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ARRAY OBSERVATION OF GROUND STRAINS INDUCED BY EARTHQUAKES

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SUMMARY

Observation of ground strains is quite important from viewpoint of rational seismic design of underground structures. Furthermore, ground strain seismograms seem helpful in examining the dynamic properties of the ground. With this in mind, array earthquake observations on the ground surface have been conducted. Four observation stations were used. And on each station, three components of the normal strains at the ground surface were observed during earthquakes. One of the stations is at ground water level. The following conclusions are reached by examining the observed results. (1)On each station, an almost pure shear strain condition seems to be produced (2)The directions of the principal strains predominate close to the specified direction and are independent of the earthquakes. (3)Further examination of the influences of ground water upon ground strains is needed. (4)The phases of maximum strain amplitude seem to be dependent on stations within 17m of each other. However, such a tendency is hardly found between stations 100m apart from each other.

INTRODUCTION

It is fundamental to research ground motion during earthquakes when examining the seismic resistance of structures. Observation of ground acceleration and velocities have been conducted and the accumulation of seismograms showing powerful forces has played a very important part in the rational design of structures.

Seismograms of large strains induced in such structures are quite fundamental for the rational seismic design of underground structures. Under such considerations, strains produced in underground structures such as subaqueous and subway tunnels, have been observed during earthquakes[Tamura,1975].

Deformation of underground structures may be caused by deformation of the surrounding ground. Then, observation of ground strains is quite important from the viewpoint of rational seismic design of underground structures. Furthermore, ground strain seismograms seem helpful in examining the dynamic properties of ground motion. With this in mind, the authors have tried to directly observe ground strains during earthquakes [Morichi,1996] [Morichi,1997].

Strains produced at any one point in the ground have 6 components, or 3 components at the ground surface. In this report, the 3 normal strains induced at the ground surface were to be observed. Steel piles were driven into three 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. Then, the same typed of measurement system was installed on an observation site 17m apart from the previous one, to research the ground strain variation.

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The following conclusions were obtained from that analysis. The maximum shear strain is a few times to sum of principal strains, therefore, an almost pure shear strain condition was considered to have been produced. The principal strain was predominantly in a specific direction.

Two more observation stations were placed in addition to the above-mentioned sites, and array observation of the ground strains was conducted for because information was wanted on ground strains over a wider area. Furthermore, the influence of the mechanical properties of soil on ground strains is to be inspected. In this study, the influence of soil saturated by ground water on strain conditions were researched.

2. OBSERVATION

2.1 Observation site

The observation site is located in the campus of Science University of Tokyo (Noda-shi,Chiba). It is situated at a latitude of 35°55•03•and a longitude of 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 with stratum were about 30m thick in which there are sandy layers.

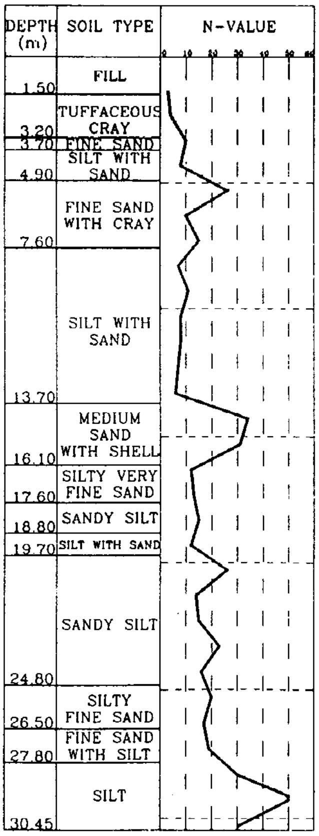


Fig.1 The result of SPT at the site

2.2 Observation method

Three components of the normal strains induced at the ground surface were observed. Steel piles (Outer diameter:75mm, Thickness:4mm) were driven into three points which correspond to the vertices of a triangle with sides of 1m in length. The depth to which the piles were driven was about 70cm. Relative dis-placements between the piles were directly observed by use of a displacement transducer (DS-100: Tokyo Sokushin 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 the most important elements to be considered for strain measurement. It must be determined by taking account of various factors. In this paper, the gauge length was determined only from a practical viewpoint such as maintenance of the apparatus, the mechanism of the transducer and so on. Fig.2 shows a schematic layout of the measurement apparatus. Furthermore, in some observation sites, a three-component servo-accelerometer or velocity seismograph was installed. Triggering of signals is performed when ground velocities exceed a present threshold (in this paper 0.03 kine). 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).

