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The Array Observation of Ground Strains Induced by Earthquakes

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Summary

Observation of ground strains is quite important from viewpoint of seismic design of underground structures. Furthermore, ground strain investigation is helpful in examining the dynamic properties of the ground. In consideration of these factors, array observations of ground strains have been continued at five stations. At each station, one of which is at ground water level, three components of the normal strains were observed during earthquakes. In addition, vertical strain was observed at one station. The following conclusions were reached by examining the observed results. (1) At each station, an almost pure shear strain condition is apparently produced; (2) The principal strain directions predominate close to the specified direction and are independent of the earthquakes; (3) Strains at the ground water level are comparable with those at the ground surface; (4) The phase of strain is dependent on phase transition at stations within 17m of each other. However, such a tendency is hardly found between stations that are 50 to 100 m apart; (5) Vertical normal strains are comparable to ones induced at the ground surface. And normal strains can be predicted through monitoring vertical accelerations.

1. Introduction

It is fundamental to research ground motion during earthquakes when examining the seismic resistance of structures. The observation of ground accelerations and velocities, and the accumulation of seismograms showing powerful forces have play a very important part in achieving rational seismic design of structures.

Deformation of underground structures may be caused by deformation of the surrounding ground. Under such consideration, strains produced in underground structures such as submerged and subway tunnels, have been observed during earthquakes [1].

Thus, observation of ground strains is quite important from the viewpoint of rational seismic design of underground structures. Furthermore, ground strain seismograms are helpful in examining the dynamic properties of ground motion. With this in mind, we took on the challenge of directly observing ground strains during earthquakes [2], [3].

There are 6 components at any one point in the ground, or 4 components at the ground surface. In this paper, the 3 normal strains induced at the ground surface were observed. Steel piles were driven into 3 points, which correspond to vertices of a triangle with sides 1m in length. Relative displacements between the piles were directly observed by use of displacement transducers during earthquakes. Incidentally, gauge length of 1m is too short to examine seismic behavior of the ground. Therefore, the same type of measurement system was afterward installed at two observation sites 17m from each other. One of measurement systems for the three sites is set at the depth of the water level, for the sake of researching the influence of water-saturated soil upon strain conditions. One more site with same type of observation system was installed 100m from the site set first time.

The following conclusions were obtained from analysis of observation results. (1) The maximum shear strain is several times that the sum of principal strains. Therefore, an almost pure shear condition was considered to have been induced; (2) The principal strains were predominantly in specific directions; (3) Strains at the ground water level are comparable to those at the ground surface; (4) Strain is dependent on phase transition at stations that are within 17m of each other. However, such a tendency is hardly found between stations 100 m or more from each other.

Three observation stations set within 17m of each others were removed as a result of new campus constructions. One observation station was built 50m from the remaining site. This new station is located about 150m from the strain observation station built first.

There are four strain components on the ground surface. Thus, observation of vertical normal strain was taken on for the sake of investigation. In this paper, analyses of observation results are described.

2. Observation

2.1 Observation site

The observation site is located on the campus of Tokyo University of Science (Noda-shi, Chiba, Japan). It is situated at latitude 35°55′03″and longitude 139°54′57″. The topographical condition of the site is generally simple with the ground surface being almost flat. Typical soil properties obtained from a representative borehole are shown in Fig.1. The site consists of ground stratum about30m thick in which there are sandy layers.

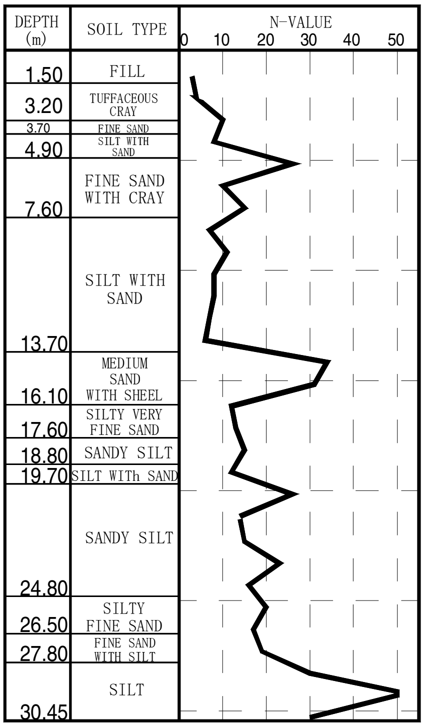

Fig.1: The result of SPT at the site

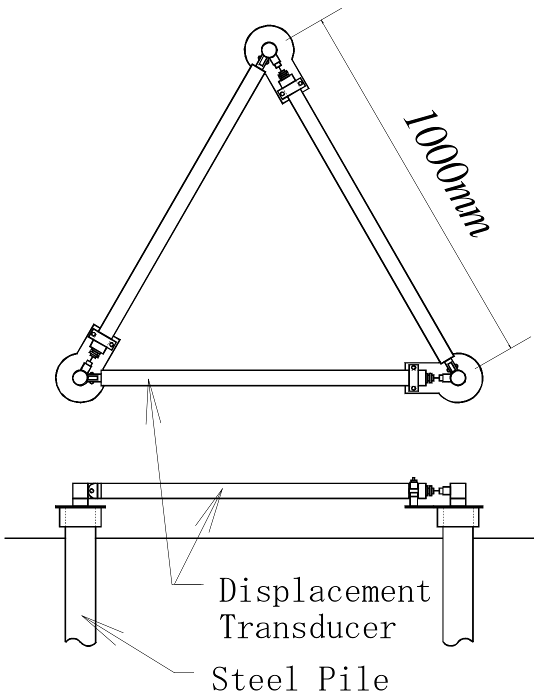

Fig.2:The schematic layout of apparatus

2.2 Observation method

Three components of normal strains induced at the ground surface were observed. Steel piles (Outer diameter: 75mm, thickness: 4mm, length: 70cm) were driven into the ground at three points mentioned above. Relative displacements between the piles were directly observed by use of a displacement transducer (DS-100: Tokyo Sokusin Co.Ltd.; Weight: 2.4kgf) during earthquakes. The observed results were divided by the original length (1m) in order to calculate the normal strains.

The distance between piles corresponds to the gauge length, which is one of most important elements to be considered for strain measurement, and various other factors must be taken into account. In this study, the gauge length was determined only from a practical viewpoint such as maintenance of the apparatus, mechanism of the transducer and so on. Figure.2 shows a schematic layout of the measurement apparatus. Vertical normal strain was observed as shown in Fig.3.

A borehole approximately 1m deep with a 10cm diameter is drilled. An anchor similar to a giant drawing pin was set at the bottom of the borehole. A steel bar is connected to the anchor, and a displacement transducer is attached to a steel plate connected to the ground surface by use of the anchors. Relative displacement was observed by measuring the displacement of the steel bar top by use of the transducer. The observed result is divided by the original length (1085mm).

