Research Notes of the N.R.C.P., No. 34, March 1979

550.34.034/.343

A Short Note
on
Borehole-Type Tiltmeters and Earthquake Prediction

By

Haruo Sato

National Research Center for Disaster Prevention, Japan

Abstract

There are a number of reports on anomalous tilt changes preceding large earthquakes. Continuous monitoring of the crustal tilt is one of the most effective approaches for the purpose of the earthquake prediction. The borehole-type tiltmeters developed for installation in boreholes have been used for the crustal tilt observation for these ten years. Drilling a borehole is not so expensive as construction of a vault, which is necessary for installation of a water-tube tiltmeter and a horizontal pendulum tiltmeter, and boreholes are possible to be made even in a plain area. The force balanced pendulum tiltmeter and the bubble tiltmeter, two types of borehole-type tiltmeters, have been developed and used in Japan and the U. S. A., respectively. NRCDP has not only developed the force balanced pendulum tiltmeter itself but has improved borehole drilling techniques and installation methods of tiltmeters. The force balanced pendulum tiltmeters installed at the bottom of boreholes of which the depths are 50-100m offer good and stable records. Long term drift of the force balanced pendulum tiltmeter is about a few arc second per year, one order larger than that of water tube tiltmeters. However, the force balanced pendulum tiltmeter is expected to be very effective to detect anomalous tilt changes of the order of 0.1 arc second or larger prior to the occurrence of large earthquakes. Now, NRCDP is going to construct 50 crustal activity observatio stations in the Kanto-Tokai area, where a large earthquake is anticipated, in the coming 5 years. High sensitive seismometers are installed all of the 50 stations, among which 17 stations are equipped with the borehole-type tiltmeters. It is expected that some of these crustal activity observation stations will detect anomalous tilt changes or anomalous seismicity prior to coming earthquakes.

1. Introduction

It has been shown by recent research works that monitoring of the crustal movement provides the most important information for earhtquake prediction. There are some historical documents in which anomalous sea retreats before an earthquake have been mentioned. The phenomenon of the sea retreat seems to be interpreted by local uplift of the land relative to the sea level (Ajigazawa earthquake, M=6.9, 1793; Hamada earthquake, M=7.1, 1872; etc.). In modern times, the data from geodetic surveys such as triangulation and precise levelling are available. Making geodetic surveys over the seismic area before and after an earthquake, crustal movements associated with the earthquake can be found. There are some instances in which land deformation prior to an earthquake was detected by a repetition of the precise levelling (Niigata earthquake, M=7.5, 1964, Fig. 1,(Tsubokawa, 1964); San Fernando earthquake, M=6.4, 1974, (Castle, et al., 1974)). Rikitake(1976) collected and classified 282 earthquake precursors, in which 105 crustal movements(land deformation, tilt and strain, fault creep anomaly, etc.,) were reported.

According to the theory of the plate tectonics, an island arc such as the Japan arc is compressed and pulled down by a subducting oceanic plate as shown schematically in Fig. 2. The crust must rupture at the interface between the continental and oceanic plates when the shearing stress at the plate boundary exceeds a certain limit. The strained crust of an island arc would rebound oceanward with an uplift. At that moment the strain energy, that has accumulated in the crust, would be releases into the energy of seismic waves and crustal movements. The mechanism of large earthquakes off the Pacific coast of Japan may be something like the one described above. The plate boundaries in the Japan arc region are delineated as shown in Fig. 3. The mechanism of earthquakes which occur in inland areas is also interpreted by a sudden release of the accumulated stress.