As shown in Fig.3, Strain1,2,3 and 4 indicate observation stations mentioned in the proceeding paragraphs. The numbers indicate the order of installation. Strain1 was installed in April 1988, at the same site as the accelerogram was first installed. Recently, in its place, a velocity seismograph has been used to measure ground motion. In order to ascertain the direction of the principal strain, as shown by the dotted line, the direction setting of the transducer was recently changed. Strain2 was used to examine the results observed in Strain1 and was installed in June 1994. In order to inspect the rationality of the setting method of using piles in parallel to the displacement transducer, one transducer was installed by use of the anchor different to the pile. Strain3 was installed in November 1996. A shallow well of about 2m depth was excavated. The level of the well bottom corresponds nearly to the surface of the ground water. A thin cylindrical shell was used to prevent the collapse of the surrounding soil. Strain3 was installed at the ground surface of the well bottom. A time record of the water surface level is shown in Fig.4. The three observation stations mentioned so far are located within a distance of 17m from each other.

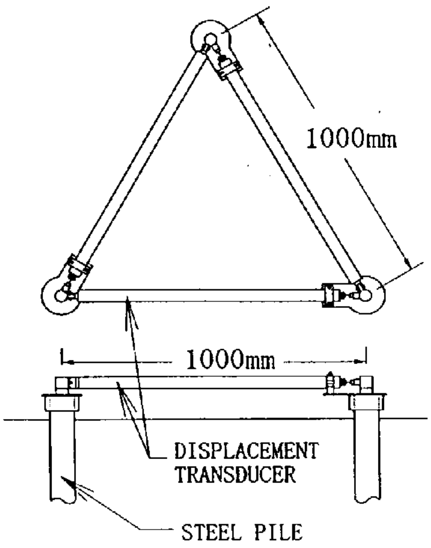


Fig2. The schematic layout of measurement apparatus

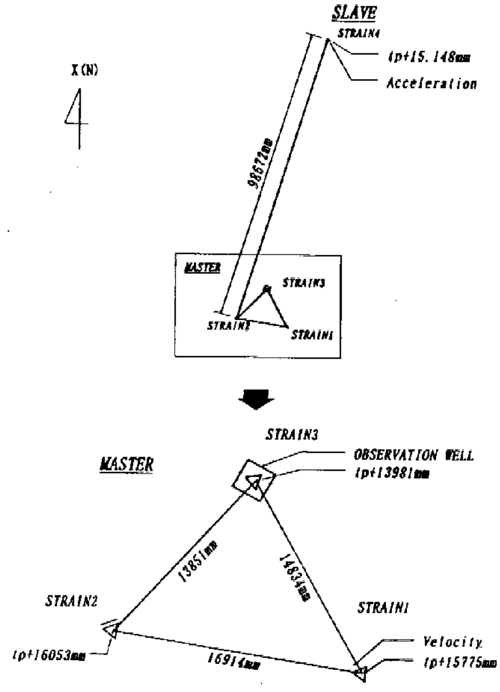


Fig.3 The survey of the observation site

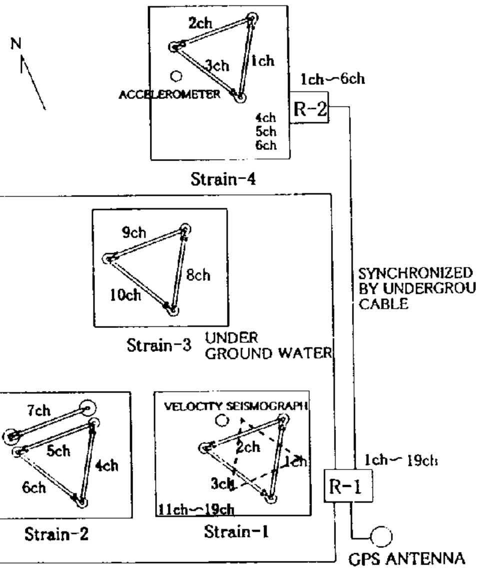


Fig.5 The outline of the observation system

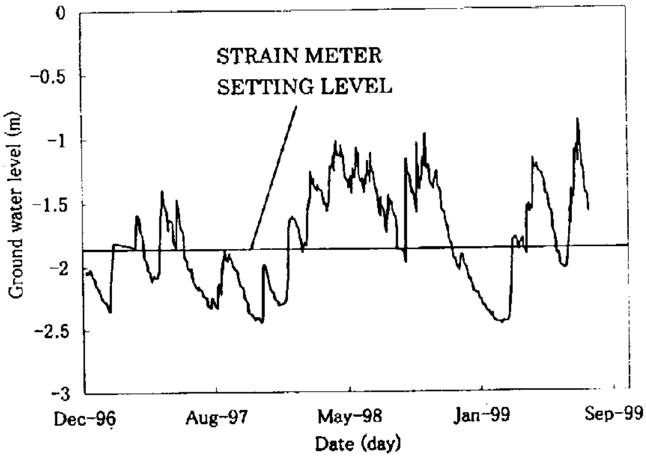


Fig.4 Ground water level

In this paper, strain variations over more than 17m were inspected. For such object, Strain4 was installed and located 100m from Strain1. An accelerograph is installed at the Strain4 station.

