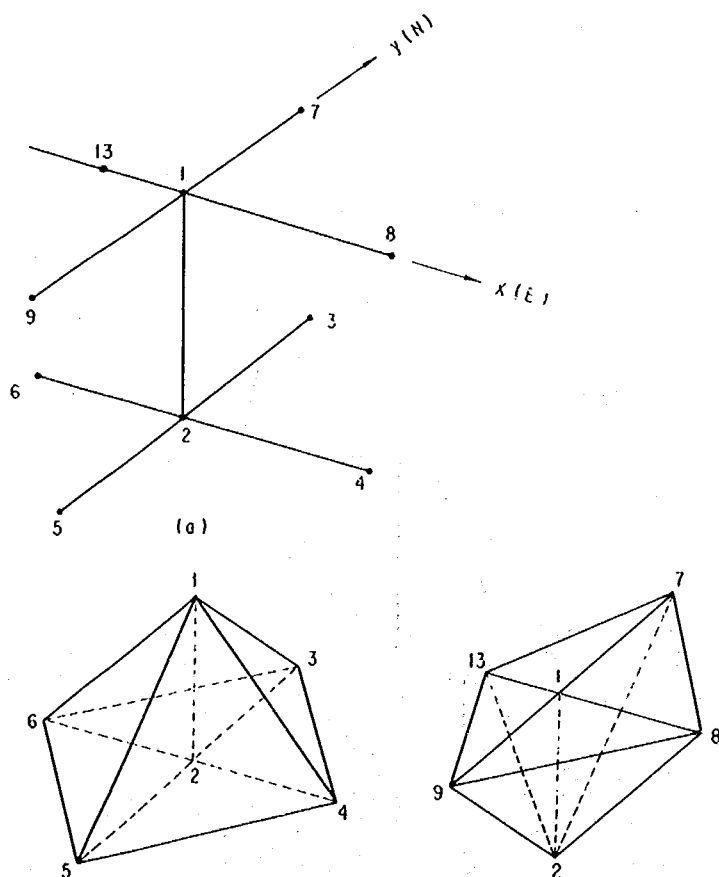
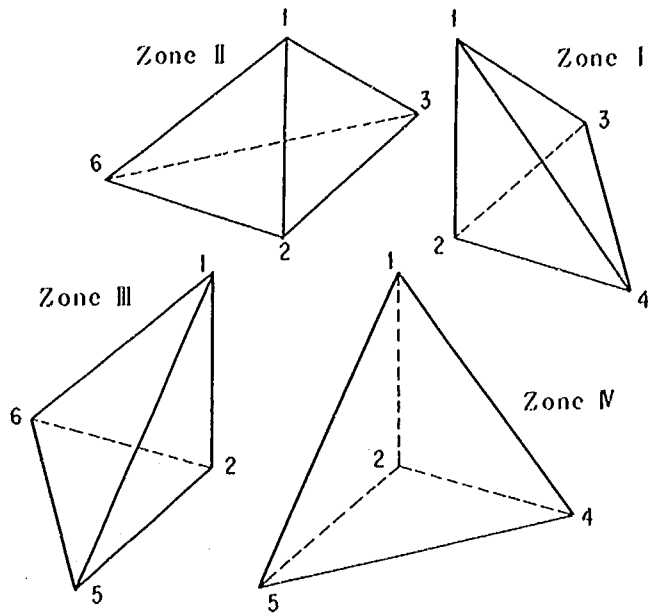
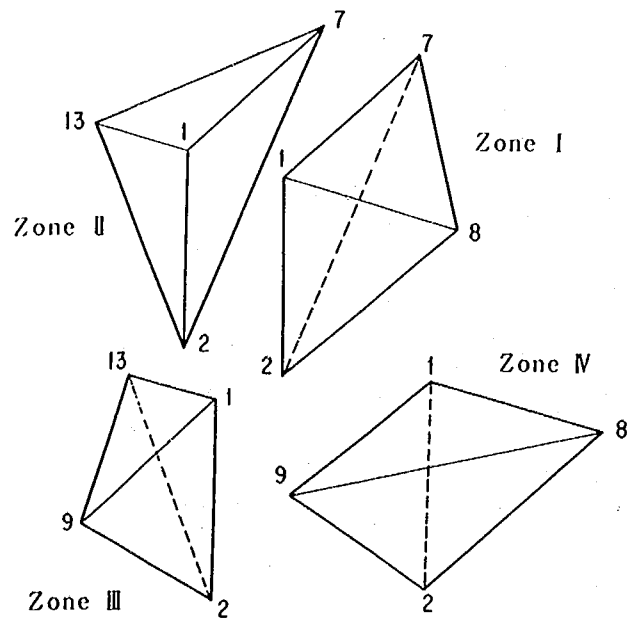


Fig. 10 Definition of Coordinate and Notation for Tetrahedrons Using Strong Motion Arrays at PWRI Site



(a) Tetrahedrons for Calculating Lower Level Strains

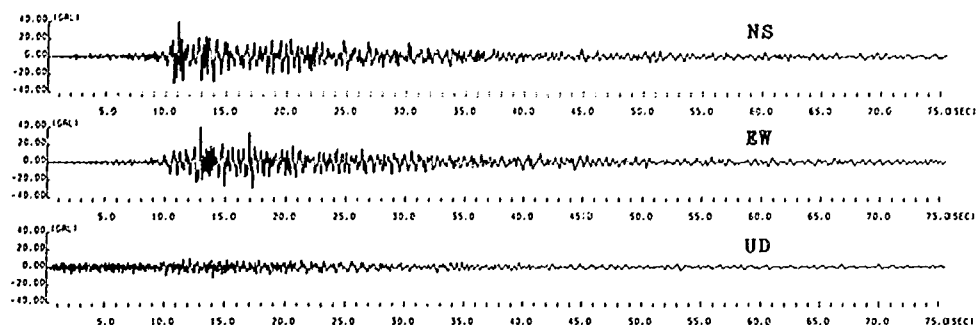


(b) Tetrahedrons for Calculating Upper Level Strains

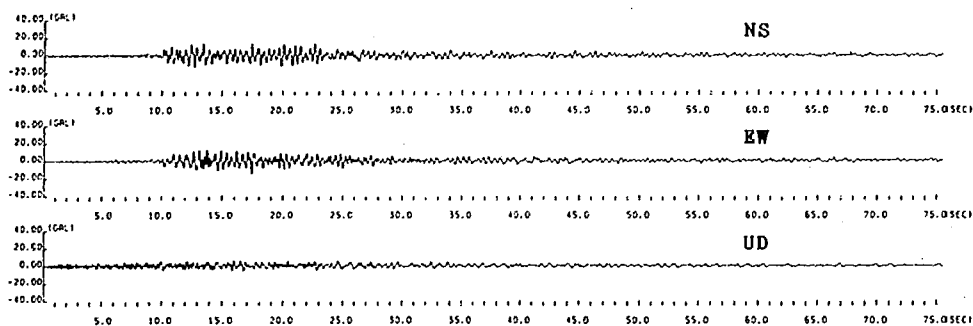
Fig.11 Formations of Tetrahedrons from Strong Motion Array Arrangement for Calculating Finite Element Ground Strains

APPENDIX A--PWRI SITE

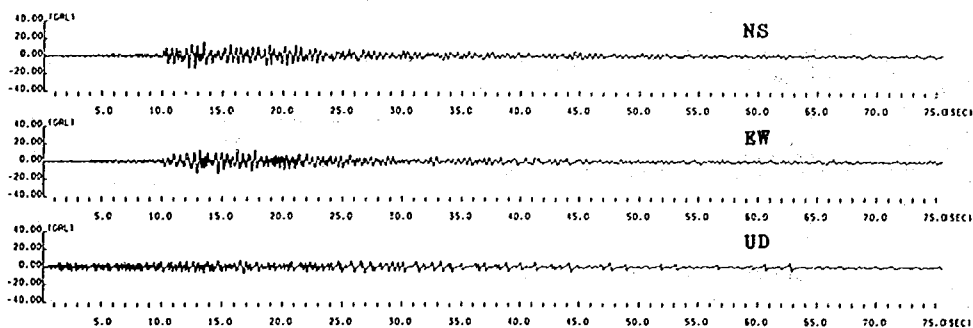
1. ACCELERATION TIME HISTORIES
2. VELOCITY TIME HISTORIES
3. DISPLACEMENT TIME HISTORIES
4. GROUND STRAIN TIME HISTORIES



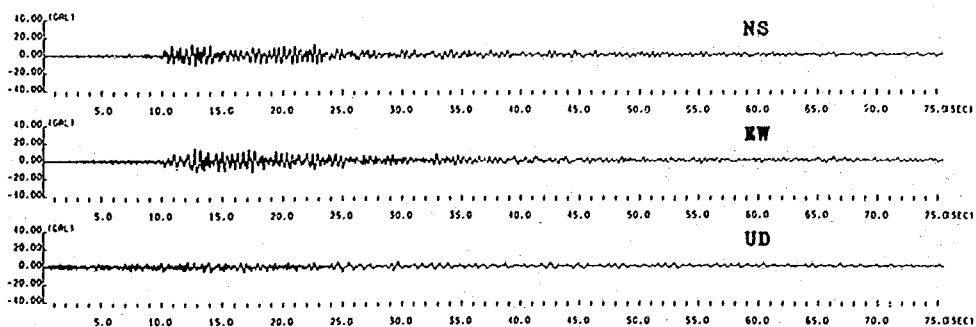
(i) Point 1 (A01-2M: C0)



(ii) Point 2 (A02-46M: C0)

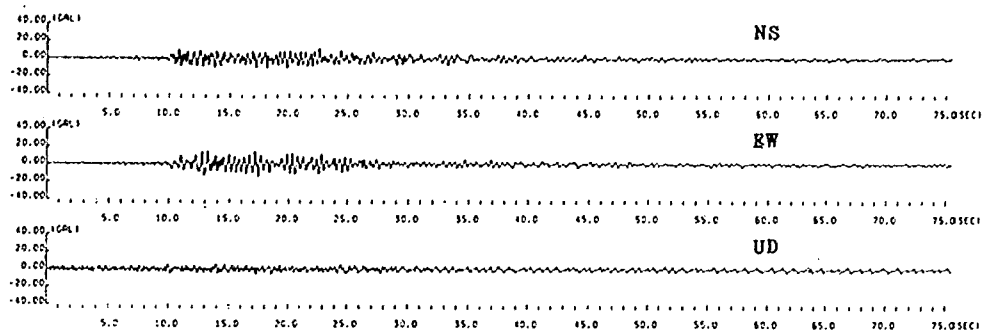


(iii) Point 3 (A03-50M: N2)