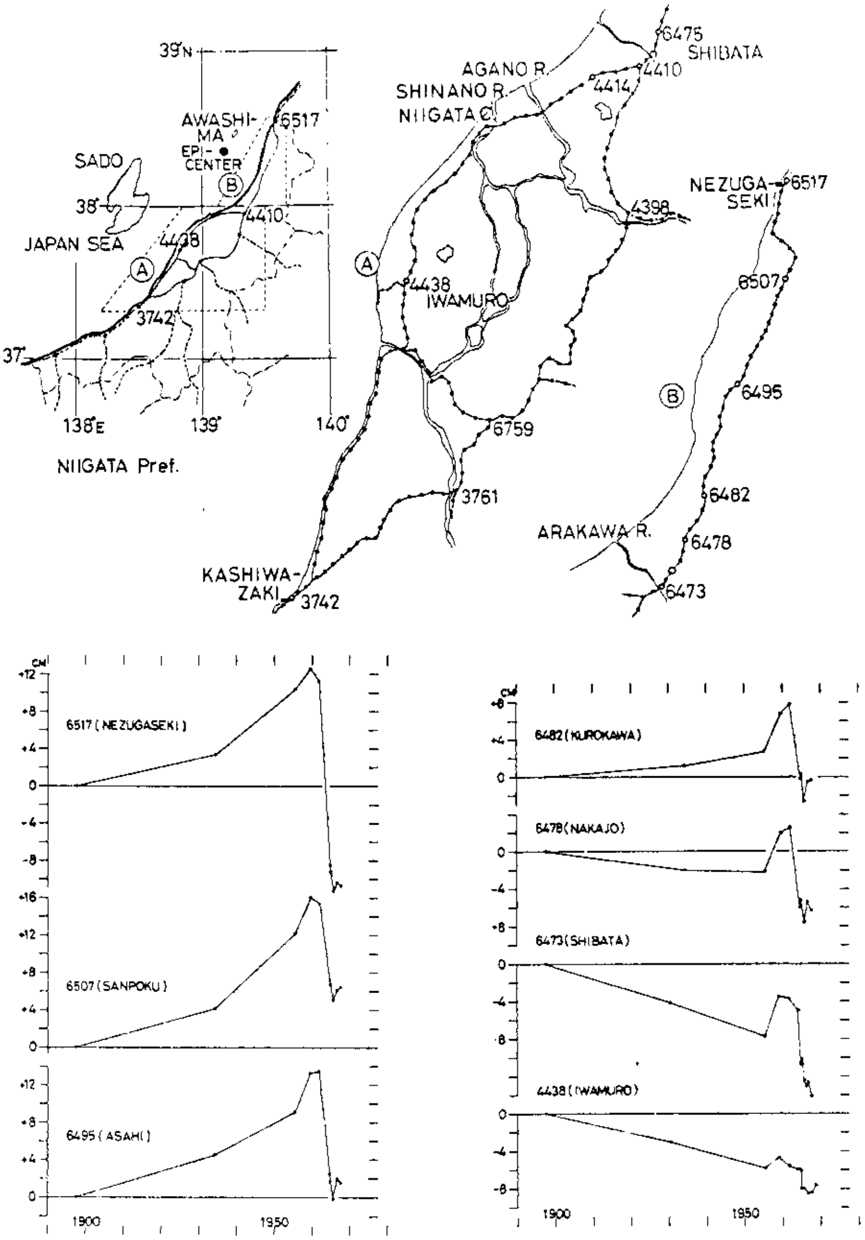


Fig. 1. Changes in height at levelling bench marks before and after the 1964 Niigata earthquake (Dambara, 1973) .

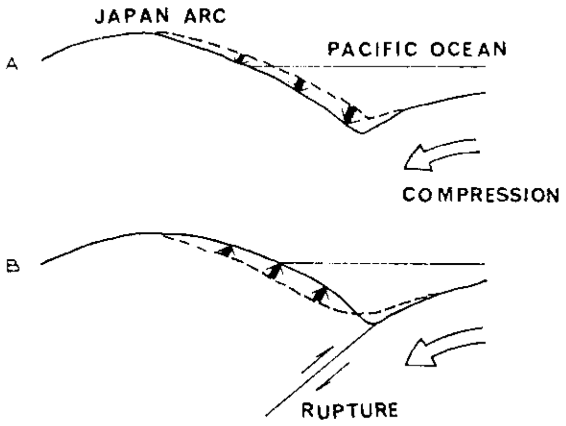


Fig. 2. Compression and rebound of an island arc. A. Compressed state. B. State of rebound (Rikitake, 1976).