Fig.5 shows the aspect of the array observation system. Strain1, 2and 3 are located within 17m of each other, and their signals are recorded by a digital data logger (Samtac-600: Tokyo Sokushin Co. Ltd.) R-1. Strain4 is located about 100m from Strain1 and their signals as well as the accelerograph signals are recorded by R-2 the same type of data logger as R-1. R-1 and R-2 are synchronized via an underground cable. This array observation system is triggered, whenever the output of the velocity seismograph (channel11 or 12 or 13) exceeds 0.03 kine. A GPS antenna is connected to R-1. The topographical conditions of Strain1,2,3 and 4 are almost the same.

3.OBSERVED RESULTS AND EXAMINATIONS

The seismograms which contained the largest acceleration among earthquakes recorded perfectly in all stations (Strain1,2,3 and 4) were due to an earthquake of magnitude 5.4 which occurred in Tokyo Bay on August 29,1998. The distance from the epicenter was about 35km. Research on these array observation results was conducted as shown in the following.

3.1 Comparison of the strain amplitudes and phases

The invariants of the strain state are the maximum shear strain and the sum of the principal strains. Fig.6 shows a maximum shear strain, •max, and the sum of the principal strains,•, recorded at Strain1 between 20s and 23s after the start of observations.

At a glance, the amplitudes of the former are found to be several times that of the latter. The amplitudes for •max are nearly the same or in an inverse phase to the ones for • in this time interval. Fig.7 shows the time record of • max and • between 20s and 23s for all stations. The strain amplitudes observed at Strain3 located at ground water level are larger than the others. While the other obser-vation stations are on the ground surface, the ground around Strain3 was saturated with water. Such a condition seems to be the reason why amplitudes induced in Strain3 are larger than the others. As the solid line indicates, the phases for the peaks of •max recorded at Strain1,2 and 3 are almost the same. However, they are not in the same phase as results obtained from Strain4.