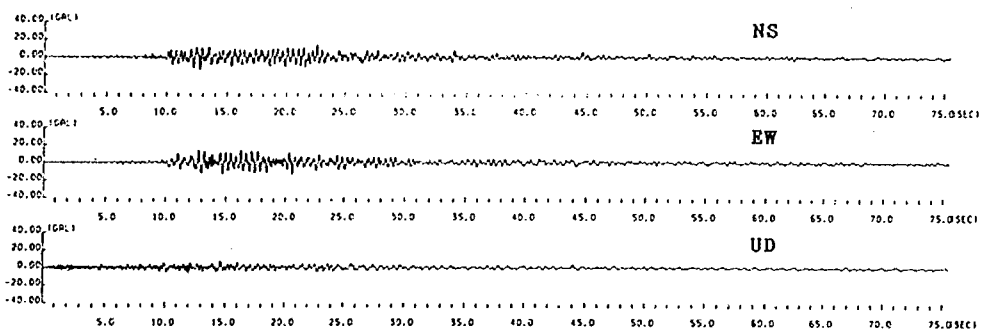


(iv) Point 4 (A04-47M: E2)

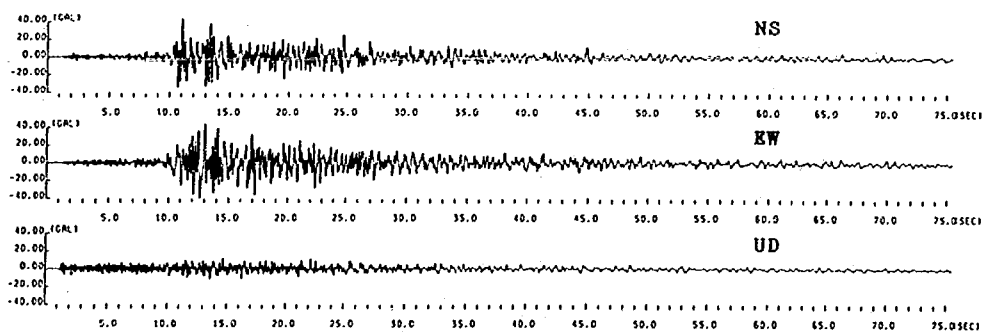
Appendix A1 Acceleration Time History at PWRI Site by EQ 13



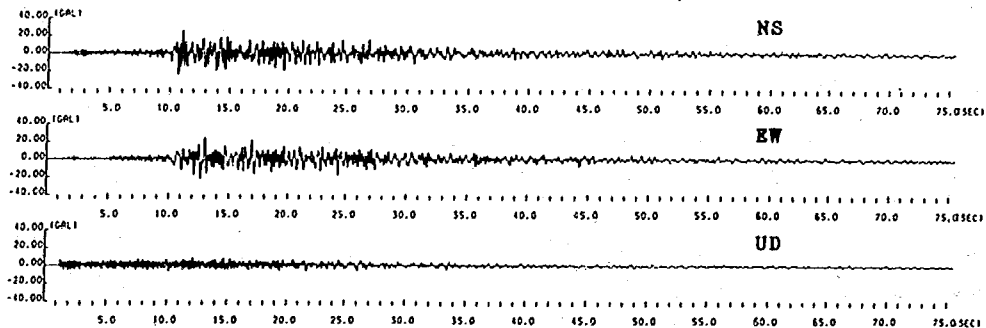
(v) Point 5 (A05 - 45M : S2)



(vi) Point 6 (A06 - 50M : W2)

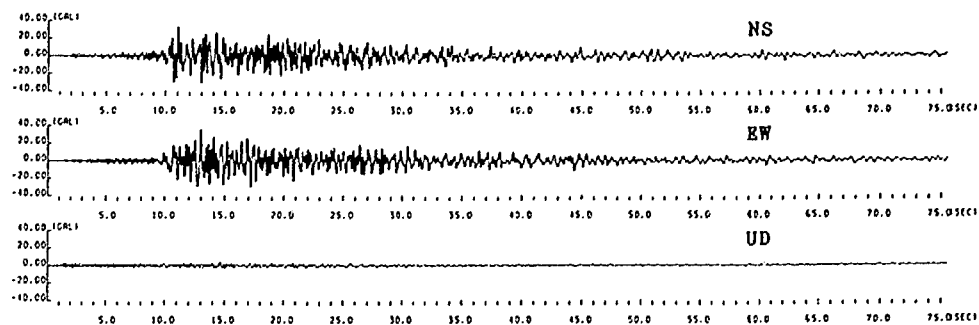


(vii) Point 7 (A07 - GR : N2)

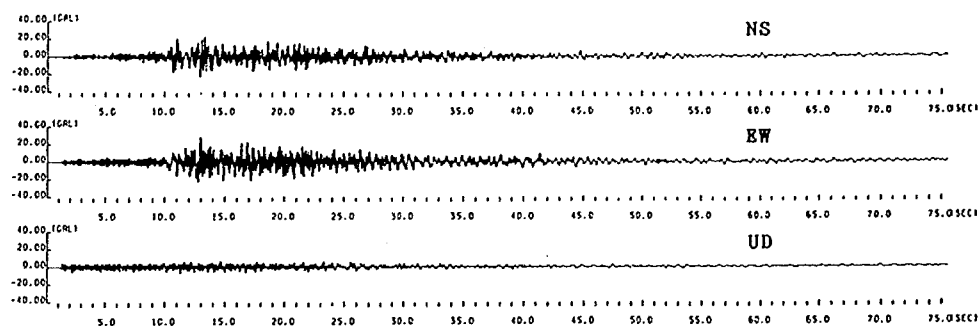


(viii) Point 8 (A08 - GR : E2)

Appendix A1 Continued

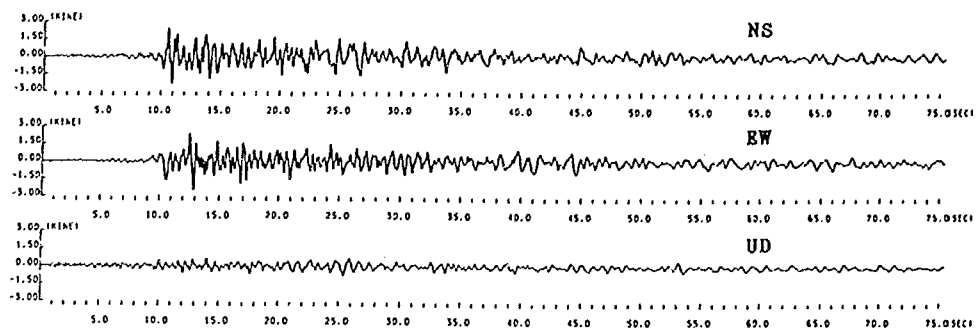


(ix) Point 9 (A09-GR : S2)

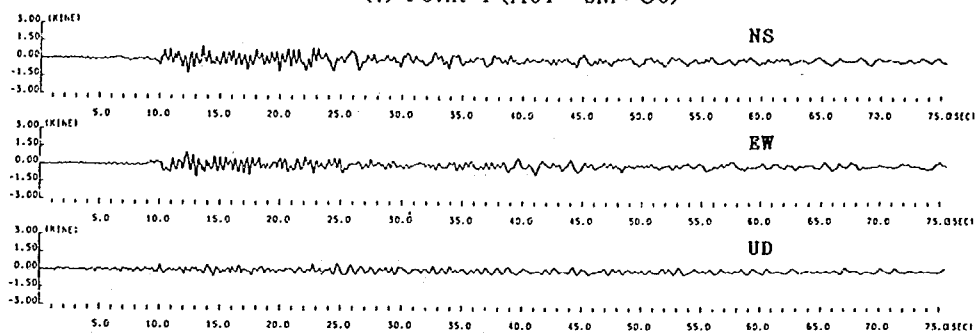


(x) Point 13 (A13-GR : W1)

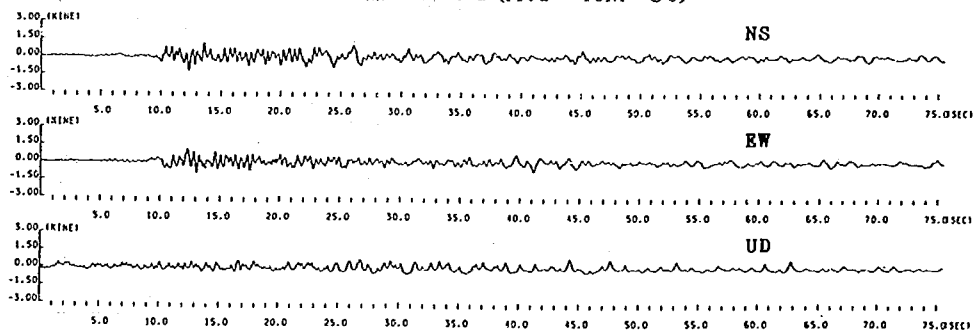
Appendix A1 Continued



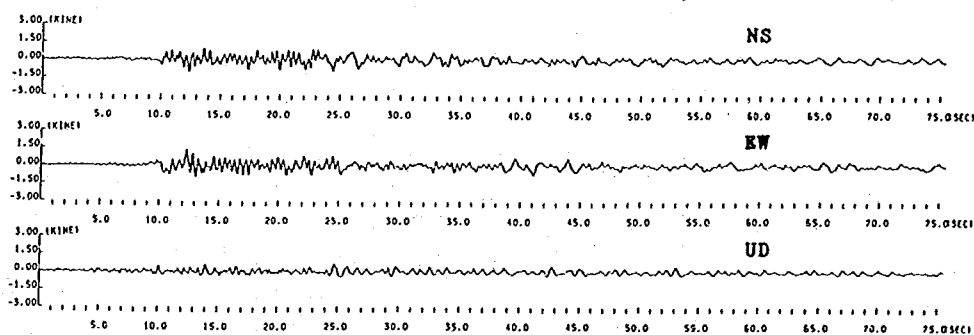
(i) Point 1 (A01-2M:C0)