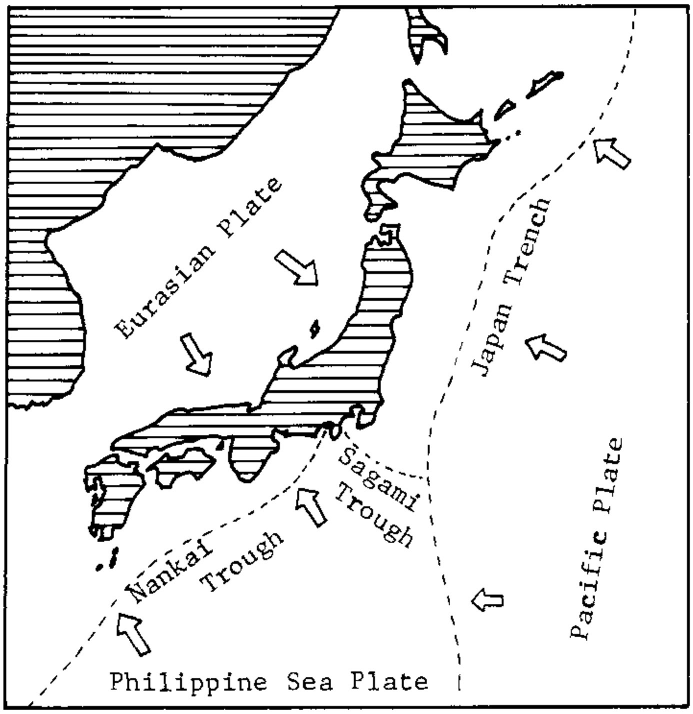


Fig. 3. Tectonic plates near and around the Japan arc.

Therefore, it is important to observe the stress accumulation, which appears as crustal movement, in order to forecast earthquakes.

Stimulated by the plate tectonics theory and the observational facts mentioned above, a repetition of geodetic surveys such as triangulation, levelling and geodimeter surveys of high accuracy have vigorously been carried out.

It is impossible however to perform a continuous monitoring of the crustal movement by means of the geodetic survey, because the geodetic survey is essentially intermittent. Therfore, continuous observation of the crustal movement with tiltmeters, strainmeters, tide gauges, etc. are important as well as thethe geodetic survey.

2. Instruments for crustal tilt observation

Among the various kinds of observations of the crustal movement, continuous observation of the crustal tilt is particularly important. Ther are three kinds of commonly used tiltmeters; water-tube tiltmeters, horizontal pendulum tiltmeters and borehole-type tiltmeters. Water-tube tiltmeters and horizontal pendulum tiltmeters which are installed in underground vaults have been used for a long time. Borehole-type tiltmeters have been utilized only recently.

-Water-tube tiltmeter-

A pair of water pots, connected with a pipe, are placed on the ground at a distance of several tens of meters. Changes in the difference in height of the water surface are proportional to the mean tilting of the ground on which the system is installed. The height of the water surface is usually read by a micrometer or an electric device(Yamada, 1973). The principle of the water-tube tiltmeter is illustrated in Fig. 4(A).

-Horizontal pendulum tiltmeter-

The axis of the pendulum deviates very slightly from the vertical, so that the pendulum oscilates with a long period. The pendulum moves in an almost horizontal plane. As the axis is slightly tilted, the pendulum tends to rotate with a fairly large angle. Therefore, this device works as a high sensitive tiltmeter. The principle of the horizontal pendulum tiltmeter is illustrated in Fig. 4(B).

-Borehole-type tiltmeter-

This type of tiltmeter has been developed for installation in a borehole. Two types are commonly used for this purpose; the vertical pendulum type and the bubble type. The details of the borehole-type tiltmeter will be described in the section after the next.