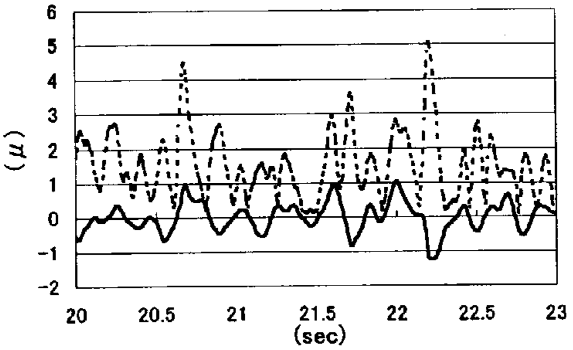


Fig.6 Time histories of γ max and Δ for Strain1

Cross correlation functions for each time record of the results were calculated to examine the phase shifting. Fig.8 shows the cross-correlation function of the maximum shear strain and the sum of the principal strains. As shown in the figures, the following revealed that results from Strain1, 2 and 3 depend on each other, while results from Strain4 are independent of the others.

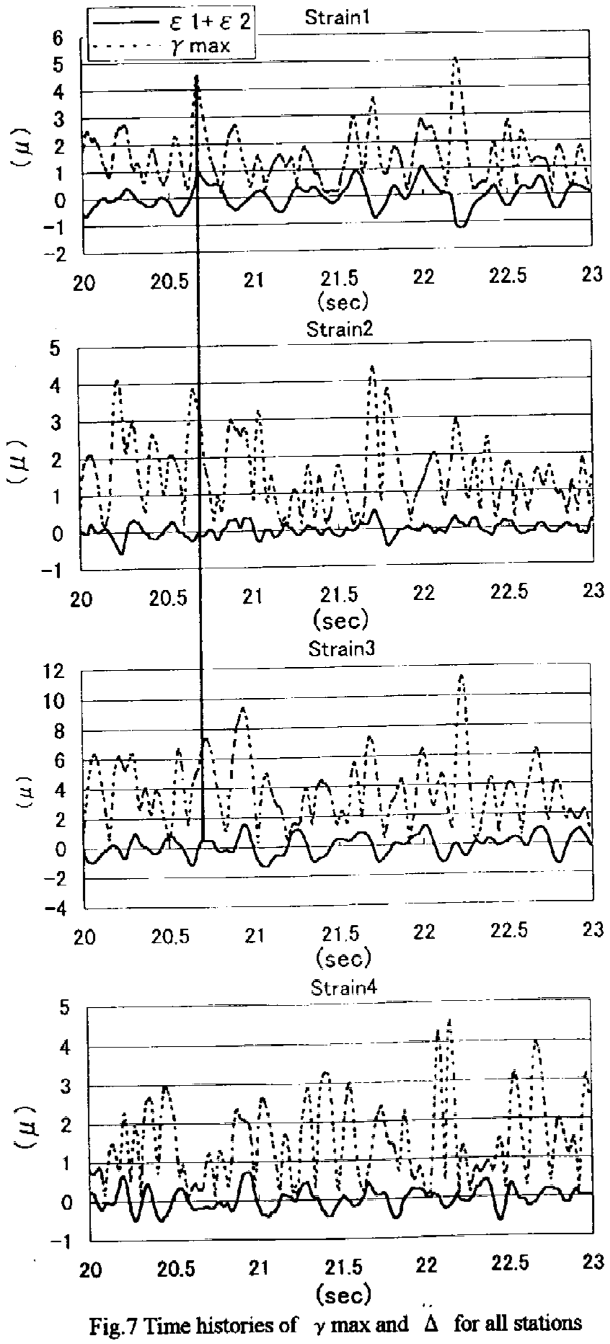
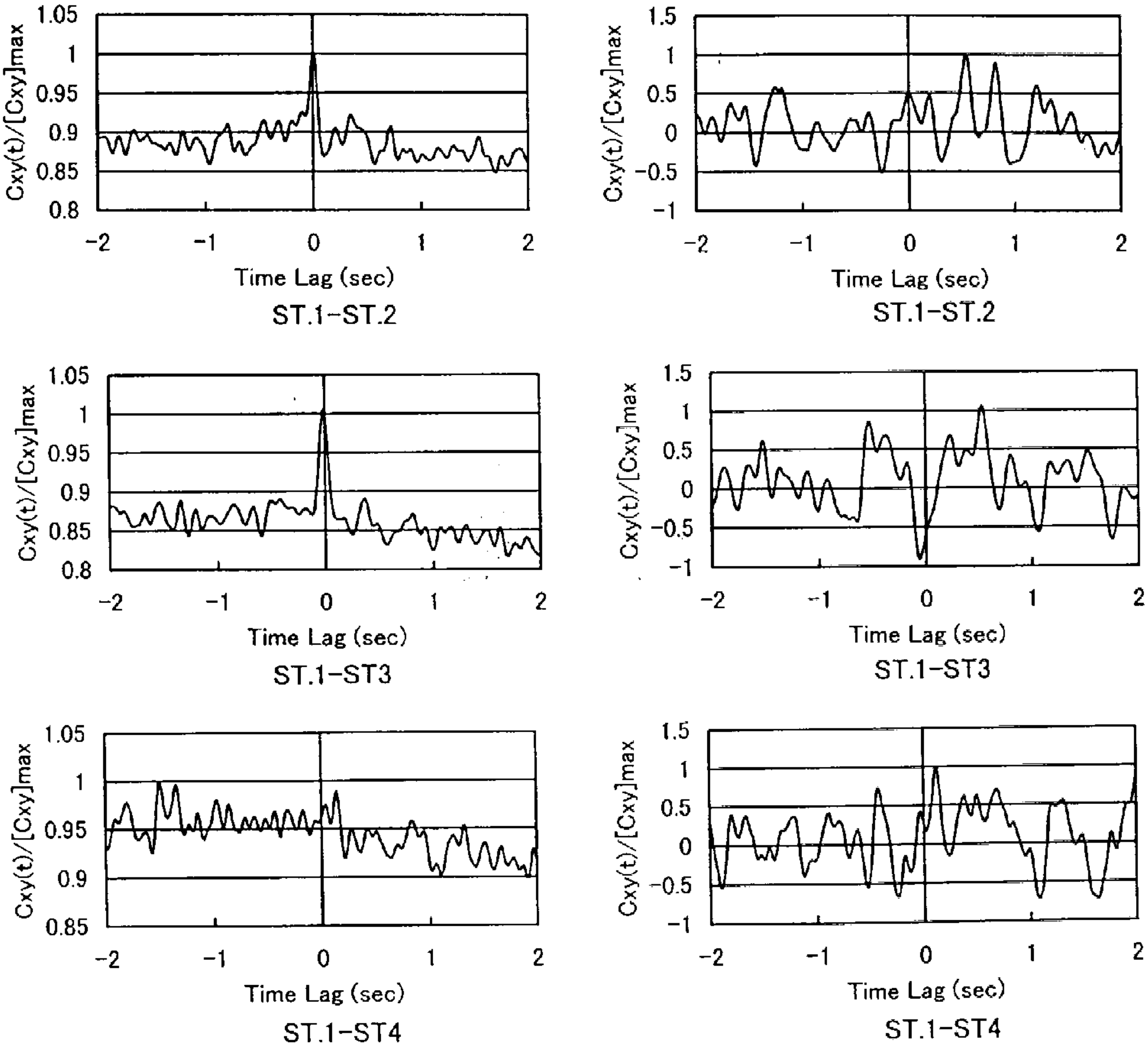