(ii) Point 2 (A02-46M:C0)

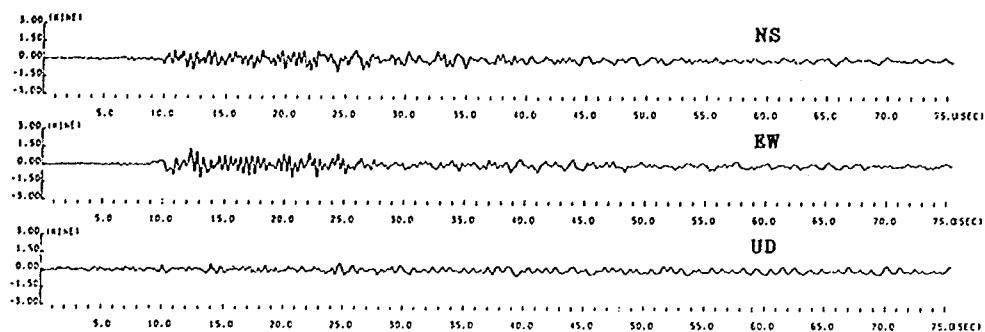


(iii) Point 3 (A03-50M:N2)

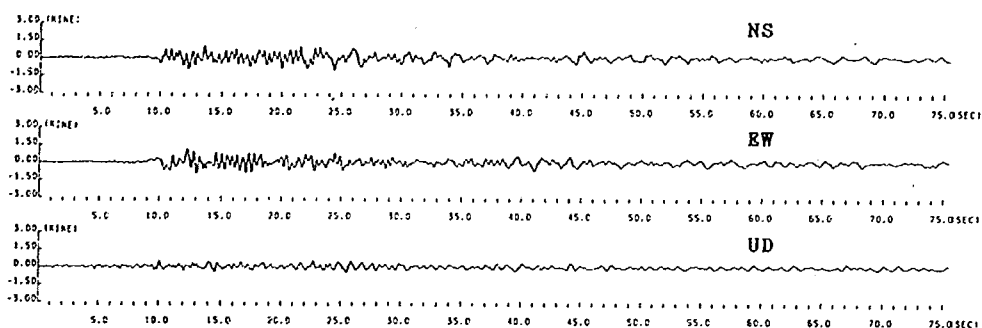


(iv) Point 4 (A04-47M:E2)

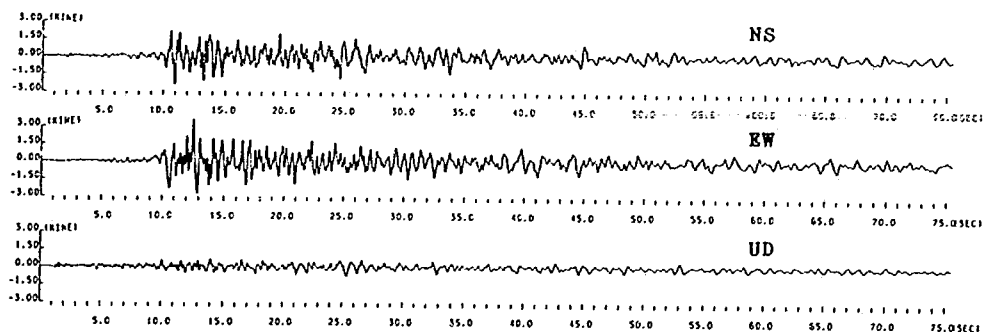
Appendix A2 Velocity Time History at PWRI Site by EQ 13



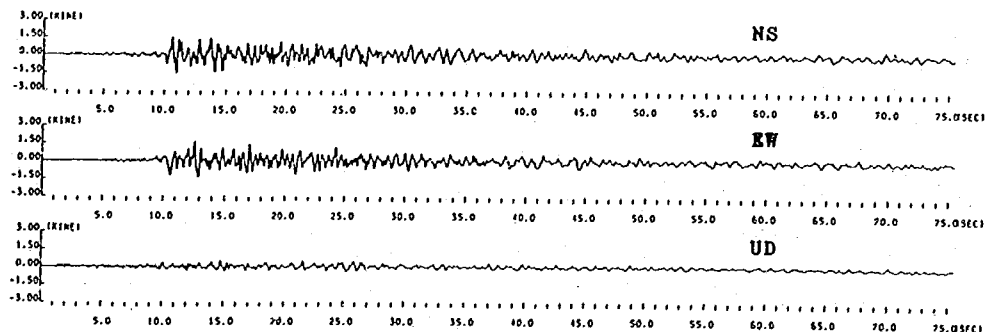
(v) Point 5 (A05 - 45M : S2)



(vi) Point 6 (A06 - 50M : W2)

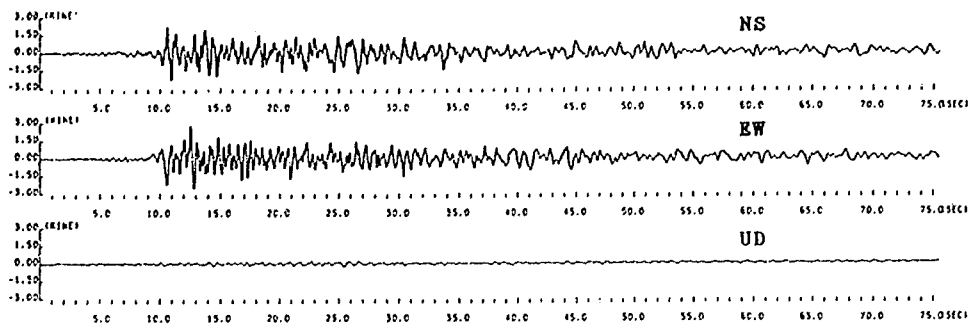


(vii) Point 7 (A07 - GR : N2)

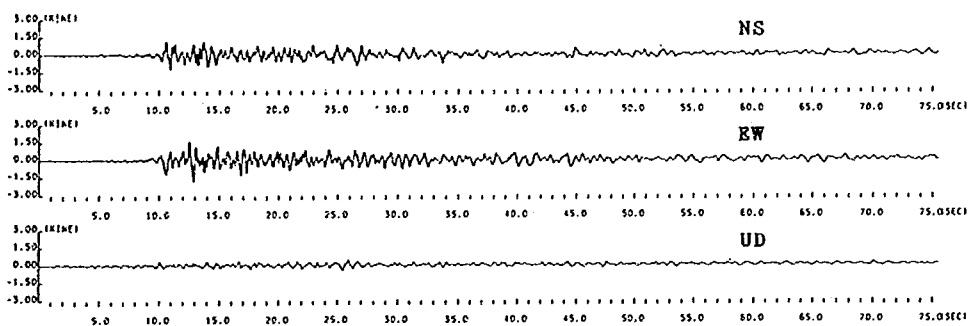


(viii) Point 8 (A08 - GR : E2)

Appendix A2 Continued

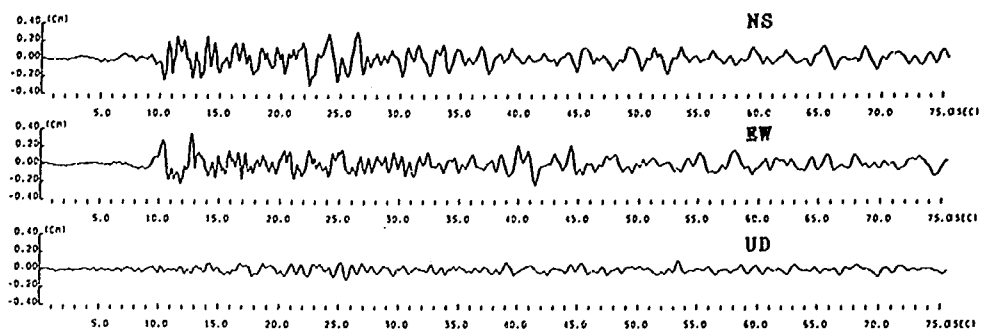


(X) Point 9 (A09-GR:S2)

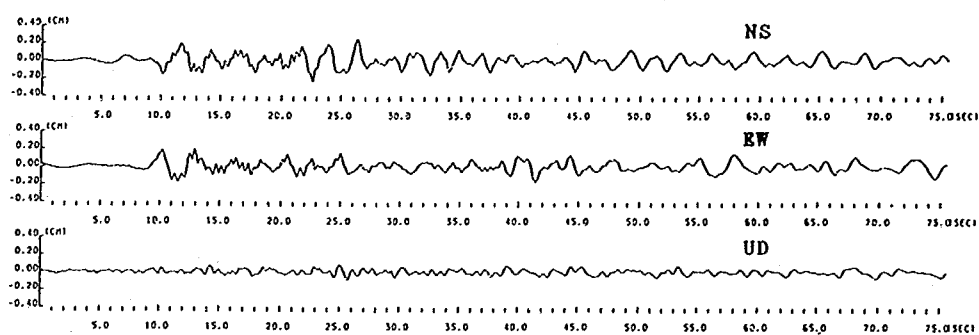


(X) Point 13 (A13-GR:W1)

