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AN EXAMINATION ON OBSERVED RESULTS OF GROUND STRAINS DURING EARTHQUAKES

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ABSTRACT

It is fundamental to examine engineering properties of earthquake induced ground strains for studying seismic resistance of underground structures. In this paper,direct measurement system of ground strains were deviced and observed results were analysed. Three normal strains on surface of ground were observed and analysed for purpose of inspecting properties of strain conditions. More than 100 earthquake records were obtained and they were found to be on nearly pure shear condition. The gauge length of this device is 1m,which seems to be too short from viewpoint of earthquake engineering. Under such consideration,same typed measurement system was installed on observation site apart 16m from the above mentioned one,for the purpose of inspecting strain condition in the wide-spread area. Examining the results obtained on two sites,it was revealed that pure shear condition were produced.

KEYWORDS

Earthquake observation, Earthquake induced ground strain, Ground strain condition

INTRODUCTION

Examination on earthquake resistance of underground structure became to be important increasingly,taking account of the heavy damage of subway tunnel due to the 1995 Southern Hyogo Prefecture earthquake. Underground structure is forced to be moved with the surrounding soil and it does not move freely as a structure on the ground surface. Therefore,seismic behavior and general characteristics of ground strain are essential parameter for seismic design of these structures.

Various studies have been conducted to observe strains on underground structures during earthquakes. Ground strain is considered to be almost equal to observed one(Sakurai *et al*,1967)(Tamura *et al*,1975)(Sato *et at*,1986). Another approach to estimate ground strains bases on the strong ground motion record. Ground motion data at only one or a few accelerographs were able to be incorporate into analyses(Kamiyama,1976)(Takada *et al*,1980). The recent development of closely spaced arrays is available for estimating ground strains(Noda *et al*,1988)(Katayama *et al*,1990)(Arakawa *et al*,1984). A

time-space stochastics process model is used for estimation of ground strains(Tamura *et al*,1992).

Undirect measurements of ground strain were utilized in the studies mentioned above. In order to obtain data of ground strain with higher accuracy,direct measurement is desired to be deviced. Considering this background,the object of this paper is laid on the development of direct measurement method for ground strain and also investigation on the observed results.

OBSERVATION METHOD

Observation Site

The observation site is located in the campus of the Science University of Tokyo(Noda city,Chiba). It is situated in lat.35° 55′ 03″ N and log.139° 54′ 57″ E. The topographical condition of the site is generally simple with the ground surface being almost flat. Typical soil properties obtained from representative borehole is shown in Fig.1. The site consists of ground with silt stratum more than 30m thick in which there are sandy layers.