Fig.7 Time histories of γ max and Δ for all stations

3.2 Directions of the principal strains

Examinations of the direction of the principal strains was conducted. Fig.9 shows the probability density of the direction of principal strains obtained in Strain1 during the period in question in time intervals of 1/100s. Similar results were obtained for other stations. The vertical lines indicate the variation width of the direction of the principal strains obtained from all earthquakes recorded up to now. That means, the directions of the principal strains are independentof the earthquakes and are specific. Fig.10 shows the variation of Mohr's strain circles with time intervals of 1/100s between 20.00s and 20.19s after starting the system. The X-axis coincides with the north. The direction of the Y-axis is obtained by counterclockwise rotation 90°from the X-axis. Let us assume that•indicates the normal strain and •indicates the shear strain. Then, the coordinates of the black circle point are (•x,•/2). As shown in Fig.10, the directions of the principal strains are almost the same and the variation states of Mohr's circles are similar for Strain1,2 and 3. However, circle variations for the results of Strain4 are not the same to the others. This trend is reasonable from the viewpoint of the maximum strain variations mentioned in the previous section.



ST.1-ST.2 ST.1-ST.2

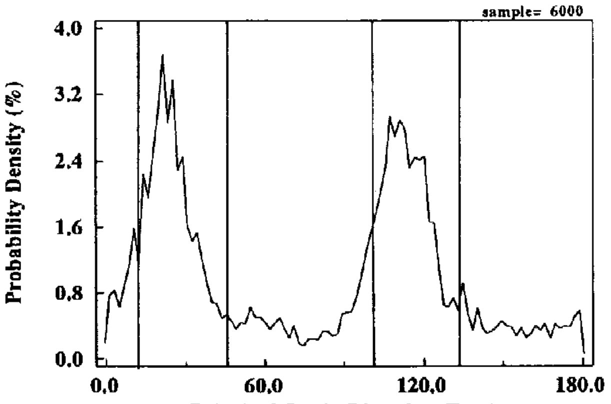
ST.1-ST3 ST.1-ST3

ST.1-ST4 ST.1-ST4

Fig.8 Cross-correlation functions for γ max and Δ

3.3 On all observed results

Array observations of strains induced on the ground surface during earthquakes have been conducted. Observations were conducted at four stations, of which three are about 17m apart from each other and the fourth is 100m from the others. Three components of normal strains were observed in each station, and ground motion was observed in the same stations. Examining the results, the followings were concluded. The directions of the principal strains obtained from each station were predominantly in the same direction. The amplitudes of the maximum shear strains are several times to the sum of the principal strains. For this reason, nearly pure shear conditions seem to be produced. The results observed from the three stations within 17m of each other show fairly dependant behavior. Such a tendency is hardly found with the results obtained from the station 100m apart from the others.



DATA : 98,8,29-1 STRAIN 1 TIME from .01 to 60.00 (sec)

Fig.9 Probability density for Strain1

The maximum values for the maximum shear strain, maximum absolute values for the principal strains, and the maximum values of velocity and acceleration of more than 10gal in the time record were listed in Table1. Acceleration and velocity are the resultant components calculated from the horizontal and vertical components. Event numbers with an attached (•) indicate earthquakes in which the strain amplitude observed on Strain3 was larger than the others. However, for the same earthquakes, such a trend was not found. In these cases, the amplitudes of the strain obtained from each station do not seem to differ much.