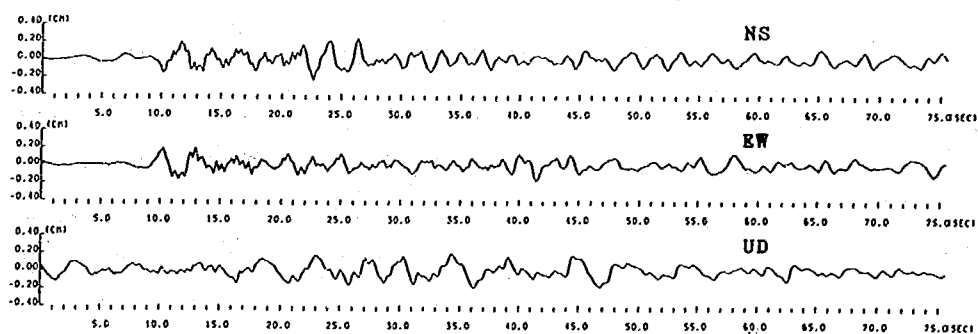
Appendix A2 Continued



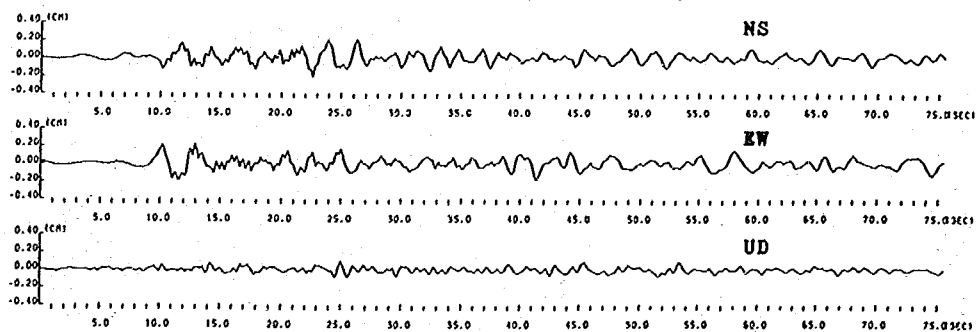
(i) Point 1 (A01 - 2M : C0)



(ii) Point 2 (A01 - 46M : C0)

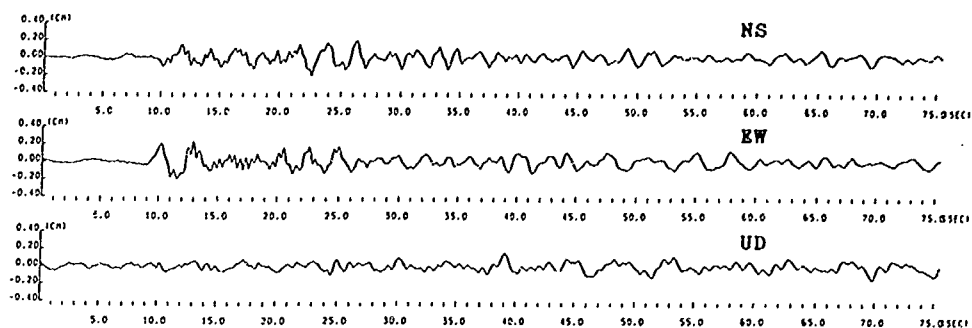


(iii) Point 3 (A03 - 50M : N2)

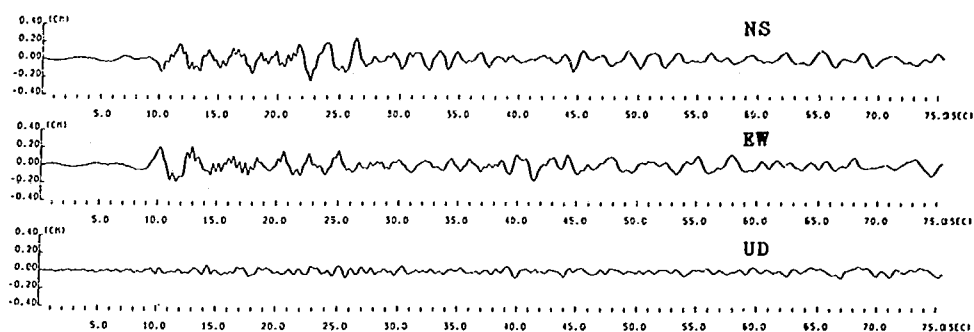


(iv) Point 4 (A04 - 47M : E2)

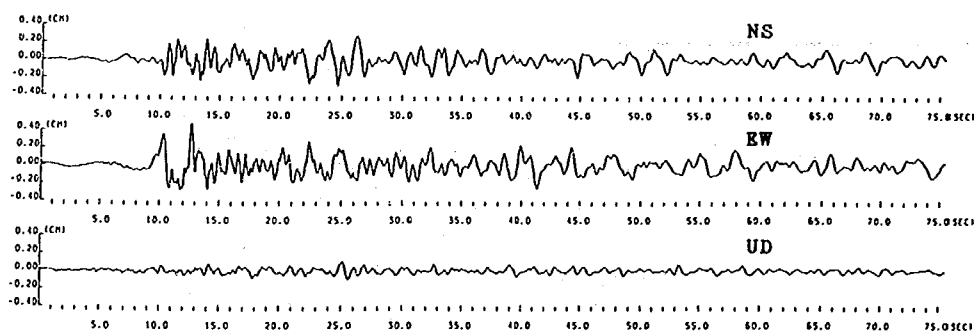
Appendix A3 Displacement Time History at PWRI Site by EQ 13



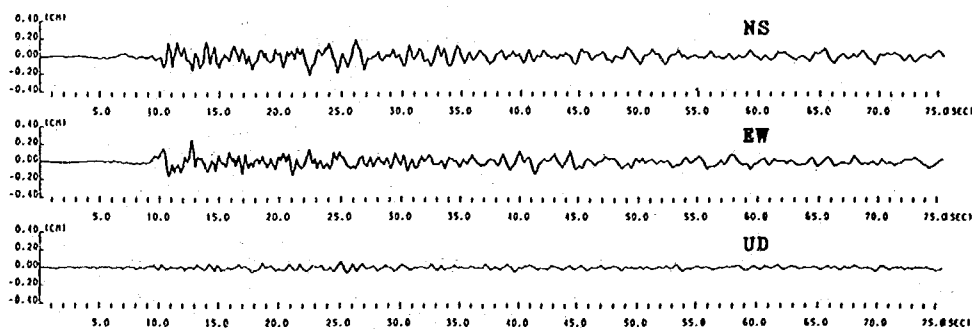
(v) Point 5 (A05 - 45M : S2)



(vD) Point 6 (A06 - 50M : W2)

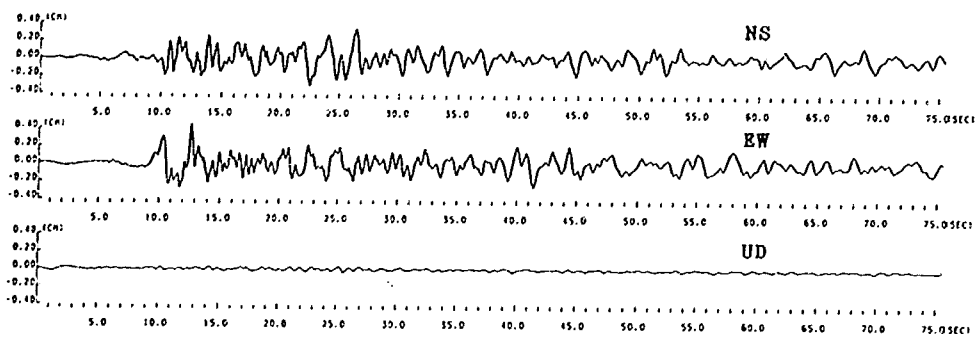


(viD) Point 7 (A07 - GR : N2)

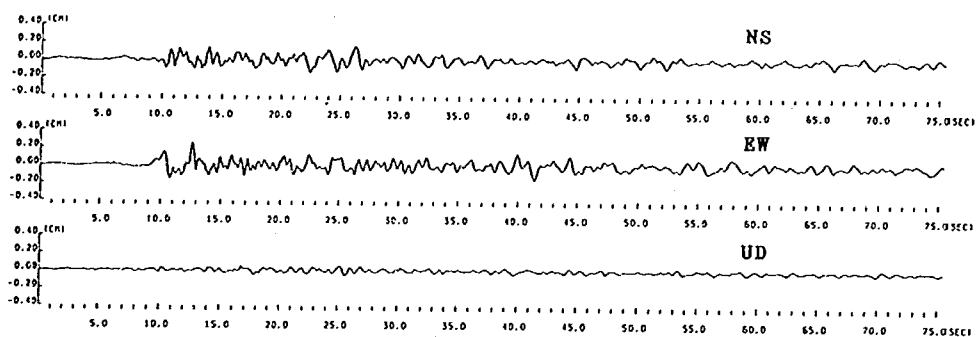


(viiD) Point 8 (A08 - GR : E2)