Furthermore, at some observation sites, a three components servo-accelerometer or velocity seismograph was installed. Signals are triggered when the ground velocity exceeds a preset threshold. The signals from the transducers are transmitted to the observation room, where they are automatically digitalized with a sampling interval of 1/100 sec by an A/D converter. The data logger has a digital card with a recording capacity of more than 0.5 hr. Timing information is internally generated, and in addition, the absolute time is corrected by utilizing Global Positioning System (GPS).

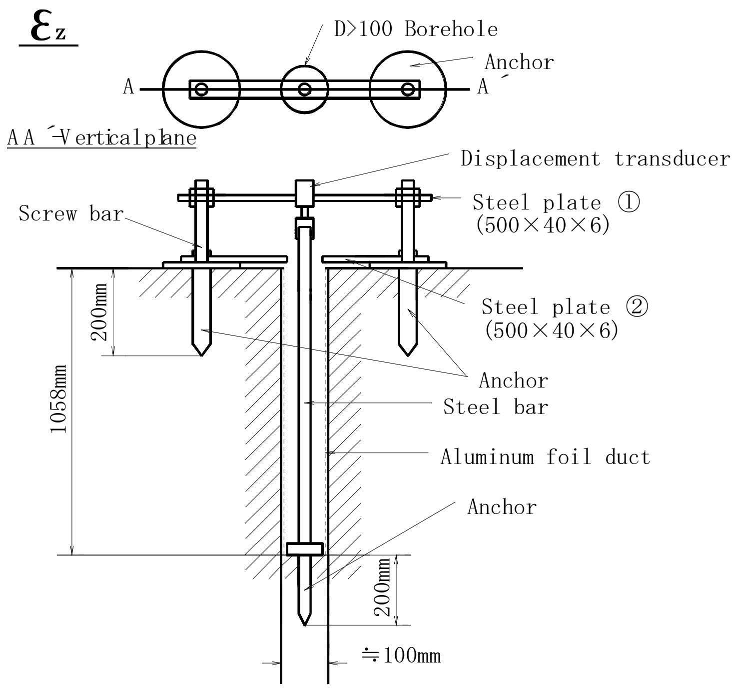

Fig.3:The schematic layout of apparatus

As shown in Fig. 4, Strain-1,-2,-3,-4 and -5 indicate observation stations mentioned in the proceeding paragraphs. Strain-1 was installed in May 1988, at the same site where accelerogram was first installed. Later, in its place, a velocity seismograph was used to measure ground motion. In order to ascertain the direction of the principal strain, the direction setting of the transducer was changed in 1998. Strain-2 was used to examine the results observed in strain-1 and was installed in June 1994. In order to examine the rationality of using piles in parallel to the displacement transducer, one transducer was installed by use of the anchor similar to a giant drawing pin. Strain-3 was installed in November 1996. A shallow well about 2m depth was excavated. The level of the well bottom corresponds closely to the surface of the ground water. A thin cylindrical shell was used to prevent the collapse of the surrounding soil. Strain-3 was installed at the surface ground of the well bottom. The time record of the water surface level is shown in Fig.5.

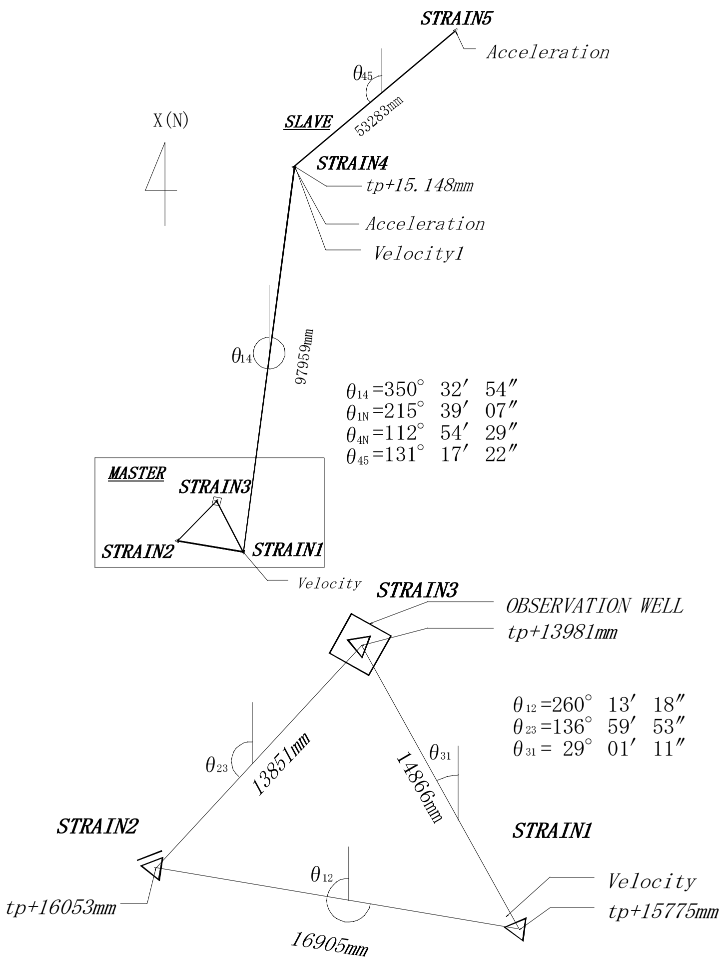

Fig.4: The survey of observation site

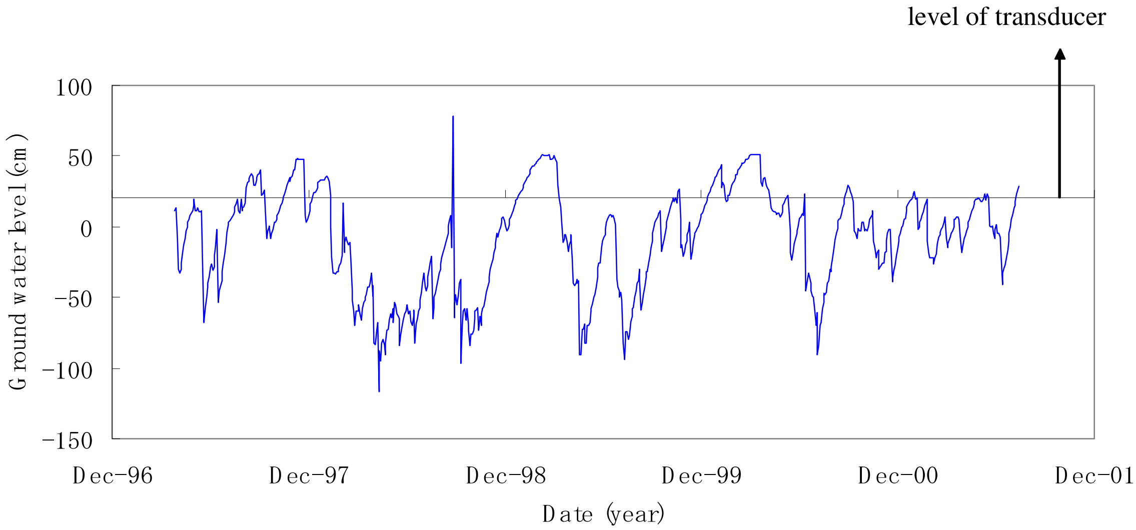

Fig.5: The time record of the water level

The three observation stations mentioned so far are located within a distance of 17m from each other. Furthermore, strain variations over more than 17m were inspected. Strain-4 located 100m from Strain-1, was installed in December 1997. Strain-1,-2 and-3 were removed due to new campus constructions in July 2001. Strain-5 was built in November 2001. This station is located 150m from Strain 1.