3. Continuous observation of the crustal tilt and earthquake precursors

For several cases, the tilt changes recorded by the water-tube tiltmeters were compared to that deduced from the precise levellings over the area in which the crustal movement observatory is located. Qualitative agreement between those two types of observations was seen for most of the cases although a quantitative comparison was not always successful(Kasahara, 1973). It has been experiences that the horizontal pendulum tiltmeter undergoes a drift movement probably because of the mechanical friction at the bearing and the instability of the mounting. It seems that the horizontal pendulum tiltmeter records a very local ground tilt because the instrument is mounted on a small tripod. Nevertheless, it is effective for monitoring a rapid tilting. It appears that changes observed by the tiltmeters are an indication of actual crustal movement.

There are a number of reports on anomalous tilt changes preceding earthquakes. Some of them may be reliable, others may not. The following are the most remarkable examples of the tilt precursors.

(A) The Tottori earthquake, Japan, M=7.4, 1943; The horizontal pendulum tiltmeter at the Ikuno mine 60 km from the epicenter recorded a tilt change amounting to 0.1 arc second or more during several hours before the earthquake as shown in Fig. 5(Sassa and Nishimura, 1951).

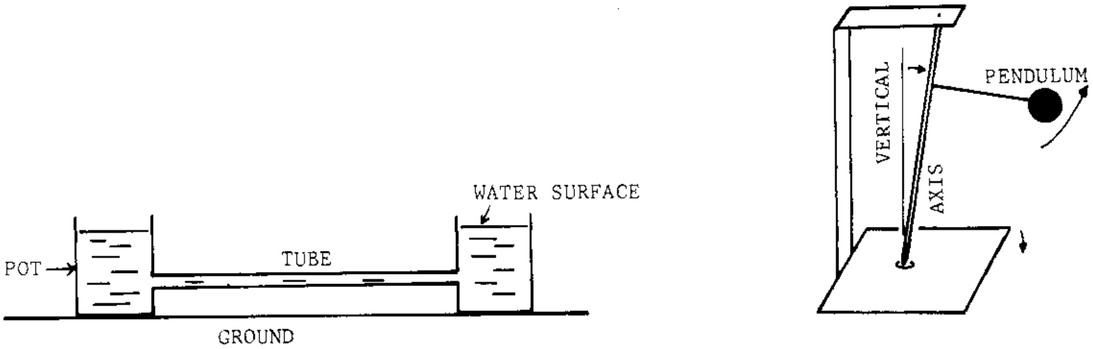


Fig. 4. A. Principle of the water-tube tiltmeter. B. Principle of the horizontal pendulum tiltmeter.

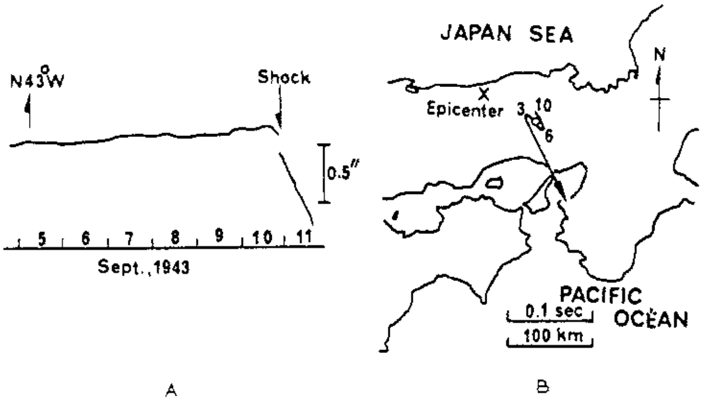


Fig. 5. Change in ground tilt as observed by horizontal pendulum tiltmeters at the Ikuno mine 60km from the epicenter of the 1943 Tottori earthquake. A. The trace of the N43°W component. B. The arrowed curve indicates the directional amount of the tilting motion. The numerals represent the time in hours prior to the earthquake occurence (Sassa and Nishimura, 1951).