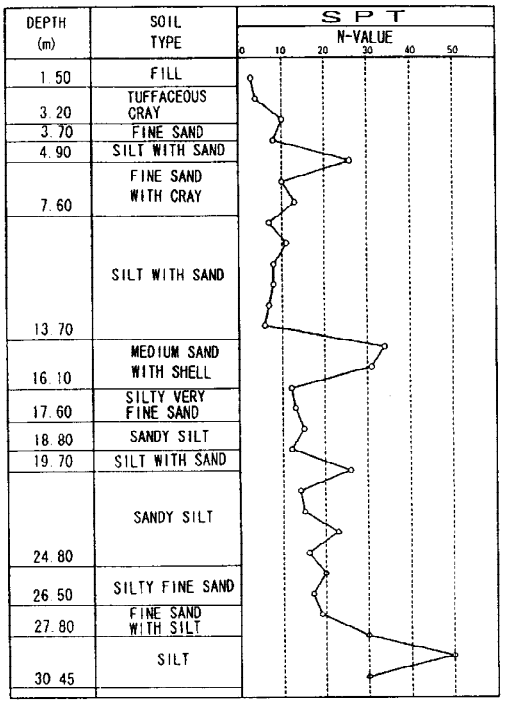

Fig.1 The result of SPT at the site

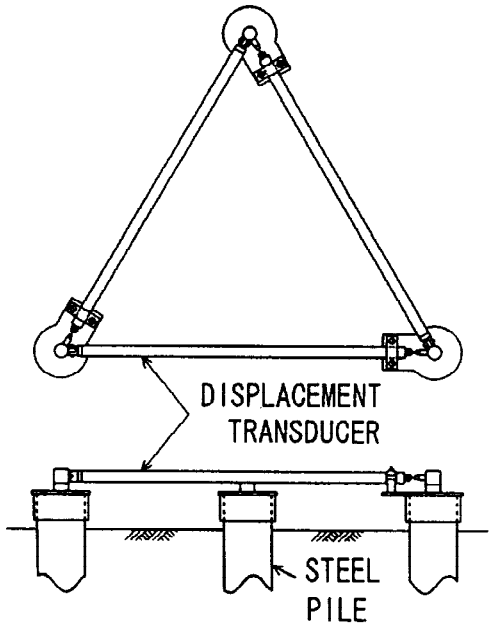

Fig.2 The schematic layout of measurement apparatus

Observation Method

The observation began in 1988. Three components of normal strain produced on ground surface were observed. Steel piles(Outer diameter:75mm,Thickness:4mm) were driven on three points which correspond to vertics of a triangle with sides having 1m in length. Driving depth was about 70 cm. Earthquake-induced relative displacements between piles were directly observed by use of displacement transducers(DS-100:Tokyo Sokushin Co.Ltd,Weight:2.1kg). The observed results were divided by original length(1m),in order to calculate strains.

Distance between piles corresponds to gauge length,which is one of the most important elements to be considered for strain measurement. It must be determined by taking account of various factors. In this paper,gauge length is determined only from practical viewpoint such as maintenance of the apparatus, mechnical restriction of transducer and so on. Figure 2 shows the schematic layout of measurement apparatus. For purpose of inspecting properties of ground strains in the wide-spread area,same typed equipment was situated on the other site apart 16m from the site mentioned above. Observation on both sites began on June 2nd 1994.

Furthermore,in the observation site,three components piezo-electric accelerometers(PV-22:Rion Co.Ltd) were installed. Triggering of the signals is performed when ground acceleration exceeds a present threshold level(in this paper 1.0 gal). The signals from transducers are transmitted to the observation room,where,they are automatically digitalized with the sampling interval of 1/100sec by A/D converter. The recorder has a digital magnetic tape with a recording capacity of more than 1 hour. Timing information is internally generated,in addition,the absolute time is corrected hourly by utilizing the signal from N.H.K.(The Japan Broadcasting Corporation).

A general layout of seismometers as well as measuring device for strains is shown in Fig.3. A1,A2 and A3 indicate the locations of accelerometers. Accelerometers installed in A1 and A2 were damaged a few years after beginning of observation,and one situated on A3 also was spoiled on June 2nd 1994. In this paper,data from A3 indicate as acceleration of the site. After July 1994,servo-accelerometer (PCS-1025:Tokyo Sokushin Co.Ltd) was installed on A4. This is used for measuring acceleration and triggering. Strain-1 means measuring site of ground strain used from beginning of observation and Strain-2 is one situated later.