Observation of vertical normal strain was proposed and started in May 2003. Apparatus for observation was installed in Strain-4. Strain-1,-2 and -3 are located within 17m of each other, and their data signal are recorded using R-1 digital data logger(Samtac-600: Tokyo Sokushin Co. Ltd.). Strain-4 is located about 100m from Strain-1 and the signals are recorded using R-2, the same type data logger as R-1. R-1 and R-2 are synchronized via a ground cable. The array observation system is triggered, whenever the velocity output of the seismograph exceeds 0.03 kine. A GPS antenna is connected to R-1. After removing Strain-1,-2 and-3, only Strain-4 and -5 were used for observation. Logger R-1 was transferred to Strain-5 and R-1 and R-2 were synchronized. The GPS antenna was transferred to Strain-4.

3. Observation results and examination

3.1 An observation result

In Fig.6, time histories are shown for normal strain ε_x, ε_y and shear strain γ_{xy} calculated from observed strains. The x-axis coincides with the north.

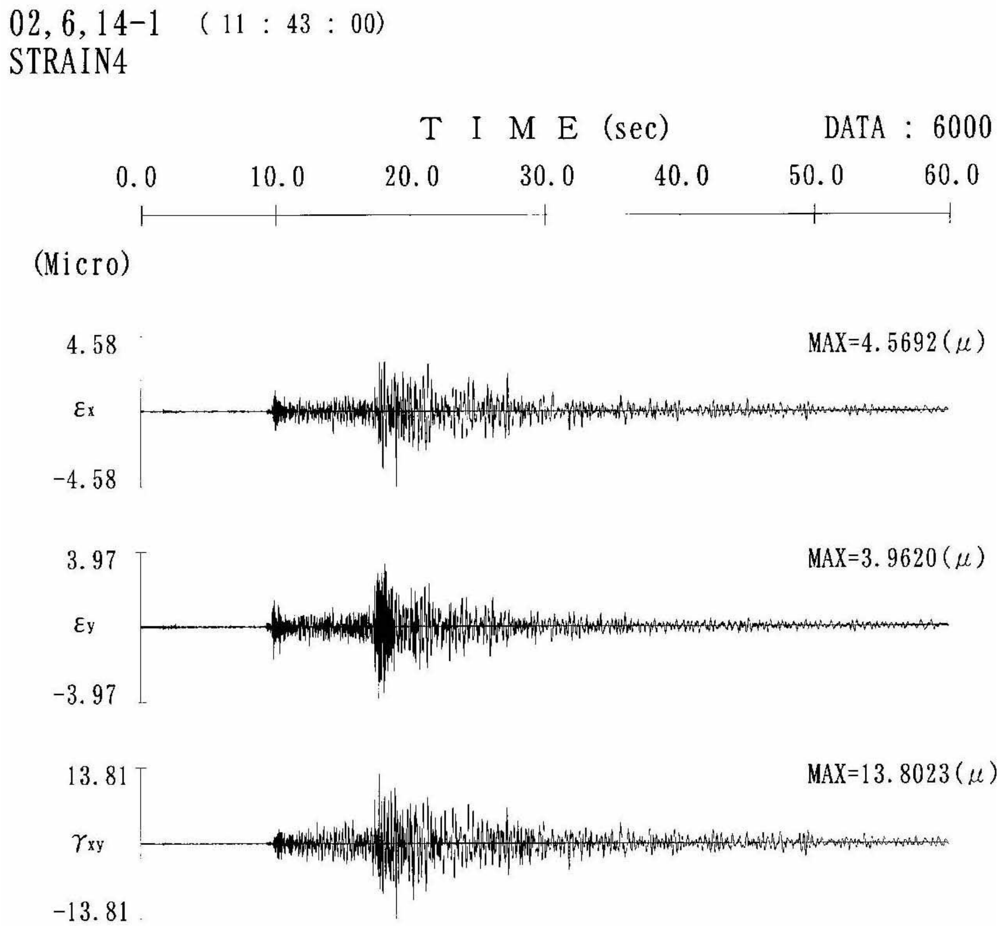

Fig.6: Example of observation result

Two normal strains are almost out of phase with each other, and their maximum time history is about three times one of γ_{xy}. For investigation, Mohr strain circles at intervals of 1/100 sec were demonstrated in Fig.7. Abscissa and latitude of black dots on circles indicate ε_x, $\gamma_{xy}/2$ respectively. Angle between radius through black dot and the ε-axis indicates double the angle between maximum principal strain direction θ and x-axis. Investigating these circles, the ground strain condition is found to be nearly pure shear and the maximum principal strain direction is considered almost constant during the phase condition. Probability density function of θ is shown in Fig.8. Because of the vibration state of the strain, maximum principal strain directions predominate in two directions, difference of which difference is 90°. Probability density function of the ratio between the sum of principal strain ($\varepsilon_x + \varepsilon_y$) and maximum shear strain γ are shown in Fig.9. This means strain state is an almost pure shear condition.