(B) Earthquakes in U.S.S.R., M=4.0 and 4.7, 1958; An earthquake of M=4.0 was followed after 30 minutes by the other one of M=4.7. The horizontal pendulum tiltmeter at the Alma-Ata station 250 km from the epicenter recorded a change amounting to 0.4 arc second during 3 hours before the earthquakes(Ostrovsky, 1970). The data is shown in Fig. 6.

Rikitake(1976) compiled precursory changes in crustal tilt reported so far on observations by water-tube tiltmeters, horizontal pendulum tiltmeters and borehole-type tiltmeters. Plots of precursor time vs. magnitude are shown in Fig. 7. The data on the horizontal pendulum tiltmeters are widely dispersed suggesting poor quality of data. The other data exhibit the tendency that the logarithmic precursor time becomes larger as the earthquake magnitude increases. Some isolated plots around $\log_{10}T = -1$ are also found.

4. Borehole-type tiltmeter

At present it is impossible to pinpoint the epicenter of an impending earthquake before it takes place. It is necessary to distribute many observation stations in the area under question in order to detect anomalous tilt changes preceding the earthquake.

Underground vaults are necessary for installation of the water-tube tiltmeters and the horizontal pendulum tiltmeters. However, the vault is very expensive and moreover it is not easy, especially in Japan, to find a satisfactory site for constructing the vault. Drilling a borehole is not so expensive as construction of a vault and boreholes are possible to be made even in a plain area. For these reasons the borehole-type tiltmeters have been developed.

Various types of small size tiltmeters have been developed for installation in boreholes during the last decade; the vertical pendulum type(Allen, 1972; Okada et al., 1975; Akashi and Fukuo, 1977) and the bubble type(Johnston, 1976; Harrison, 1976).

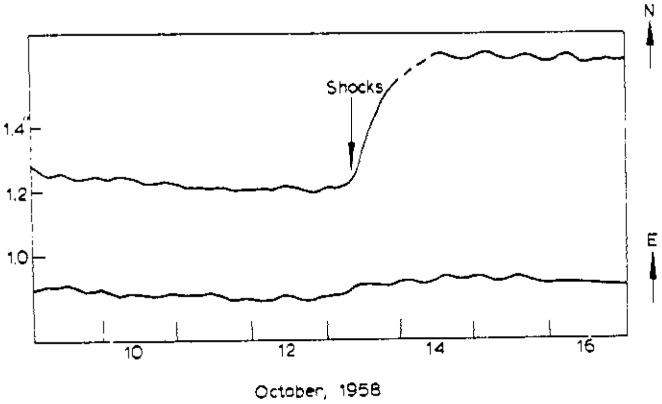


Fig. 6. Anomalous change in ground tilt at the Alma Ata station in U. S. S. R. associated with two earthquakes on October 13, 1958 (Ostrovsky, 1970).

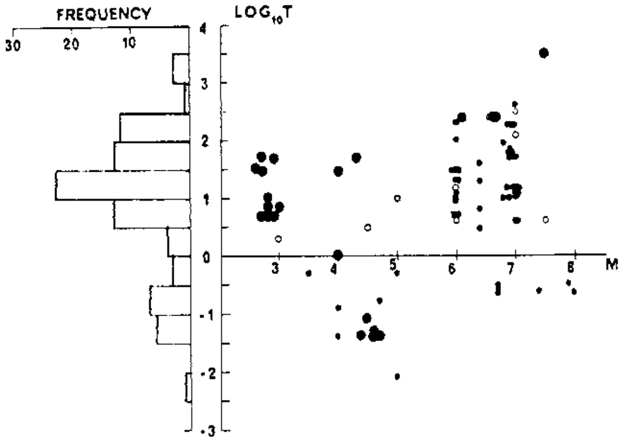


Fig. 7. Histogram of the data for tilt and strain combined with the logarithmic precursor time in day vs. magnitude plots. Large solid, small solid and open circles denote data taken by water-tube and borehole-type tilt-meters, horizontal pendulum tiltmeters and strain meters, respectively (Rikitake, 1976).