Appendix A3 Continued

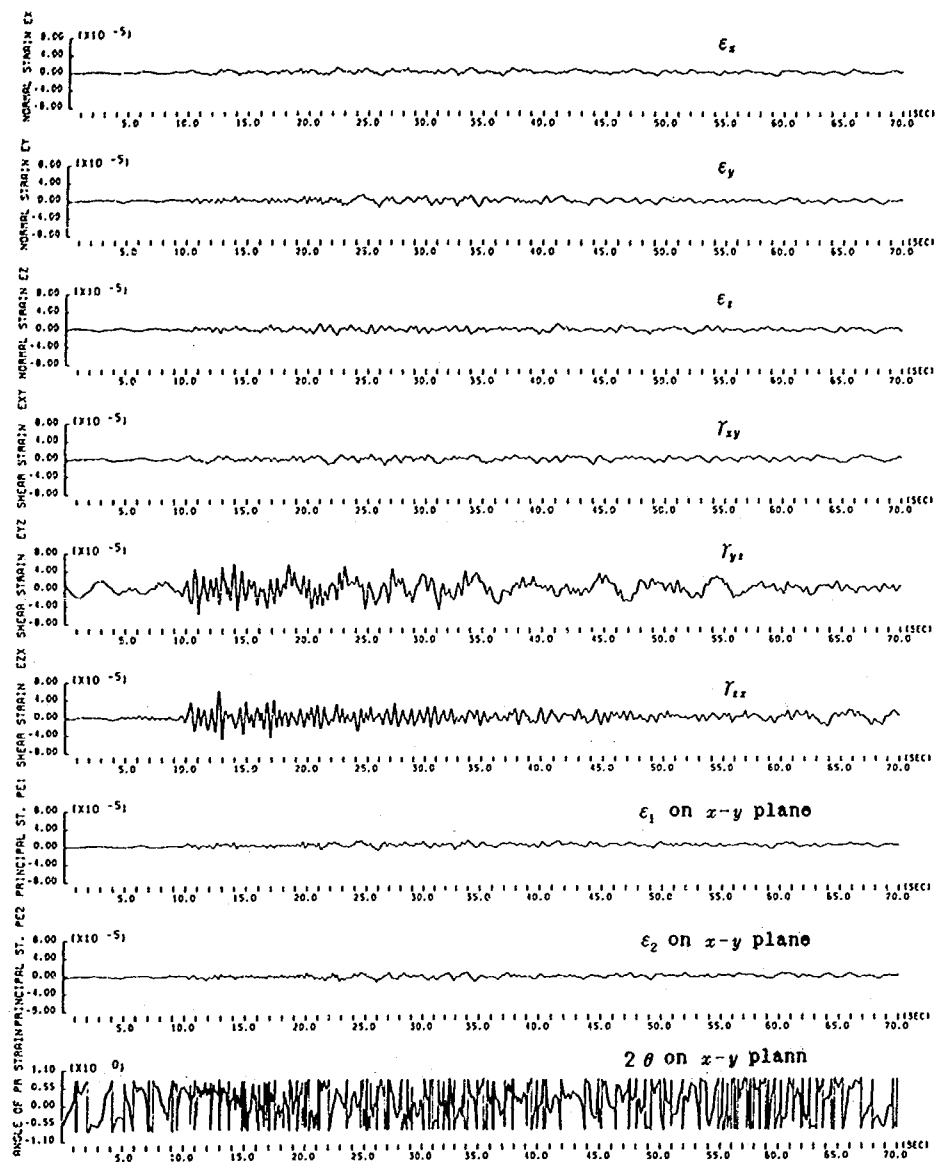


(IX) Point 9 (A09-GR : S2)



(X) Point 13 (A13-GR : W1)