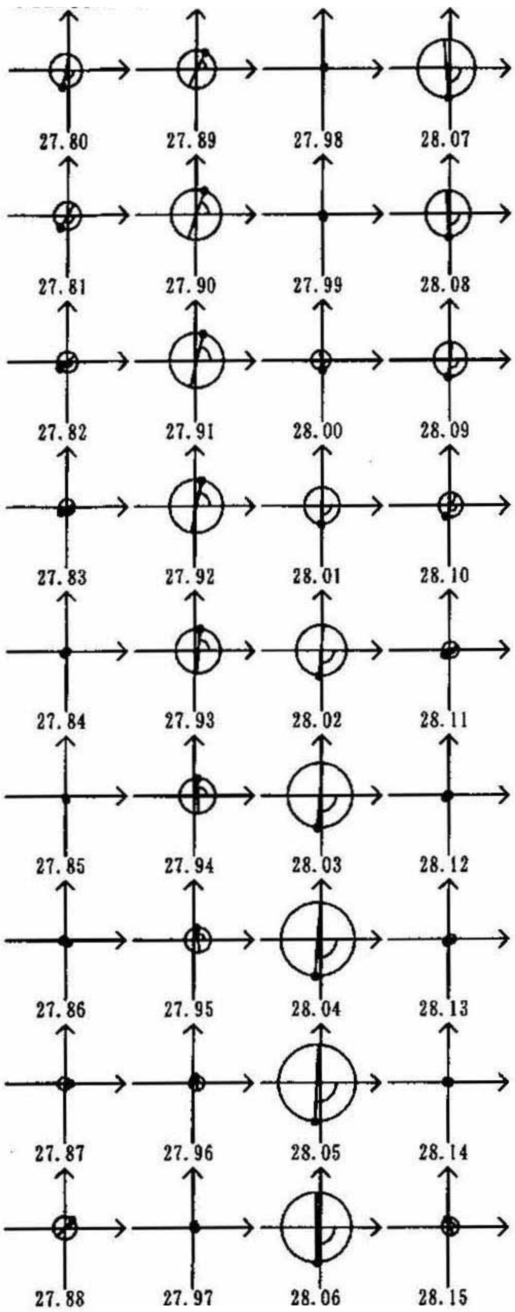

Fig.7: Mohr strain circles

3.2 Strain state in Strain-1,-2,-3,-4 and -5

Examining an example result observed in Strain-4, the strain state is an almost pure shear condition and the principal strain directions predominate in specific directions. All observation station results were investigated in the followings. Fig.10 shows the variation of Mohr strain circles with time intervals of 1/100 s between 10.00sec and 10.10 sec after starting the system. As shown in Fig.10, the principal strain directions are almost the same and the variation state of the circles are similar for Strain-1,-2 and -3. However, circle variations for Strain-4 are not the same as the others.

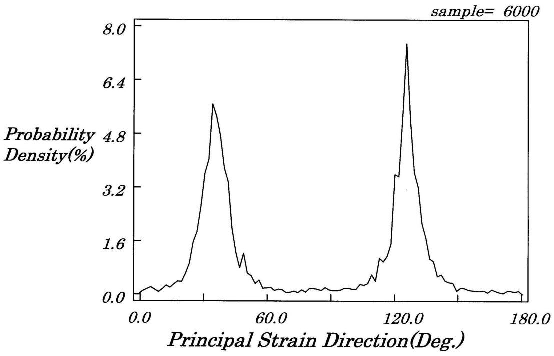

Fig.8: Probability density of principal strain direction

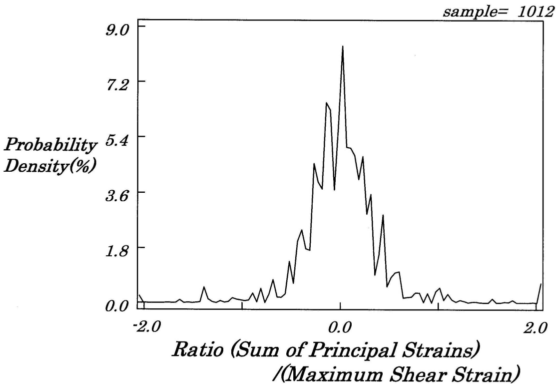

Fig.9: Probability density of ratio

Cross correlation functions for each time record were calculated to examine the phase shifting. Figure 11 shows the cross correlation function of the maximum shear strains. As shown in the figures, the following revealed that results from Strain-1,-2 and -3 depend on each other, while results from Strain-4 are independent of the others. This statement is also reasonable from the results of the strain circle mentioned above.