These borehole-type tiltmeters have an electrical output so that it is possible to monitor the crustal tilt changes using a telemetering system. The bubble tiltmeters are very popular in the U.S.A., while the force balanced pendulum tiltmeters predominate in Japan. The mechanism and the installation method of these two borehole-type tiltmeters are briefly mentioned.

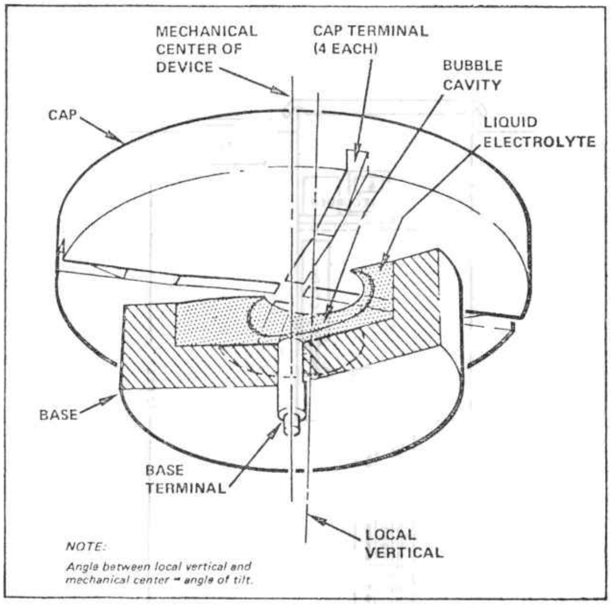
-Bubble tiltmeter-

"The heart of the bubble tiltmeter is a simple bubble level sensor using an electrically conductive fluid. The tiltmeter sensor consists of a cylindrical glass cap and a base as shown in Fig. 8. The cap has four orthogonally located platinum strip electrodes and the base has one centered platinum electrode. The assembled unit is filled with a conducting fluid containing a bubble which, when leveled, covers an equal area of each of the cap electrodes. The opposite cap electrodes are connected to a pair of fixed resistors, thus forming a bridge. As the case is tilted, the bubble, which remains fixed with respect to gravity, moves so as to partially uncover one electrode and to allow the opposite electrode to have more of its surface covered with fluid. This unbalances the bridge and introduces an output voltage which, over the tiltmeter range, is a linear function of the tilt angle"(Kinemetrics Inc., 1975). The bubble sensor is in a cylindrical case(5cm dia. x 107cm long) for installation in a borehole as shown in Fig. 9.

A typical installation method in a shallow borehole is illustrated in Fig. 10. A ceramic casing pipe is cemented in the borehole. The bubble tiltmeter is embedded tightly with fine silica sand in the casing pipe(Allen et al., 1973; Bacon et al., 1975).

-Force balanced pendulum tiltmeter-

A pendulum is suspended from the case with a universal joint. Magnets and electrodes are attached to the pendulum, and coils and electrodes are attached to the case. A pair of electrodes, one on the pendulum and one on the case, form a condenser, and a pair of magnet and coil form an electromagnet. There are four



Sensor Assembly

Fig. 8. Bubble sensor.