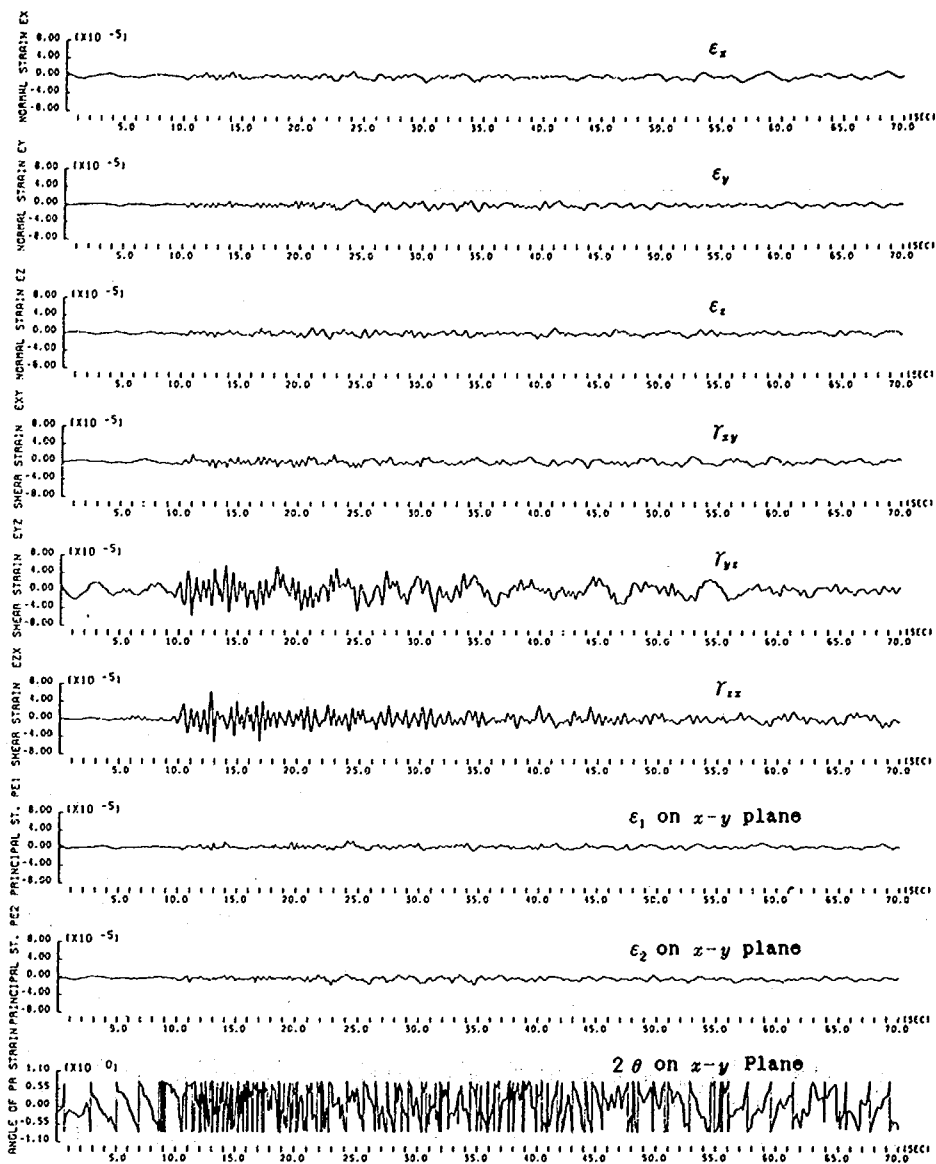
Appendix A3 Continued



(ii) Lower Level of Zone 1

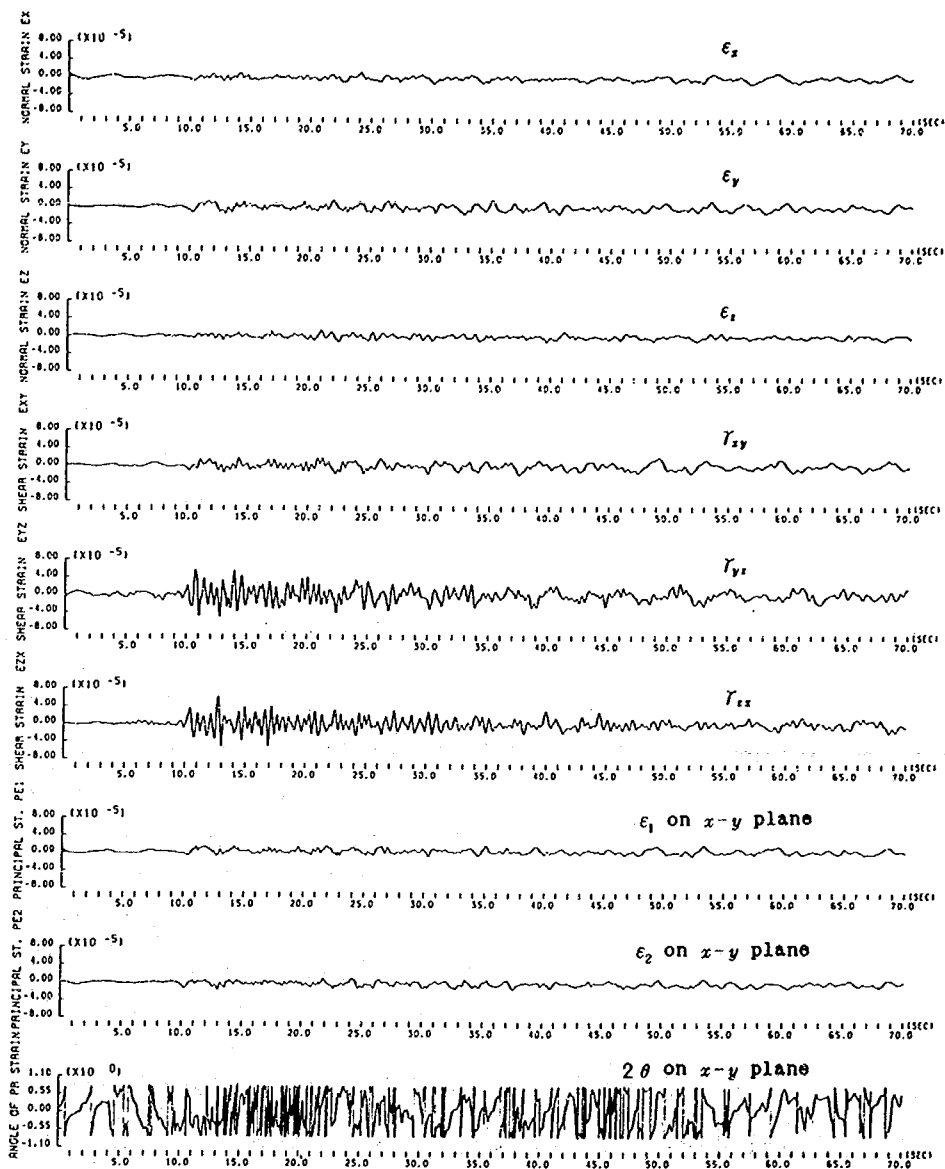
Appendix A4 Continued

Appendix A4 Ground Strains at PWRI Site by EQ 13



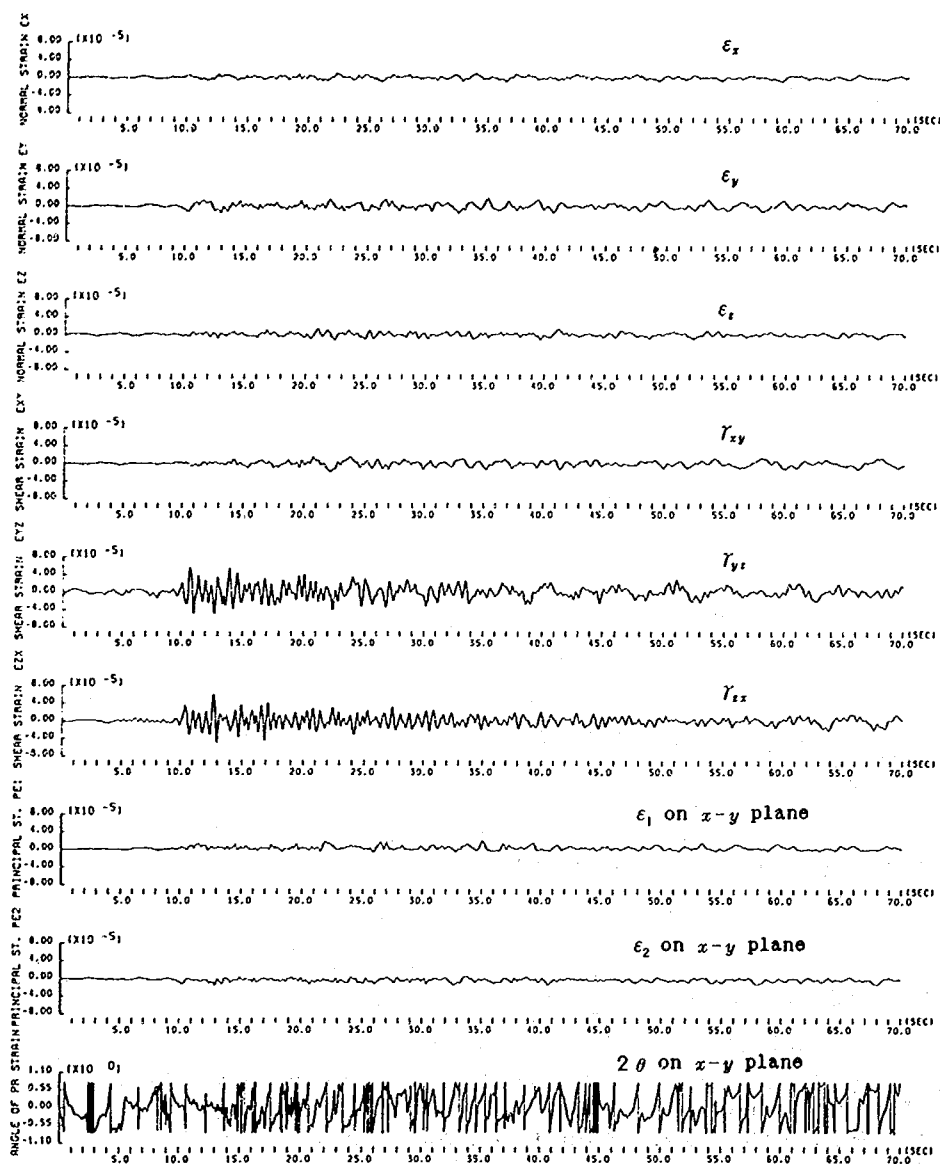
(i) Lower Level of Zone II

Appendix A4 Continued



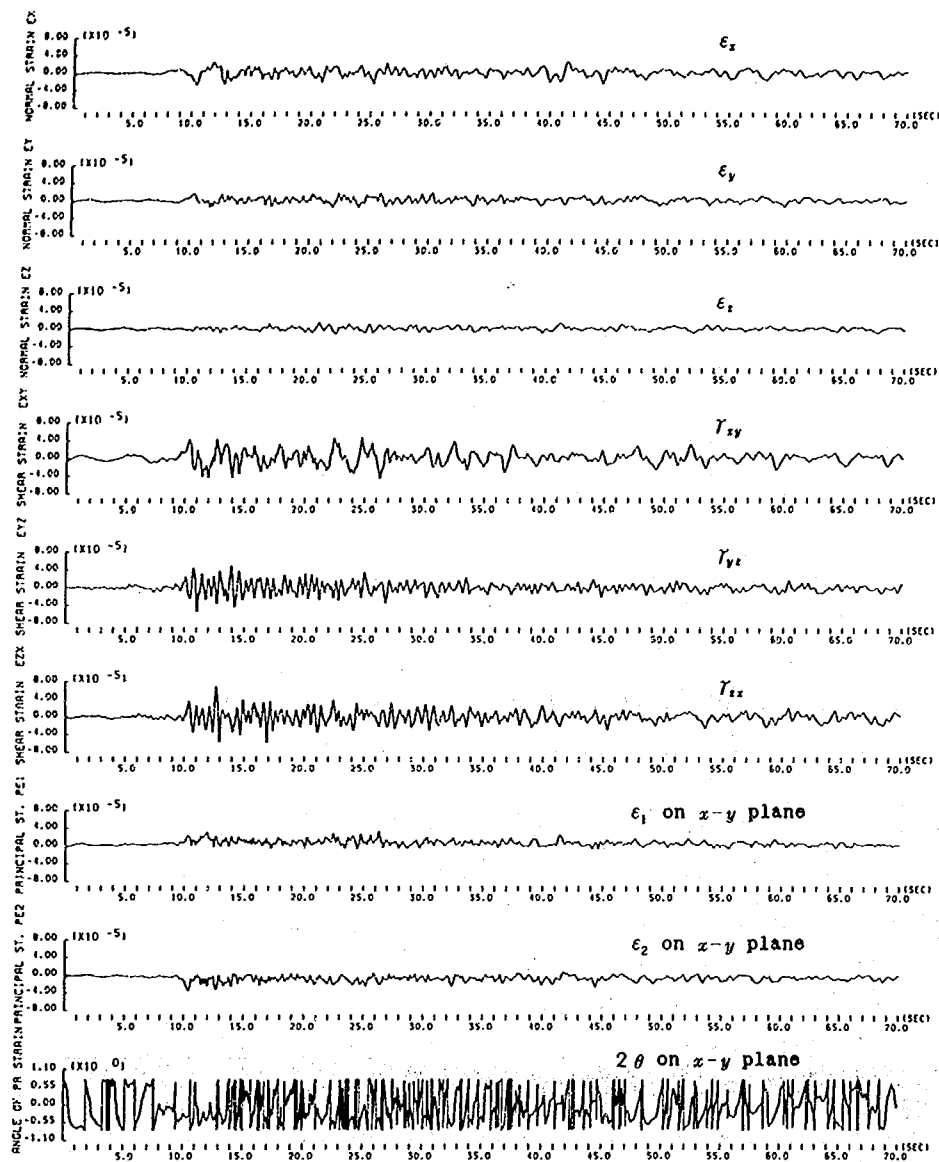
(iii) Lower Level of Zone III

Appendix A4 Continued



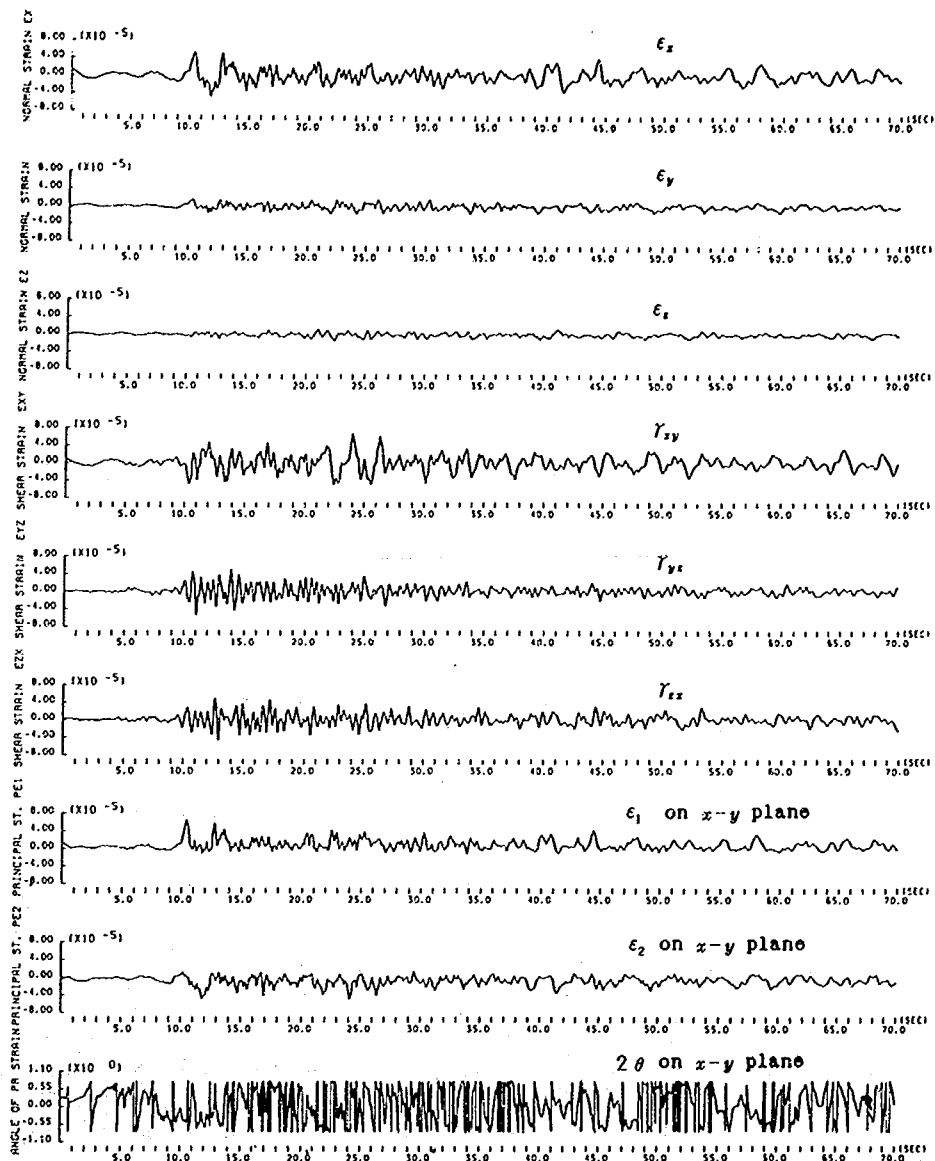
(iv) Lower Level of Zone IV

Appendix A4 Continued



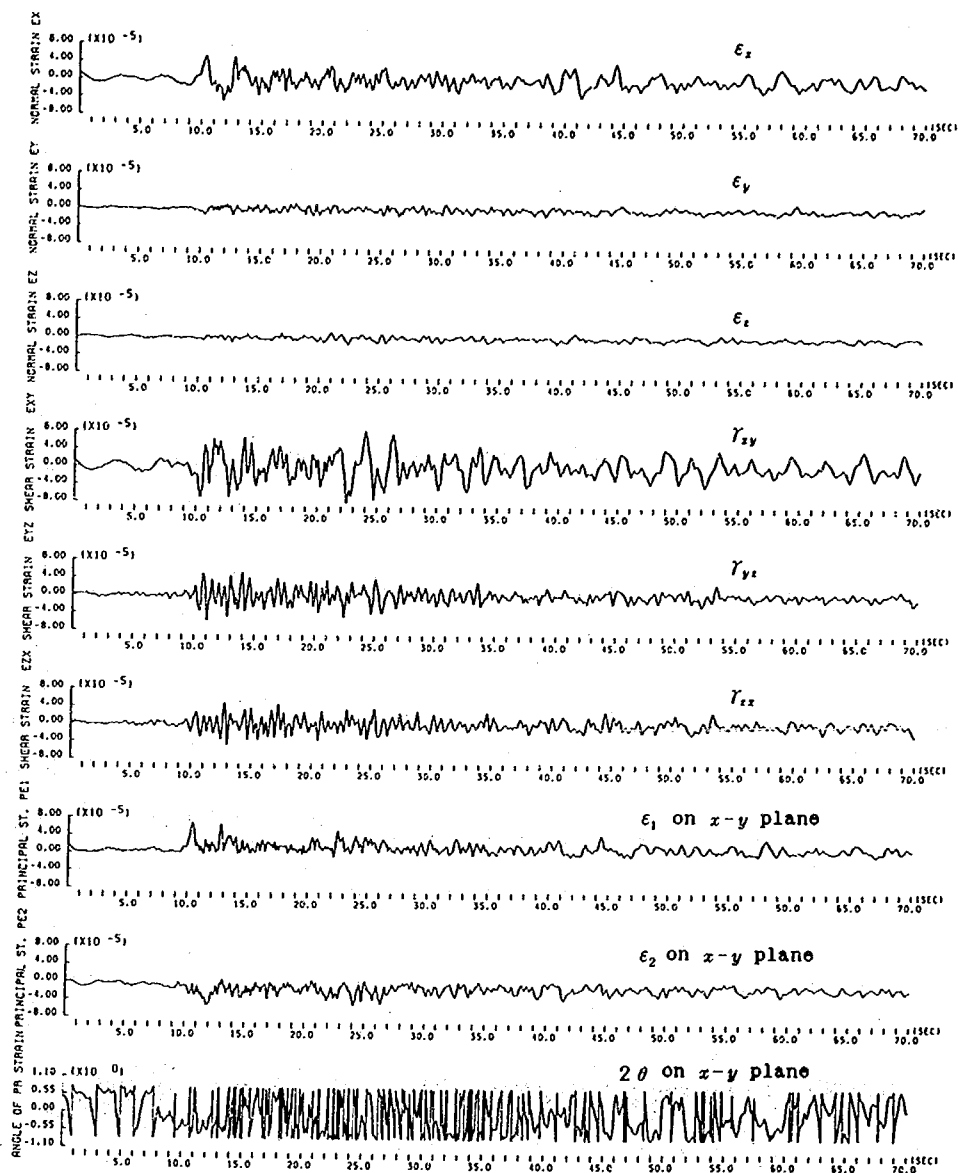