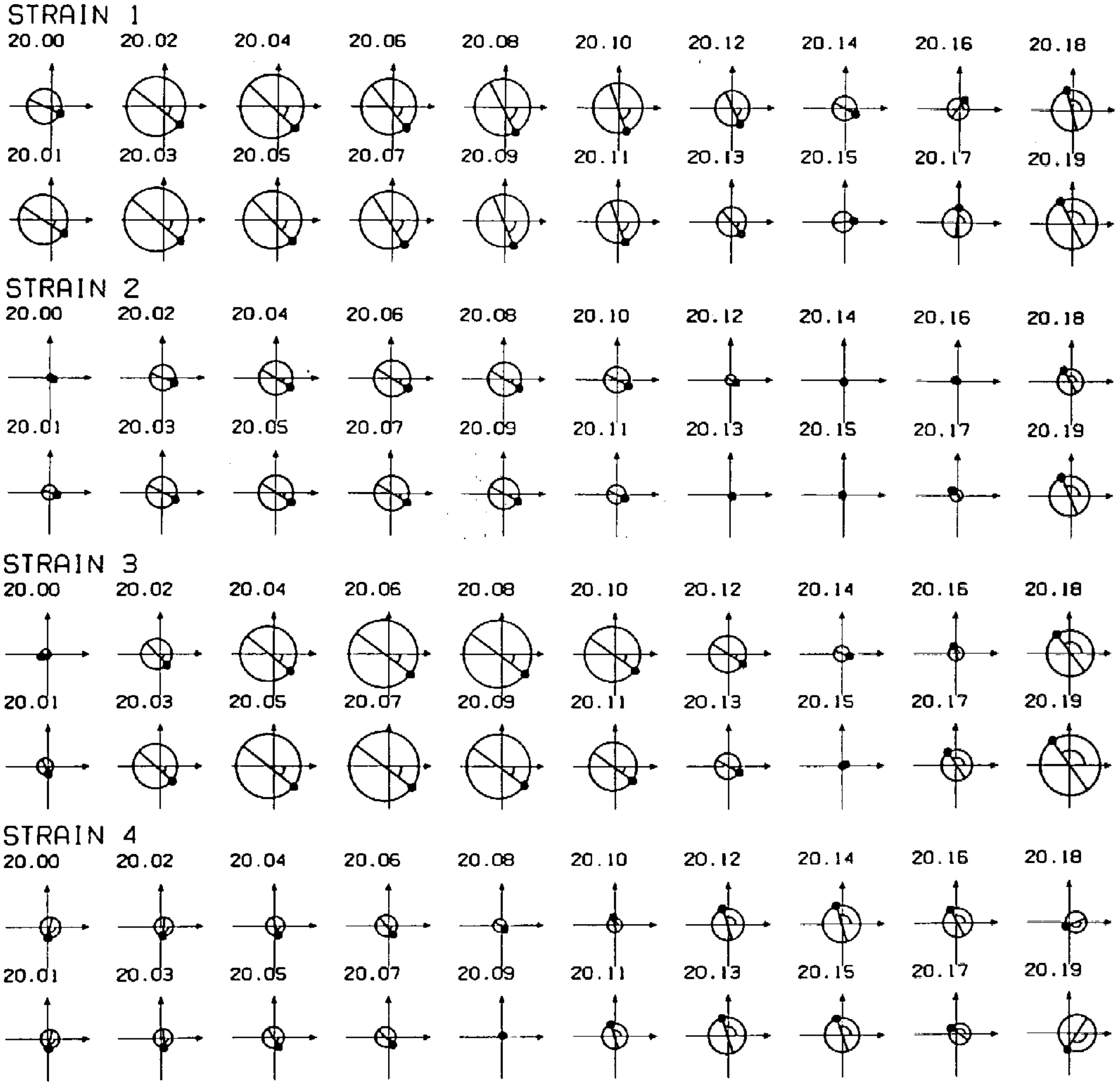


Fig.10 Mohr's strain circles (Date: 1998,8,29 Data: 20.00~20.19sec)

4. CONCLUSIONS

We conducted array earthquake observations on the ground surface using four observation stations. Three normal strain components were observed on the ground surface during earthquakes. The gauge length was 1m. One station is at ground water level which is 2m below ground level. Examining the observed results leads to the following conclusions. •On each station, the amplitudes of the maximum shear strain was several times that of the sum of the principal strains. Thus, an almost pure shear strain condition seems to be produced. •The directions of the principal strains are predominantly in an almost specific direction and are independent of the earthquakes. •Further examinations of the influence of ground water on ground strains is needed . •The phases of the maximum strain amplitude of stations 17m apart from each other seem to be dependent. However, such a tendency is hardly found in the station 100m apart from others.