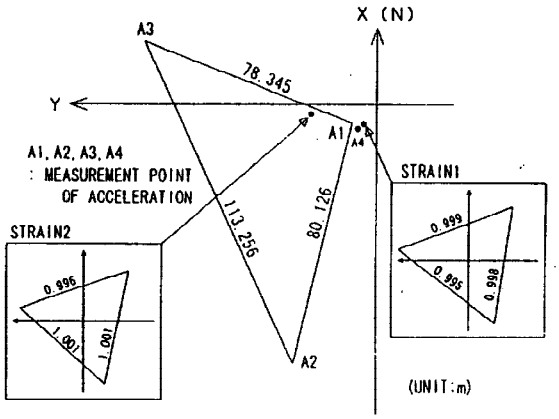

Fig.3 Layout of the observation site

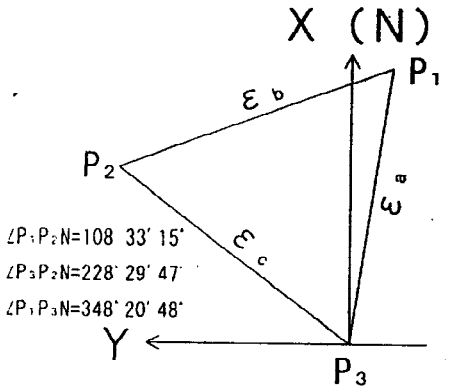

Fig.4 The coordinate system of Strain-1

EXAMINATION ON OBSERVED RESULTS

Results observed in the site Strain-1

A total of 119 earthquakes have been recorded. By using observation records of ground strains,two components of normal strains(ε_x, ε_y) and shear strain(γ_{xy}) were calculated for inspecting properties of strains(As indicated in Fig.4,direction of x-axis is corresponded to north). Figure 5 shows ground strains(ε_x, ε_y, γ_{xy}) of the observation result which was recorded on March 23 1995. Inspecting the results,phase angle between ε_x and ε_y seems almost π. Figure 6 shows time history of principal strains(ε_1, ε_2),max.shear strain(γ_{max}) and angle θ between direction of max. principal strain and x-axis. It is found that variation of θ is about 90° .

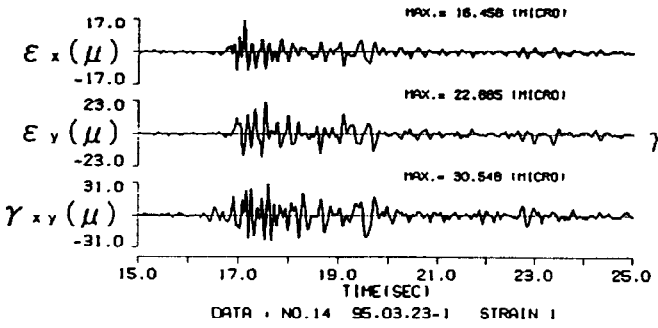

Fig.5 The time variation of ε_x, ε_y, γ_{xy}

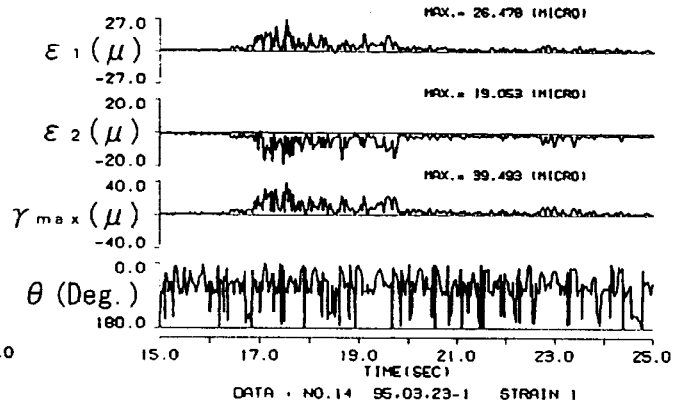

Fig.6 The time variation of ε_1, ε_2, γ_{max} and θ

Variation in every 1/100 second of Mohr strain circle were demonstrated in Fig.7. Coordinates of small black circle means(ε_x, $\gamma_{xy}/2$). Invesigating the results,the followings are obtained.

① When radius of Mohr circle shows minimum value, θ changes almost by 90° suddenly. On the other hand, θ is almost constant,when radius shows large value.

② During radius shows large value,Mohr circle contains original point of (ε , $\gamma/2$)plane.

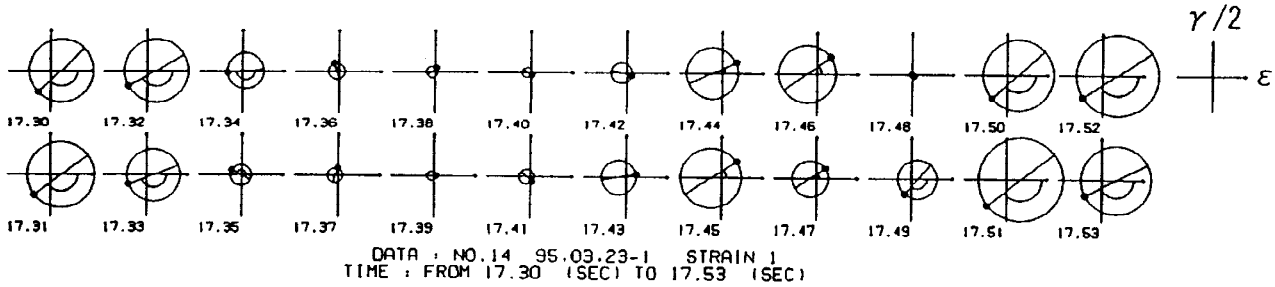

Fig.7 The variation of Mohr's strain circle

The aboves were investigated deeply in the following. Concerning ①,probability density of θ between maiximum principal strain and x-axis were calculated. An example is shown in Fig.8. Two peaks were found easily in probability density and difference of them is about 90° . As for all records,number of earthquakes is shown in abscissa and values of two peaks of θ were plotted on ordinate as shown in Fig.9. At a glance,direction of maximum principal strain is almost constant for all earthquakes.