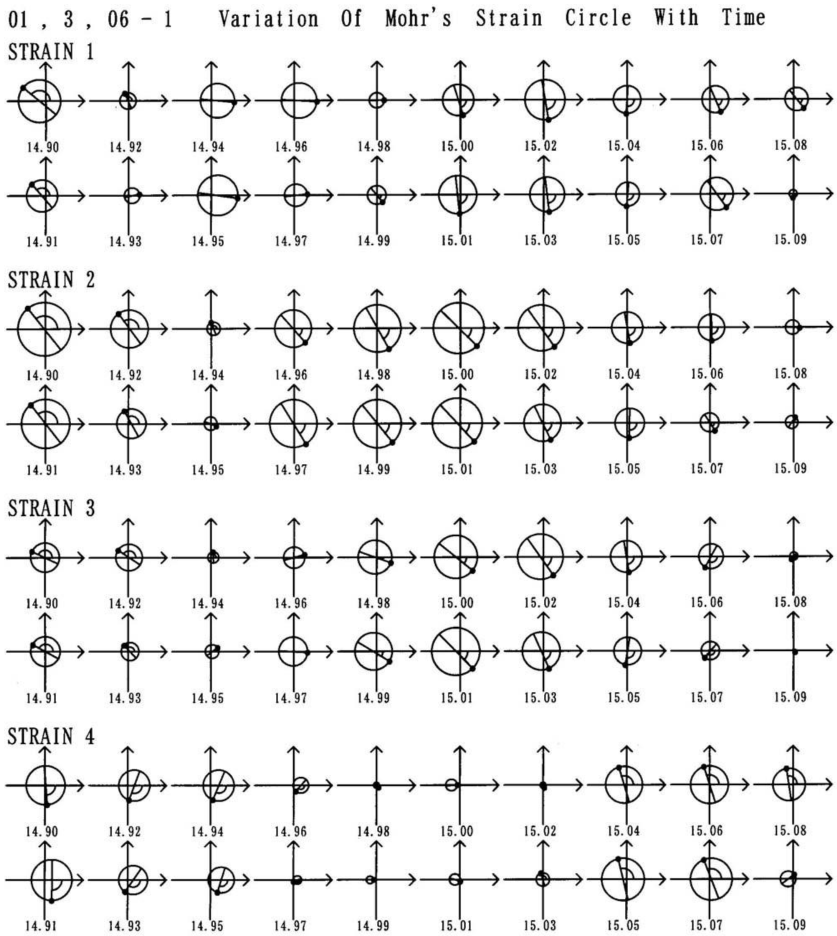

Fig.10: Mohr strain circles at each station

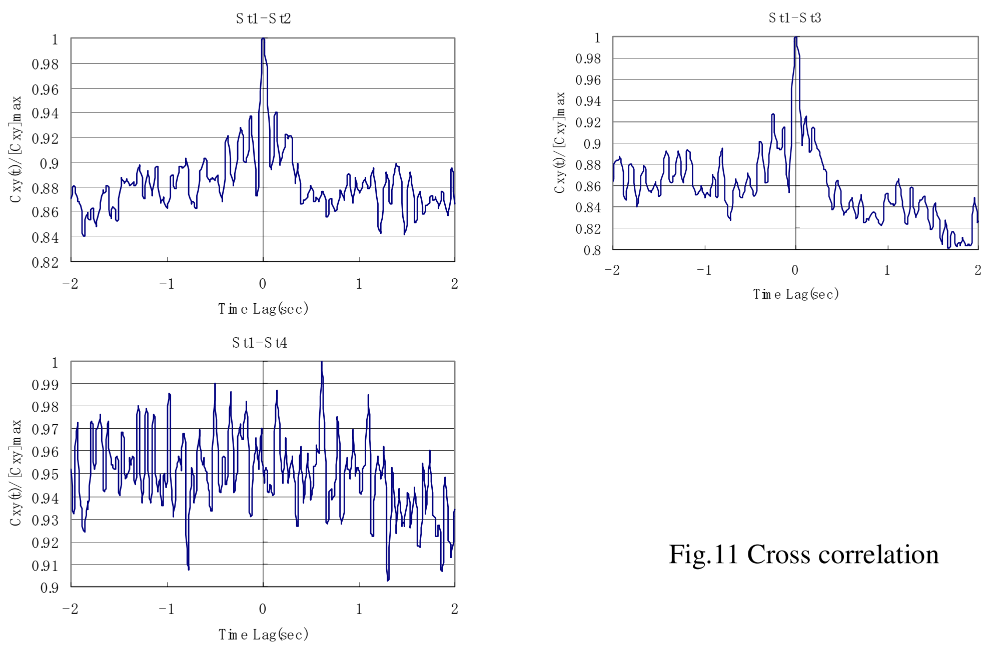

Fig.11 Cross correlation

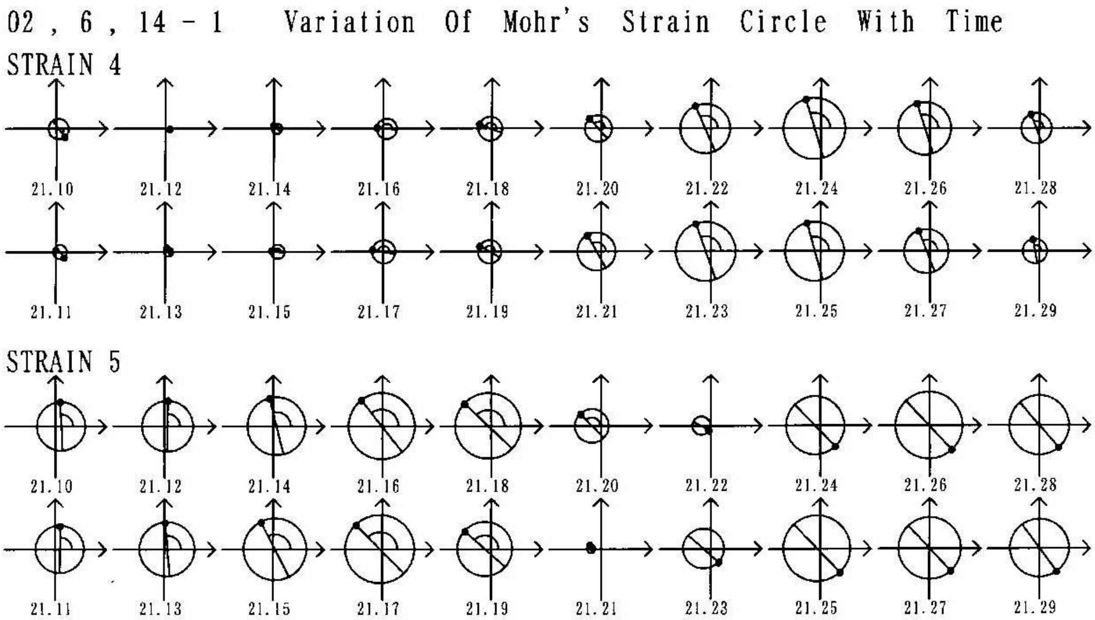

Fig 12-1 Mohr strain circles

The same examination was carried out on the results from Strain-4 and -5. Fig. 12 shows the variation of Mohr strain circles obtained in both stations as well as the cross correlation function. These indicate that the results from Strain-5 are independent of the ones from Strain-4.

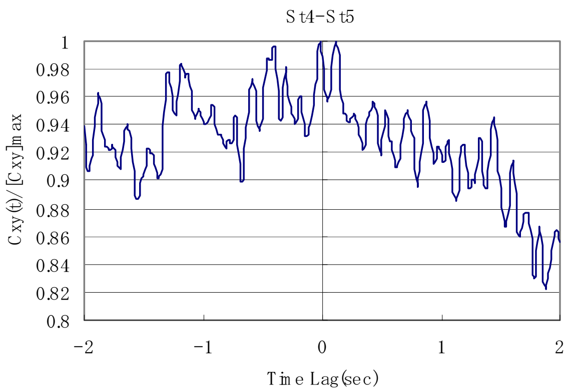

Fig.12-2 Cross correlation

For all observation records, the numbers of earthquake events are shown on the abscissa, and the values of two peaks of θ are plotted on the ordinate, as shown in Fig. 13. At a glance, the maximum principal strain directions predominate in specific directions for all earthquakes.

3.3 Strain amplitude

More than 450 earthquakes were observed. Maximum values for the time history of maximum shear strain, maximum absolute values for the principal strains, and velocity and acceleration are listed in Table-1. In each earthquake listed, the observed ground acceleration was more than 15 gal. After July 2003, the maximum time history values of vertical normal strain ε_z are included.