(V) Upper Level of Zone I

Appendix A₄ Continued



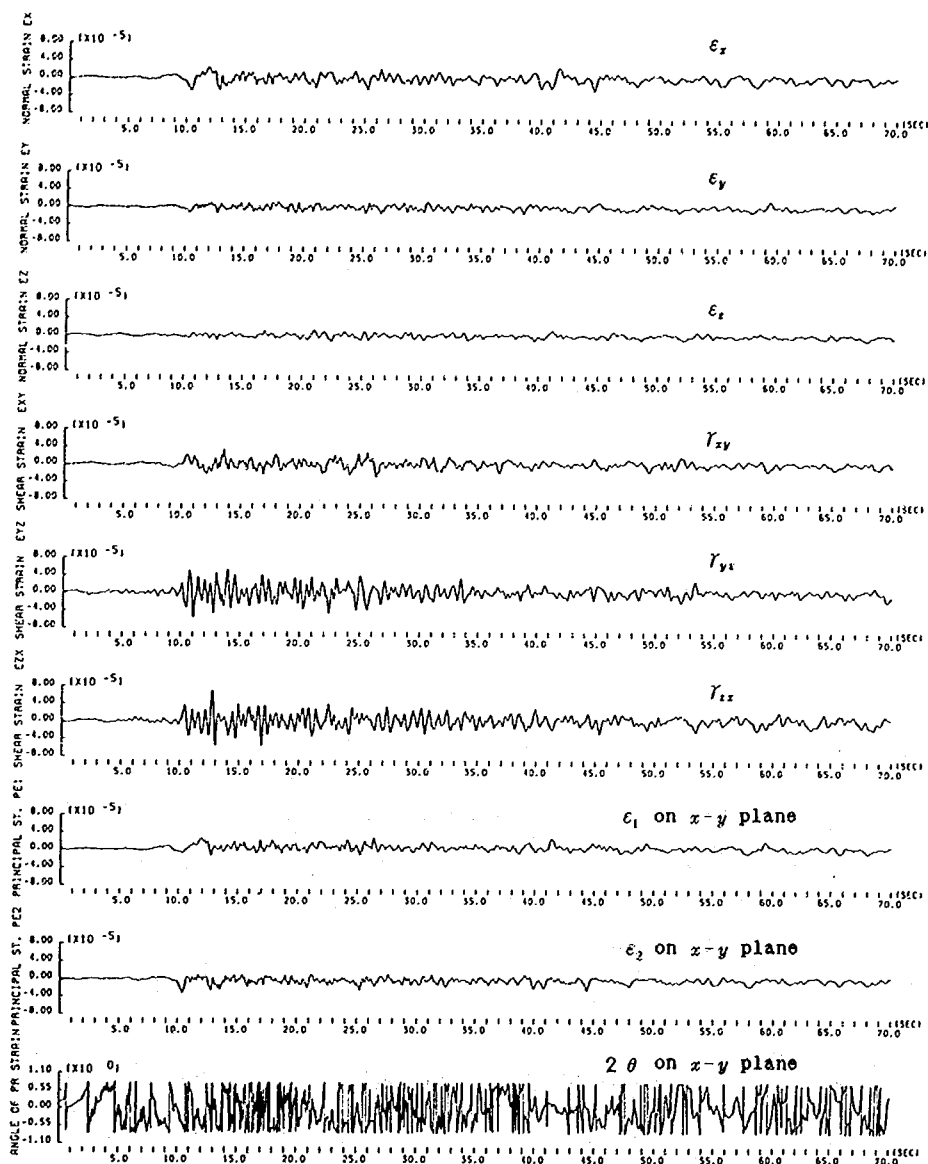
(VD) Upper Level of Zone II

Appendix A₄ Continued



(vii) Upper Level of Zone III

Appendix A₄ Continued

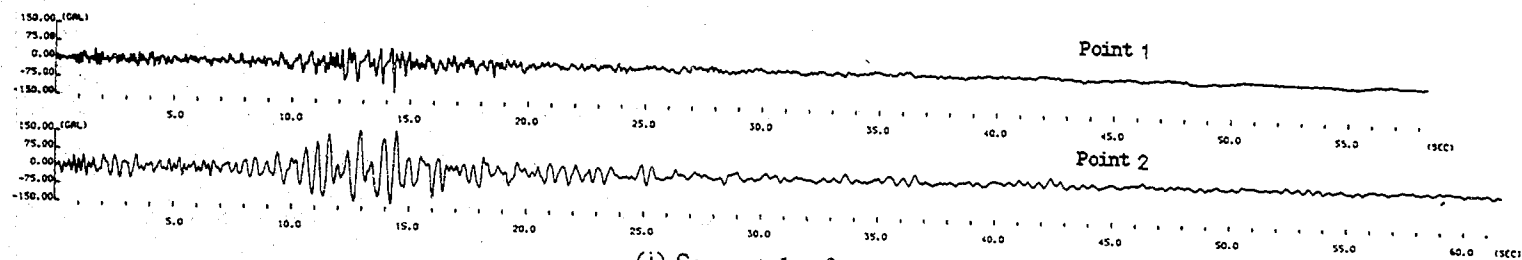


(vii) Upper Level of Zone IV

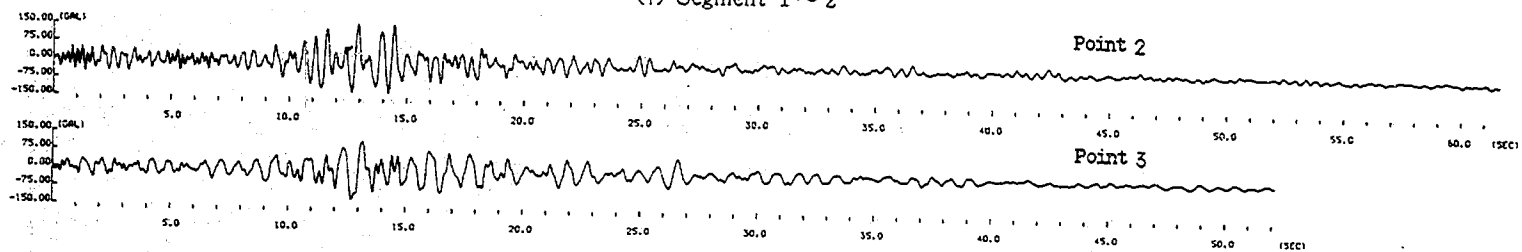
Appendix A₄ Continued

APPENDIX B—ASHITAKA SITE

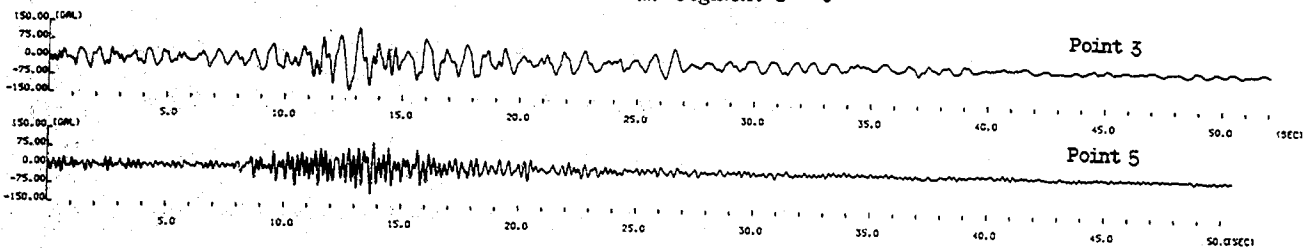
1. ACCELERATION TIME HISTORIES
2. VELOCITY TIME HISTORIES
3. DISPLACEMENT TIME HISTORIES
4. GROUND STRAIN TIME HISTORIES