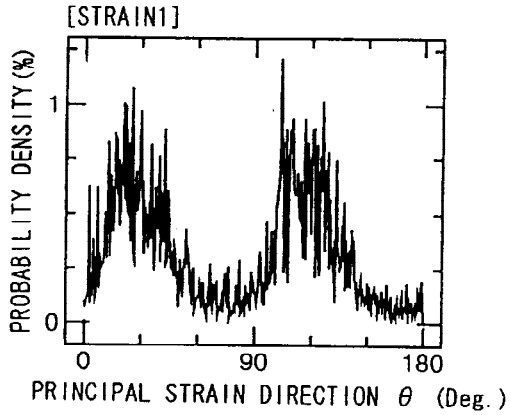

Fig.8 Probability density distribution of principal strain direction

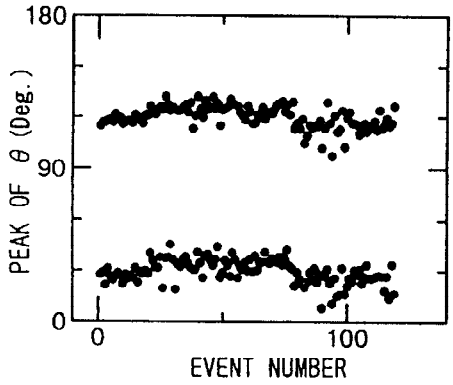

Fig.9 Relation between the peak of θ and the event number

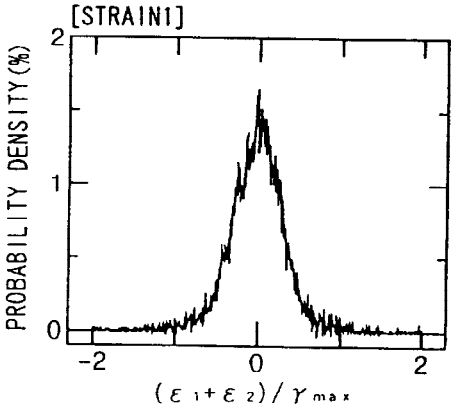

Fig.10 Probability density distribution of the ratio $(\varepsilon_1+\varepsilon_2)/\gamma_{max}$

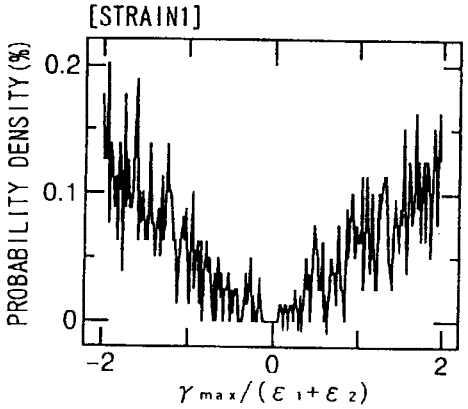

Fig.11 Probability density distribution of the ratio $\gamma_{max}/(\varepsilon_1+\varepsilon_2)$

Concerning②,probability density of sum of principal strains($\varepsilon_1+\varepsilon_2$)divided by max.shear strain γ_{max}, $((\varepsilon_1+\varepsilon_2)/\gamma_{max})$ during duration time are shown in Fig.10. Curve of probability density seems to have the peak at 0 which means pure shear state. In order to inspect the probability in which $\varepsilon_1=\varepsilon_2$,value of $(\gamma_{max}/(\varepsilon_1+\varepsilon_2))$ were calculated as shown in Fig.11. States which show pure dilatation condition were not able to find. In case of pure shear state,center of Mohr circle corresponds to the original point. The strain state shown in this case seems nearly pure shear condition. All other records have the same characteristics to this case.

Event number of earthquakes,maximum value of γ_{max} more than 3.5μ,maximum absolute values of principal strains(ε_1 or ε_2) and maximum value of acceleration in time history were listed in Table-1. Acceleration means resultant component calculating from two horizontal and vertical component.