Table 1:The list of observation records

NO	date	time	Epicenter			Depth	M	Maximum Value				
			Location		Distance			Accel.	Velocity	Strain		
			Latitude	Longitude	(km)	(km)		(gal)	(kine)	ST.	ε (μ)	γ (μ)
1	1996/12/21	10:28:56	South Ibaraki Pref. 36° 06.0′ N	139° 52.0′ E	21	53	5.4	33.3	1.36	1 2 3	8.04 3.76 6.70	11.5 6.66 11.6
2	1997/3/23	14:59:08	South Ibaraki Pref. 35° 58.0′ N	140° 06.0′ E	17	72	5	18.2	1.08	1 2 3	5.26 2.41 6.82	7.66 4.52 11.8
3	1997/8/9	5:35:01	South Saitama Pref. 35° 49.0′ N	139° 30.0′ E	39	67	4.7	20.3	1.38	1 2 3	7.70 2.74 9.06	11.9 4.89 17.8
4	1997/11/2	7:13:13	South Ibaraki Pref. 36° 04.0′ N	139° 55.0′ E	17	51	4.3	18.0	0.651	1 2 3	2.80 1.80 3.73	4.82 3.39 7.00
5	1998/4/27	7:06:56	South Ibaraki Pref. 36° 06.0′ N	140° 48.0′ E	23	50	4.3	strain1 25.2 strain4 -	0.681	1 2 3 4	1.86 1.98 4.07 -	3.12 3.81 7.62 -
6	1998/6/8	8:02:48	South Ibaraki Pref. 36° 06.0′ N	139° 54.0′ E	20	50	4.4	strain1 15.0 strain4 24.2	0.293	1 2 3 4	1.38 1.17 1.61 0.867	1.98 2.13 2.71 1.59
7	1998/8/29	8:46:35	Tokyo Bay 35° 36.0′ N	140° 00.0′ E	35	70	5.4	strain1 26.3 strain4 29.6	1.23	1 2 3 4	3.09 2.43 5.98 2.30	5.02 4.36 11.2 4.47
8	1999/3/26	8:31:35	North Ibaraki Pref. 36° 30.0′ N	140° 36.0′ E	89	50	5.1	strain1 19.6 strain4 35.8	0.720	1 2 3 4	3.77 1.47 3.26 1.72	8.01 3.07 7.25 2.93
9	2000/11/17	23:22:16	South Ibaraki Pref. 36° 12.0′ N	140° 6.0′ E	35	50	4.1	strain1 25.5 strain4 39.6	0.476	1 2 3 4	5.43 1.81 5.11 3.39	8.87 2.47 9.19 6.30
10	2001/4/20	1:45:00	South Ibaraki Pref. 36° 6.0′ N	139° 48.0′ E	23	70	4.4	strain1 19.1 strain4 31.2	0.600	1 2 3 4	3.92 1.62 8.14 2.23	6.95 2.88 15.4 3.82
11	2001/5/31	8:59:00	South Ibaraki Pref. 36° 12.0′ N	139° 48.0′ E	33	50	4.6	strain1 18.5 strain4 33.7	0.573	1 2 3 4	4.59 1.75 6.94 2.95	8.09 3.08 13.9 4.39
12	2002/2/5	19:57:00	South Ibaraki Pref. 36° 18.0′ N	140° 00.0′ E	43	70	4.4	strain4 22.4 strain5 19.5	0.930	4 5	2.79 6.66	4.77 12.2
13	2002/2/12	22:44:00	Off Ibaraki 36° 36.0′ N	141° 00.0′ E	123	40	5.5	strain4 17.6 strain5 14.2	0.803	4 5	3.44 5.92	6.24 10.7
14	2002/6/14	11:42:00	South Ibaraki Pref. 36° 12.0′ N	139° 54.0′ E	31	50	5.2	strain4 86.7 strain5 74.6	3.01	4 5	8.92 18.9	15.4 31.6
15	2002/12/23	5:31:00	South Ibaraki Pref. 36° 12.0′ N	140° 00.0′ E	32	50	4.1	strain4 32.8 strain5 31.1	0.651	4 5	2.24 4.76	3.78 8.12
16	2003/2/1	3:15:00	South Ibaraki Pref. 36° 06.0′ N	139° 54.0′ E	20	40	3.8	strain4 19.7 strain5 19.7	0.473	4 5	1.96 2.23	3.84 4.34
17	2003/3/13	12:13:00	South Ibaraki Pref. 36° 06.0′ N	139° 54.0′ E	20	50	5.1	strain4 48.6 strain5 40.1	1.42	4 5	5.61 8.83	11.0 17.5
18	2003/5/6	23:48:00	South Ibaraki Pref. 36° 06.0′ N	139° 54.0′ E	20	40	4.3	strain4 39.0 strain5 31.2	1.02	4 5	3.89 7.34	6.86 13.3

19	2003/5/12	0:57:00	North Western Chiba Pref. 35° 48.0′ N 140° 06.0′ E	21	60	5.1	strain4 37.3 strain5 40.8	1.78	4 5	5.90 12.0	11.1 20.2
20	2003/5/26	18:24:00	Off Miyagi Pref. 38° 48.0′ N 141° 48.0′ E	361	60	7	strain4 21.7 strain5 16.0	1.77	4 5	5.67 8.54	10.2 14.5
21	2003/8/4	20:57:00	North Ibaraki Pref. 36° 30.0′ N 140° 36.0′ E	89	50	5	strain4 26.8 strain5 18.4	0.567	4 5 Z	3.19 3.71 3.74	5.55 6.93
22	2003/9/20	12:55:00	East Off Chiba Pref. 35° 06.0′ N 140° 18.0′ E	97	80	5.5	strain4 22.6 strain5 23.4	2.30	4 5 Z	7.94 14.0 4.27	14.4 24.8
23	2003/10/15	16:30:00	North Western Chiba Pref. 35° 36.0′ N 140° 06.0′ E	39	80	5	strain4 20.9 strain5 19.9	1.01	4 5 Z	5.43 7.70 4.80	10.1 14.8

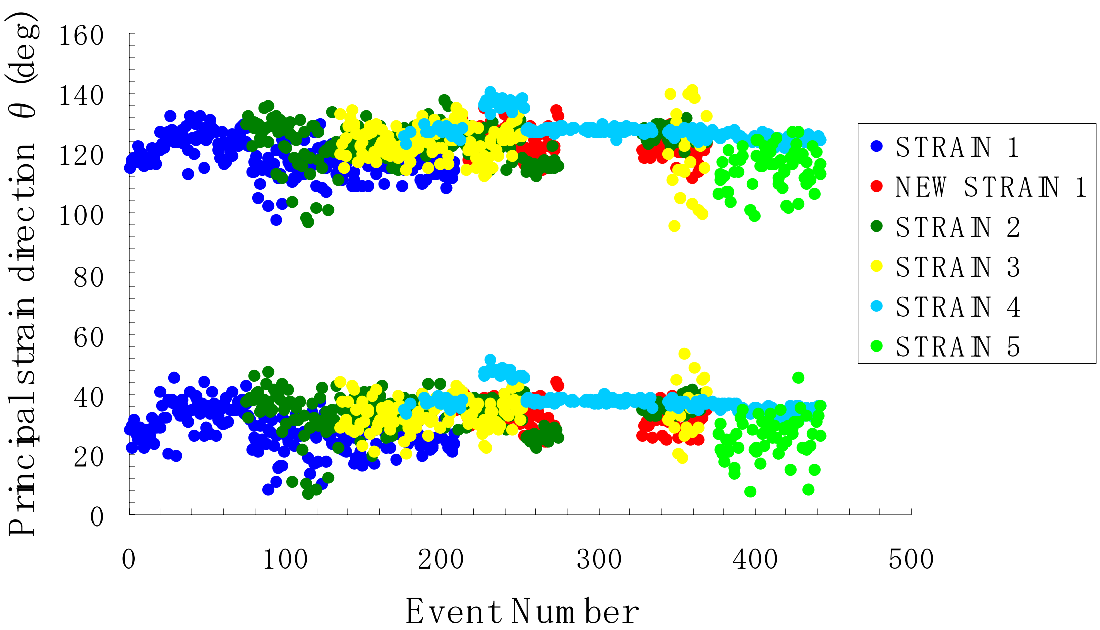

Fig.13: Principal strain directions of results

Fig. 14 shows relationship between maximum value of the time history of maximum shear strain and that of acceleration. At a glance, strain amplitudes observed in Strain-3 were comparable to the others. Similar results were obtained for the case of absolute value of principal strains.

3.4 Vertical normal strain

Vertical normal strain was observed in Strain-4. Time histories of normal strain ε_x, ε_y and ε_z and shear strain γ_{xy} are shown in Fig.15. At a glance, amplitudes of ε_z are comparable to those of other normal strains. At beginning of an earthquake, an abrupt amplitude increase is found only in ε_z.