(i) Segment 1 ~ 2

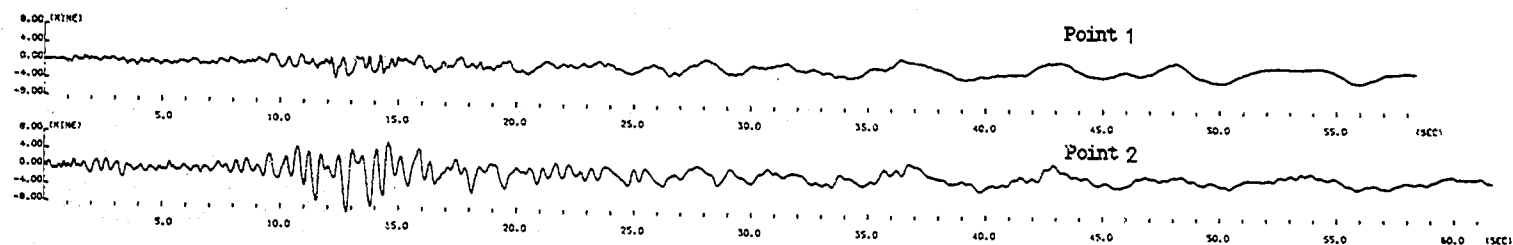


(ii) Segment 2 ~ 3

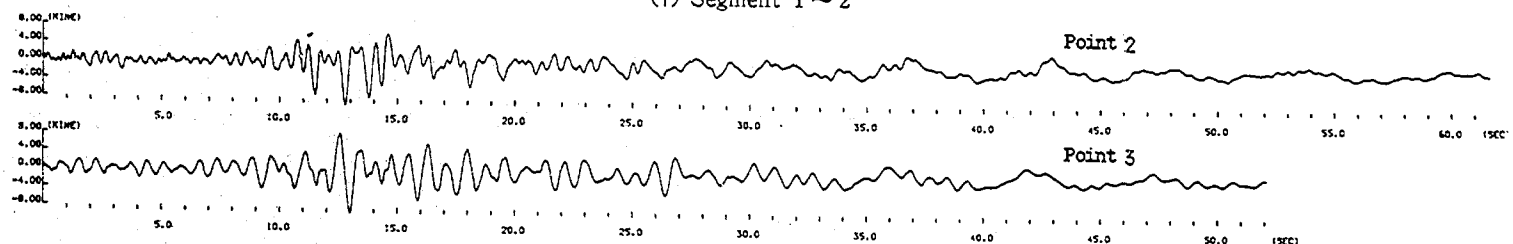


(iii) Segment 3 ~ 5

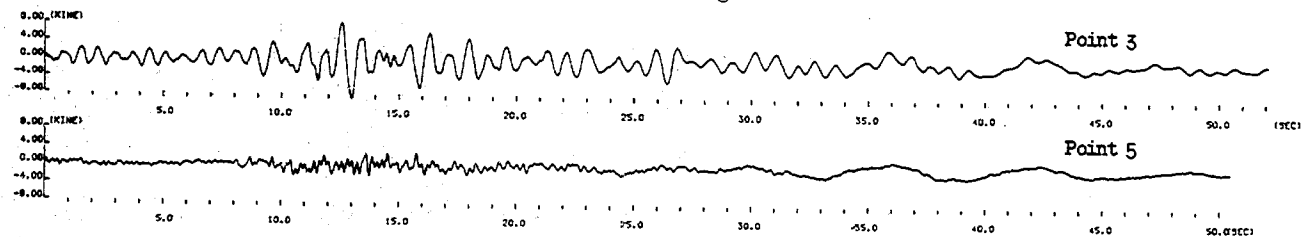
Appendix B1 Time History of Accelerations[gal] for Three Array Segments in Ashitaka Site



(i) Segment 1 ~ 2

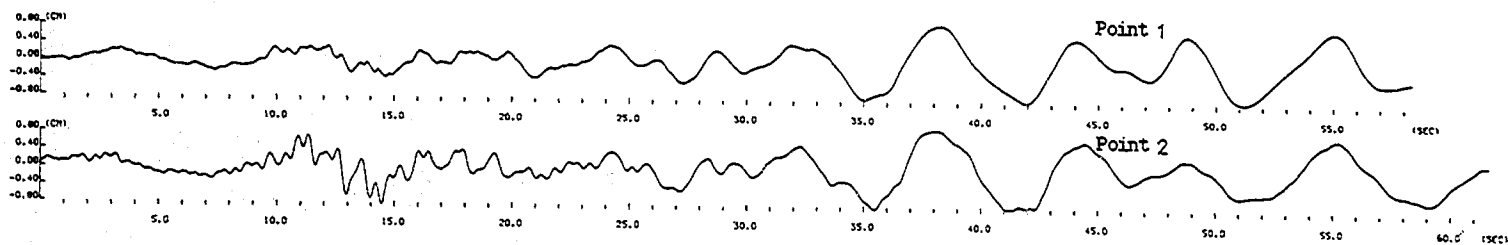


(ii) Segment 2 ~ 3

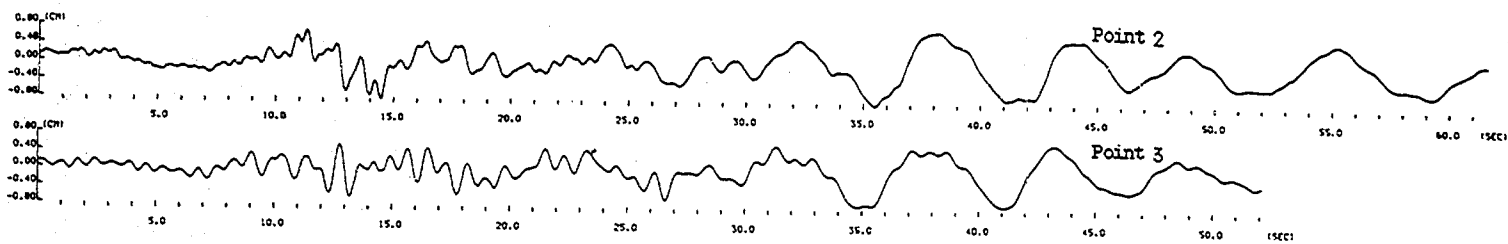


(iii) Segment 3 ~ 5

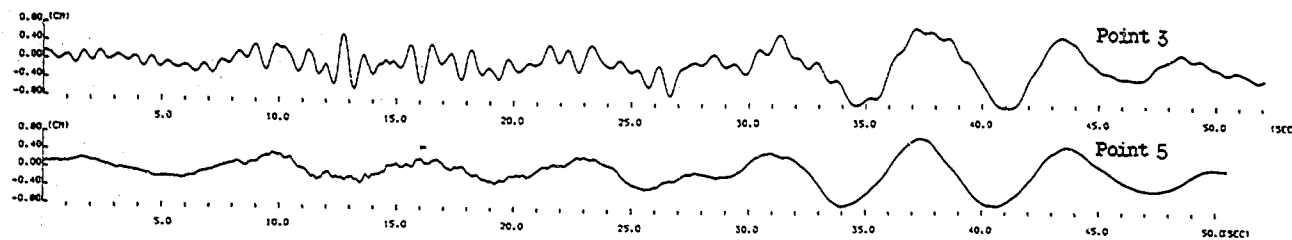
Appendix B2 Time History of Velocities[cm/sec] for Three Array Segments in Ashitaka Site



(i) Segment 1 ~ 2

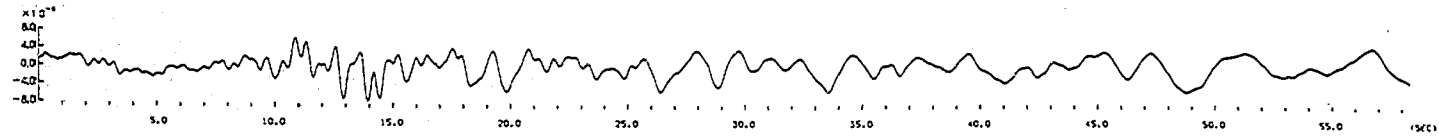


(ii) Segment 2 ~ 3

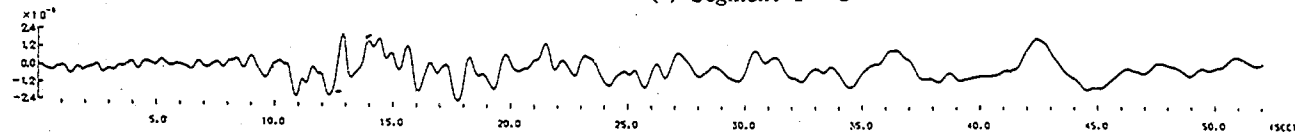


(iii) Segment 3 ~ 5

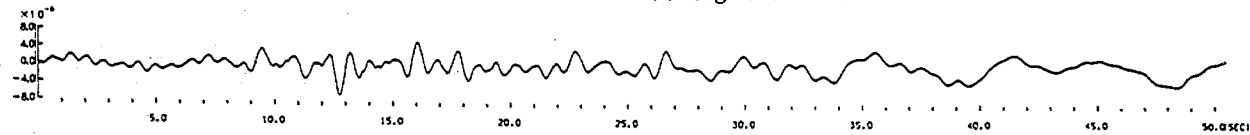
Appendix B3 Time Histories of Displacements [cm] for Three Array Segments in Ashitaka Site



(a) Segment 1 ~ 2



(b) Segment 2 ~ 3



(c) Segment 3 ~ 5

Appendix B4 Time Histories of Ground Strains [$\times 10^{-6}$] for Three Array Segments in Ashitaka Site