Table1 The list of observation records

No.	Date	Time	Epicenter Region	Dis. (km)	Hypocenter Latitude Longitude	Depth (km)	M *1	Maximum Value ACCEL. (gal)	STRAIN(μ) *2 ε	γ
1	89.02.19	21:27:18	SOUTH WESTERN IBARAGI PREF.	11	36° 01.1' N 139° 54.5' E	55	5.6	83.5	13.4	24.9
2	90.08.05	12:36:59	EAST OFF IBARAGI PREF.	120	36° 24.1' N 141° 06.6' E	39	5.8	6.26	2.10	3.73
3	90.08.23	08:47:31	KUJUKURI COAST BOSO PENINSULA	77	35° 20.7' N 140° 23.8' E	50	5.4	6.96	2.68	4.21
4	90.10.06	23:33:26	SOUTH WESTERN IBARAGI PREF.	89	36° 29.1' N 140° 36.8' E	51	5.0	13.3	2.86	4.39
5	91.10.19	08:31:26	SOUTH WESTERN IBARAGI PREF.	18	36° 05.0' N 139° 55.2' E	59	4.3	19.1	2.21	3.86
6	91.11.19	17:24:16	MIDDLE CHIBA PREF.	36	35° 36.3' N 140° 01.5' E	81	4.9	14.7	1.87	3.59
7	93.05.21	11:36:46	SOUTH WESTERN IBARAGI PREF.	14	36° 02.5' N 139° 54.0' E	61	5.3	141.	21.9	40.6
8	93.10.12	00:55:40	FAR SOUTH OFF TOKAI	459	32° 01.3' N 138° 14.4' E	390	7.1	18.9	7.70	12.6
9	94.10.04	22:25:40	EAST OFF HOKKAIDO	1060	44° 22' N 147° 40' E	30	8.1	15.3	3.95 3.50	6.47 6.78
10	94.11.04	19:06:36	SOUTH WESTERN IBARAGI PREF.	17	36° 04' N 139° 55' E	59	4.5	35.5	4.18 3.16	7.07 5.99
11	94.12.28	21:22:12	FAR OFF SANRIKU	603	40° 27' N 143° 43' E	0	7.5	5.23	4.08 2.02	6.39 3.96
12	95.01.07	07:39:53	IWATE PREF.	533	40.3° N 142.4° E	30	6.9	5.31	2.42 1.81	3.94 3.55
13	95.01.07	21:34:52	SOUTH WESTERN IBARAGI PREF.	41	36° 17' N 139° 59' E	70	5.4	60.9	8.50 6.24	12.4 11.5
14	95.03.23	07:24:41	SOUTH WESTERN IBARAGI PREF	22	36° 06' N 140° 01' E	58	5.1	131.	26.5 13.6	39.5 24.4

*1 Magnitude by Japan Meteorological Agency
*2 upper STRAIN1 , lower STRAIN2

Inspecting values of strain listed in the Table-1 for each earthquakes,maximum value of γ_{max} is almost twice of one of principal strain. In Fig.12,relation between maximum value of γ_{max} and one of absolute values of principal strains is shown for all observation records up to now. This relation is formulated as follows(1) and endorses that pure shear state produced.

$$\gamma_{max} = 1.74 \times \max\left(|\varepsilon_1|, |\varepsilon_2|\right)^{0.97} \qquad \text{[STRAIN-1]} \qquad (1)$$

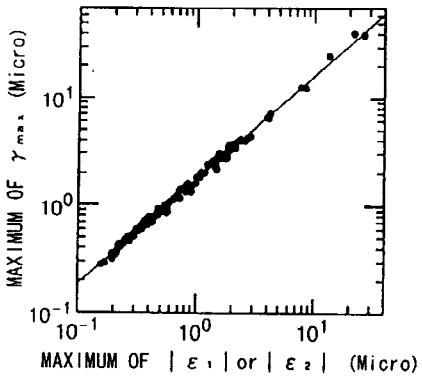

Fig.12 Relation between the max of γ_{max} and the max.of $|\varepsilon_1|$ or $|\varepsilon_2|$

Figure.13(14) shows relation between maximum value of maximum shear strain(absolute value of maximum principal strain) and maximum value of acceleration. Two figures show that strain is thought to be increased with increase of acceleration. Furthermore, maximum strain corresponding to a given acceleration increases with seismic magnitude.