Table.1 Observation earthquakes

NO.	DATE / TIME		EPICENTER			DEPTH (km)	M	MAXIMUM				
	DATE	TIME	HYPOCENTER		DISTANCE (km)			ACC. (gal)	VEL. (kine)	STRAIN		
			LATITUDE	LONGITUDE						ST.	ε (μ)	γ (μ)
1*	1996/12/21	10:28:56	South Ibaraki		21	53	5.4	33.33	1.358	1	8.042	11.499
			36° 06.0′ N	139° 52.0′ E						2	3.763	6.664
										3	6.701	11.59
2*	1997/3/23	14:59:08	South Ibaraki		17	72	5	18.24	1.077	1	5.258	7.664
			35° 58.0′ N	140° 06.0′ E						2	2.412	4.516
										3	6.816	11.756
3*	1997/8/9	5:35:01	South Saitama		39	67	4.7	20.27	1.376	1	7.702	11.885
			35° 49.0′ N	139° 30.0′ E						2	2.737	4.886
										3	9.059	17.849
4*	1997/9/8	8:40:56	Tokyo Bay		41	108	5.1	10.92	0.708	1	2.184	3.574
			35° 33.0′ N	140° 00.0′ E						2	1.74	3.178
										3	4.735	8.779
5	1998/1/2	6:47:02	South Ibaraki		13	48	3.5	master	high	1	1.054	1.622
			36° 02.0′ N	139° 55.0′ E				12.14	0.277	2	0.531	0.989
								slave	low	3	0.76	1.263
								14.87	0.274	4	0.39	0.637
6*	1998/3/8	13:47:00	South Ibaraki		23	40	4.7	master	high	1	1.598	2.209
			36° 06.0′ N	139° 48.0′ E				13.127	0.366	2	1.201	2.216
								slave	low	3	1.862	3.511
								–	0.364	4	–	–
7*	1998/4/9	17:46:15	Off Fukushima		146	90	5.4	master	high	1	1.8793	2.9503
			36° 54.0′ N	141° 00.0′ E				12.811	0.4431	2	1.4507	2.6321
								slave	low	3	2.6341	4.3407
								–	0.4387	4	–	–
8*	1998/4/26	7:38:16	East off the Izu Penisular		126	10	4.9	master	high	1	0.1697	0.3111
			35° 00.0′ N	139° 06.0′ E				1.0442	0.0575	2	0.197	0.3653
								slave	low	3	0.4168	0.7129
								–	0.0573	4	–	–
9*	1998/6/8	8:02:48	South Ibaraki		20	50	4.4	master	high	1	1.3816	1.9848
			36° 06.0′ N	139° 54.0′ E				15.049	0.2927	2	1.1699	2.13
								slave	low	3	1.6097	2.7125
								24.243	0.2871	4	0.8666	1.587
10*	1998/8/29	8:46:35	Tokyo Bay		35	70	5.4	master	high	1	3.0927	5.017
			35° 36.0′ N	140° 00.0′ E				26.326	1.2305	2	2.4277	4.3644
								slave	low	3	5.9821	11.209
								29.568	1.3002	4	2.3043	4.4711
11*	1998/11/8	21:41:03	Tokyo Bay		36	80	4.9	master	high	1	2.0575	3.7423
			35° 36.0′ N	140° 00.0′ E				15.803	0.6008	2	1.8176	3.2978
								slave	low	3	2.7894	5.6799
								1.1851	0.5964	4	–	–
12	1999/3/26	8:31:35	North Ibaraki		89	50	5.1	master	high	1	3.7667	8.0087
			36° 30.0′ N	140° 36.0′ E				19.624	0.7196	2	1.4675	3.0683
								slave	low	3	3.26	7.2503
								35.849	0.7216	4	1.7164	2.9284
13*	1999/4/25	21:27:21	North Ibaraki		83	50	5.2	master	high	1	2.9049	4.288
			36° 30.0′ N	140° 30.0′ E				11.204	0.5543	2	1.1873	2.5849
								slave	low	3	2.8376	4.9964
								14.874	0.5568	4	1.2983	1.9384

5. REFERENCES

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