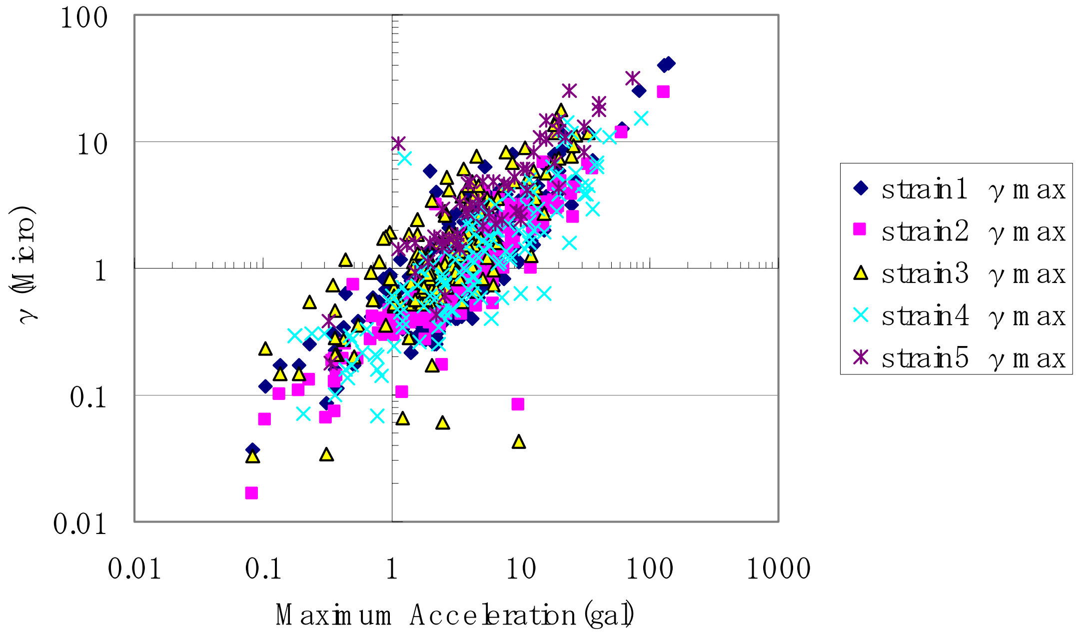

Fig.14: Relationship between maximum shear strain and acceleration

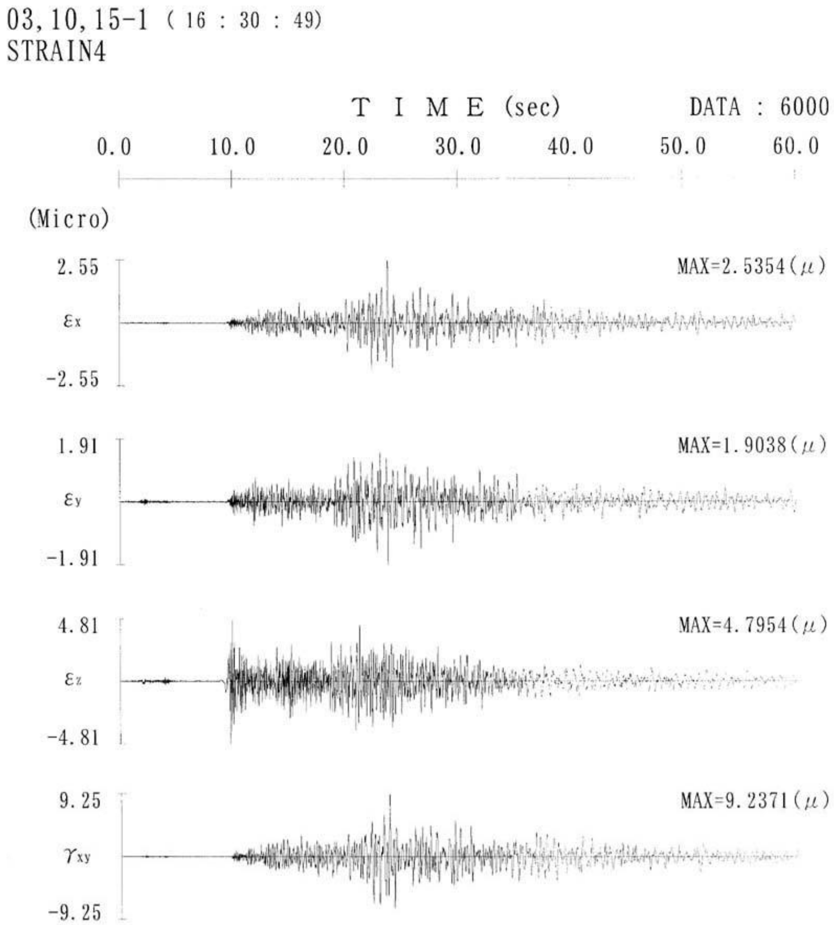

Fig.15: Example of observation result

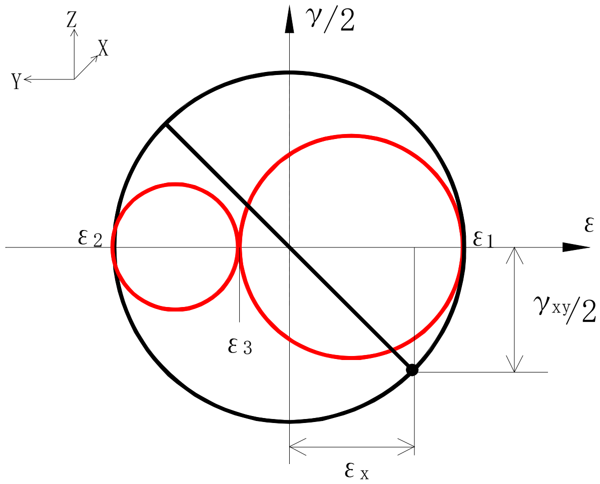

Fig.16: Mohr strain circle

Mohr strain circle is shown in Fig.16. The black circle indicates the strain condition on ground surface. ε_1 and ε_2 are principal strains on ground surface. ε_z is third principal strain$\varepsilon3$. Then, red colored circles are added due to ε_z. Strain circles are shown as Fig.17.

The relationship between normal strains and accelerations in same direction were inspected as shown in the example in Fig.18. ε_a, ε_b and ε_c are records observed at the ground surface. Accelerations are drawn in red. Investigating strain curves and acceleration ones, especially ε_z and vertical acceleration Az are found to be clearly out-phase. Then, the probability of ε_z and Az occurring out-phase was examined. Fig. 19 shows that the probability increases due to acceleration increase and at most rises to 80 %. Therefore, it would be possible to predict vertical normal strain by monitoring acceleration as shown in Fig.20.