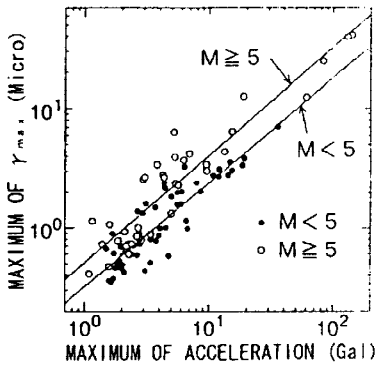

Fig.13 Relation between the max.of γ_{max} and the max.of acceleration

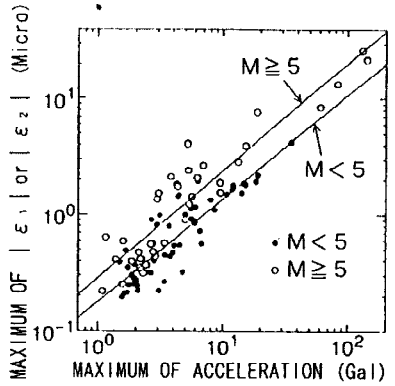

Fig.14 Relation between the max.of $|\varepsilon_1|$ or $|\varepsilon_2|$ and the max.of acceleration

Figure 15(16) shows relation between maximum value of maximum shear strain(absolute value of maximum principal strain) and epicentral distance. Value of strain corresponding to a given epicentral distance increases with seismic magnitude. Furthermore,attenuation of maximum strain seems to become gentle with increase in seismic magnitude. Similar indications(Nakamura *et al*,1982),(Okamoto,1984) were reported.

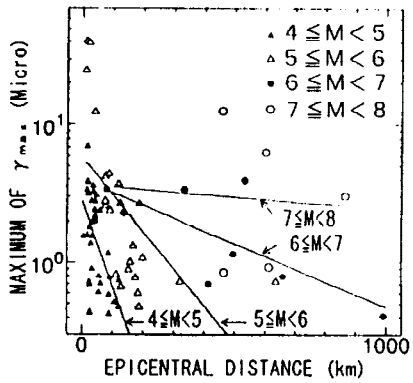

Fig.15 Relation between the max.of γ_{max} and Epicentral distance

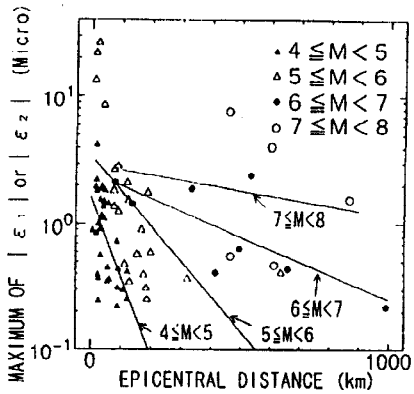

Fig.16 Relation between the max.of $|\varepsilon_1|$ or $|\varepsilon_2|$ and Epicentral distance

Comparison between records(Strain-1) and ones(Strain-2)

Same typed system(Strain-2) was installed and began earthquake obsevation on June 1994. Mohr strain circle calculated with a record observed in both sites were shown in Fig.17. As a whole,they don't seem to be similar each other. In the followings,properties of both data were examined.

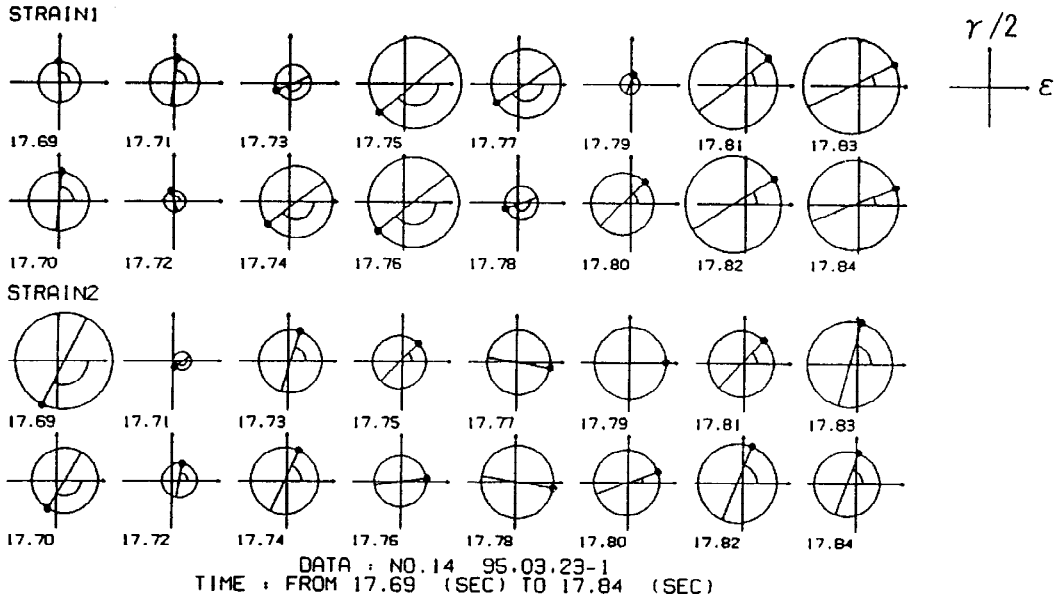

Fig.17 Comparison of Mohr's strain circle of strain-1 and strain-2

In the similar way as Fig.8 and Fig.9,probability density of angle θ was calculated and obtained two peaks were plotted as shown in Fig.18. White circles were obtained for strain-2,and directions of maximum principal strains seems to same as the case for Strain-1. Also,in the same manner as Fig.10,probability density of $((\varepsilon_1+\varepsilon_2)/\gamma_{max})$ were calculated and the result is shown in Fig.19. At a glance,this is similar to the one of strain-1.

Relation between maximum values of γ_{max} and one of absolute values of principal strains are calculated for all observation records of strain-2. The follow is the result.

$$\gamma_{max}=1.88\times\max\left(|\varepsilon_1|,|\varepsilon_2|\right)^{1.01} \qquad \text{[STRAIN-2]} \qquad (2)$$

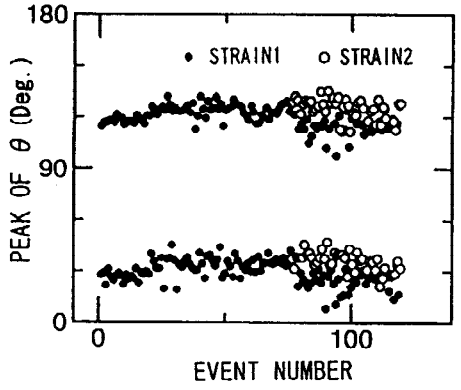

Fig.18 Relation between the peak of θ and the event number

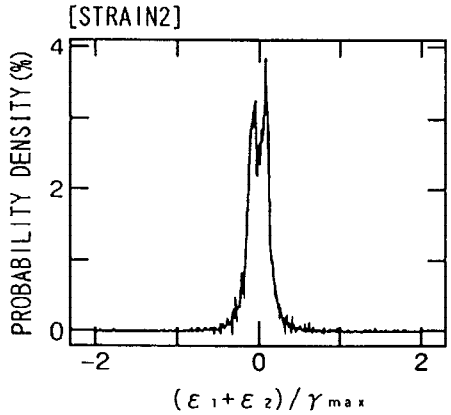

Fig.19 Probability density distribution of principal strain direction

As shown in the aboves,strain conditions on both sites seems to be quite similar.

CONCLUSIONS

Strains produced on the ground surface were observed during earthquakes and properties of strain condition were investigated. Gauge length is 1m,which seems to be too short from earthquake engineering point of view. Then,same typed apparatus is installed in new site,and began observation in two sites. Examining the results, the followings were obtained.

① Almost pure shear strain conditions were produced in the spread area.

② Directions of principal strains are almost same for all observation results.

③ Maximum values of maximun shear strains are nearly twice to ones of absolute principal strain during durarion time of records

④ Strain is thought to be increased with increase of acceleration. Maximum strain corresponding to a given acceleration increases with seismic magnitude.

⑤ Strain value correspoding to a given epicentral distance increases with seismic magnitude. Attenuation of maximum strain seems to become gentle with increase in seismic magnitude.

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