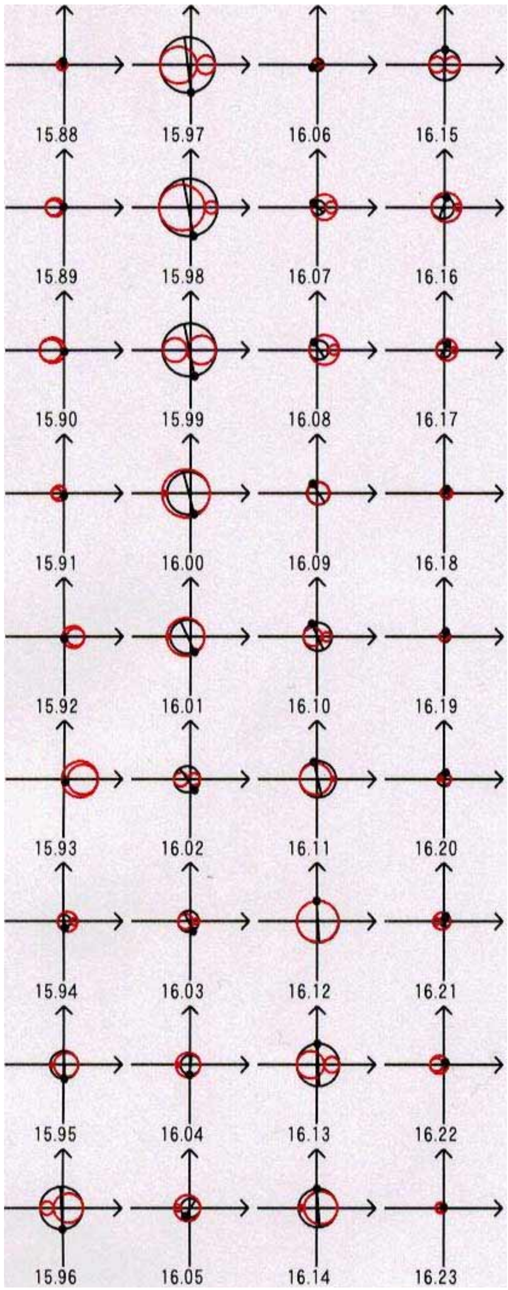

Fig.17: Variation of circle

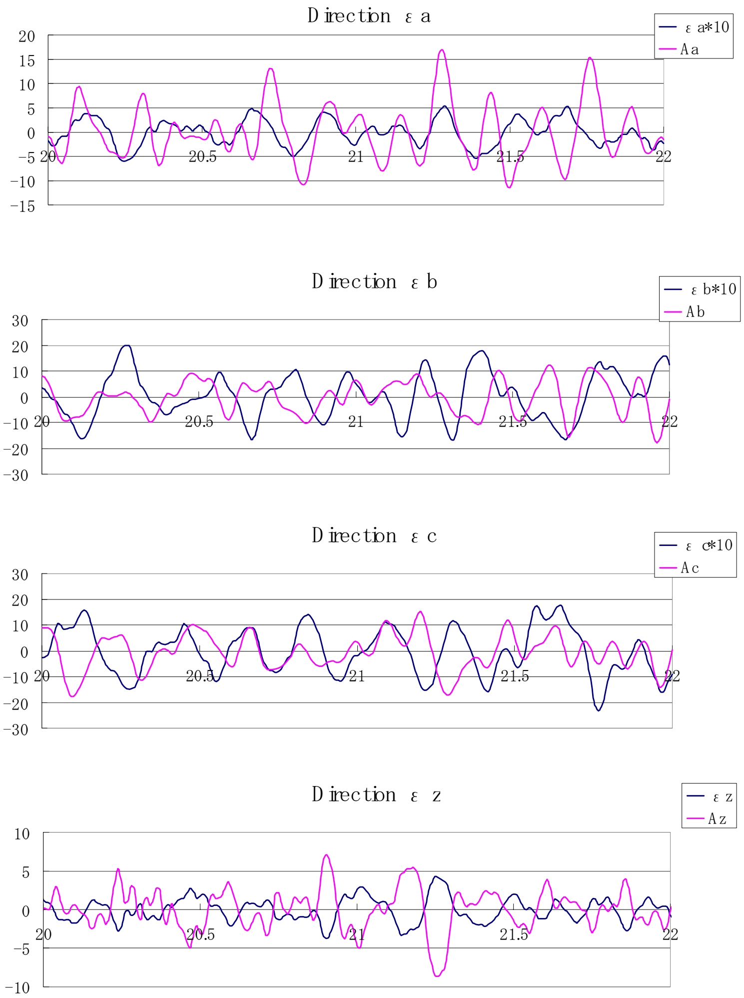

Fig.18: Comparison between strain and acceleration

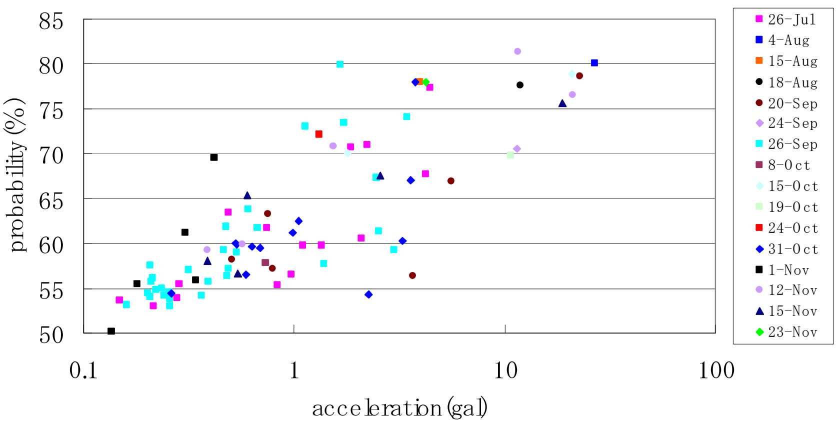

Fig.19: Probability increase due to acceleration

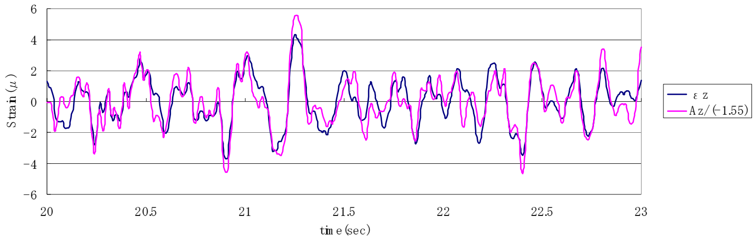

Fig.20: Prediction of vertical strain

4. Conclusion

Array observation of ground strain induced during earthquakes was carried out. Three normal strains at the ground surface were observed using 1m-long gauge. Five observation stations, Strain-1,-2,-3,-4 and -5 were utilized. In Strain-3, influence of ground water on strain was investigated. In Strain-4, vertical normal strains as well as three surface strains were observed. Strain-1,-2 and-3 are located within 17m of each other. The distance between Strain-1 and -4 is 100m and between Strain-1 and -5 about 150m. The following conclusions were reached.

(1) At each station, an almost pure shear strain condition is apparently produced; (2) The directions of the principal strains predominate close to the specified direction, and are independent of the earthquakes; (3) Strains at the ground water level are comparable to those at the ground surface; (4) Strain is dependent on phase transition at stations that are within 17m of each other. However, such a tendency is hardly found between stations 50 to 100 m from each other; (5) Vertical normal strains are comparable to ones induced at the ground surface. And normal strains can be predicted by monitoring of vertical accelerations.

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