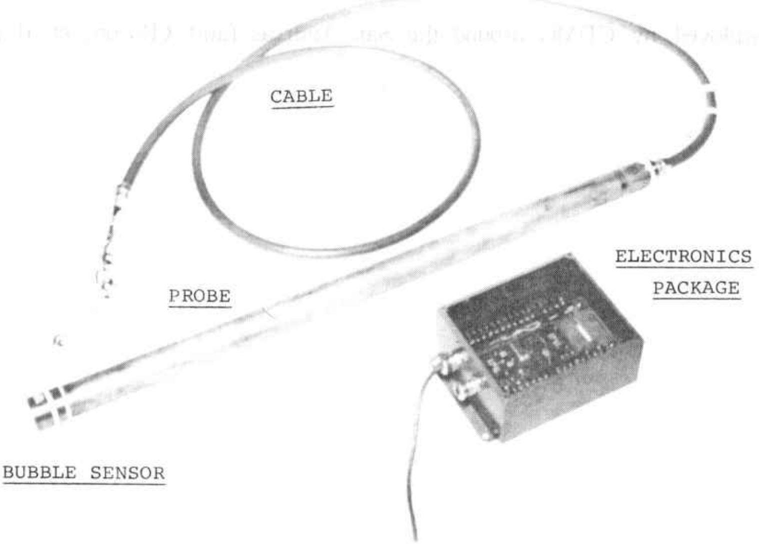


Fig. 9. Bubble tiltmeter.

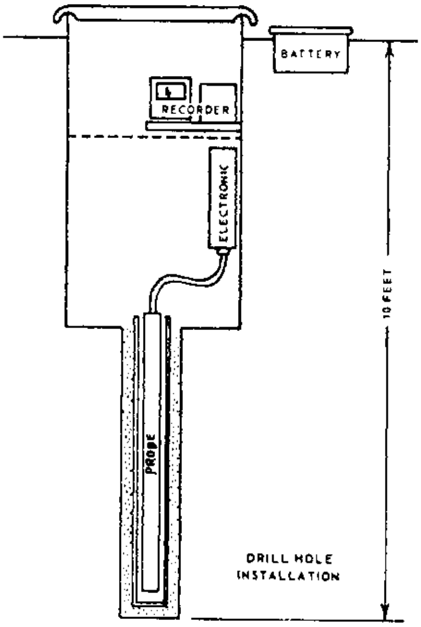


Fig. 10. The installation borehole and the equipment used for the bubble tiltmeter employed by CDMG around the San Andreas fault (Bacon, et al., 1975).

condensers and two electromagnets. The condensers and the electromagnets linked by electric circuit form the force balance system. As the case is tilted, the pendulum moves and capacitance of each condenser changes. An electric current that is proportional to the capacitance change flows into each the electromagnets which balances the pendulum at the neutral position. The output voltage is proportional to each feedback current. The pendulum is always kept at the neutral position so that this tiltmeter is free from the drift movement caused by creeping of the universal joint. The tiltmeter is set on a reset mechanism, which enables precise levelling of the tiltmeter by a remote control system. The tiltmeter and the reset mechanism are assembled in a cylindrical case as illustrate in Fig. 11(A) (Akashi and Fukuo, 1977). The tiltmeter, togather with the thermometer and the seismometers, are assembled in a cylindrical stainless vessel as shown in Fig. 11(B). Fig. 11(C) shows the setting device with three arms for fixing the vessel on the side wall of the stainless casing pipe of 4 inch dia. at the bottom of the borehole.

The borehole is carefully drilled by using a rotary boring machine. A pilot hole is drilled and then it is reamed to the size of 175 mm dia, when we must be careful not to break the side wall of the well. The inclination of the borehole must be in the range of ± 3° from the vertical in order to make it possible to level the tiltmeter at the bottom of the borehole, because the range of the reset angle of the tiltmeter is ± 3°. Steel casing pipes of 5 inch dia. with a stainless casing pipe of 4 inch dia. attached at the end are cemented by expansion cement(Sato and Takahashi, 1978). A standard observation station well is illustrated in Fig. 12.

5. Crustal tilt observation using borehole-type tiltmeters

In the U.S.A., various kinds of borehole-type tiltmeters have been developed and the installation method in a shallow borehole has been improved(Allen, et al., 1973; Bacon, et al., 1975). Many borehole-type tiltmeters have been distributed in middle and southern California, where the San Andreas fault is very active. In recent years, the bubble tiltmeter is the most popular type in the area.

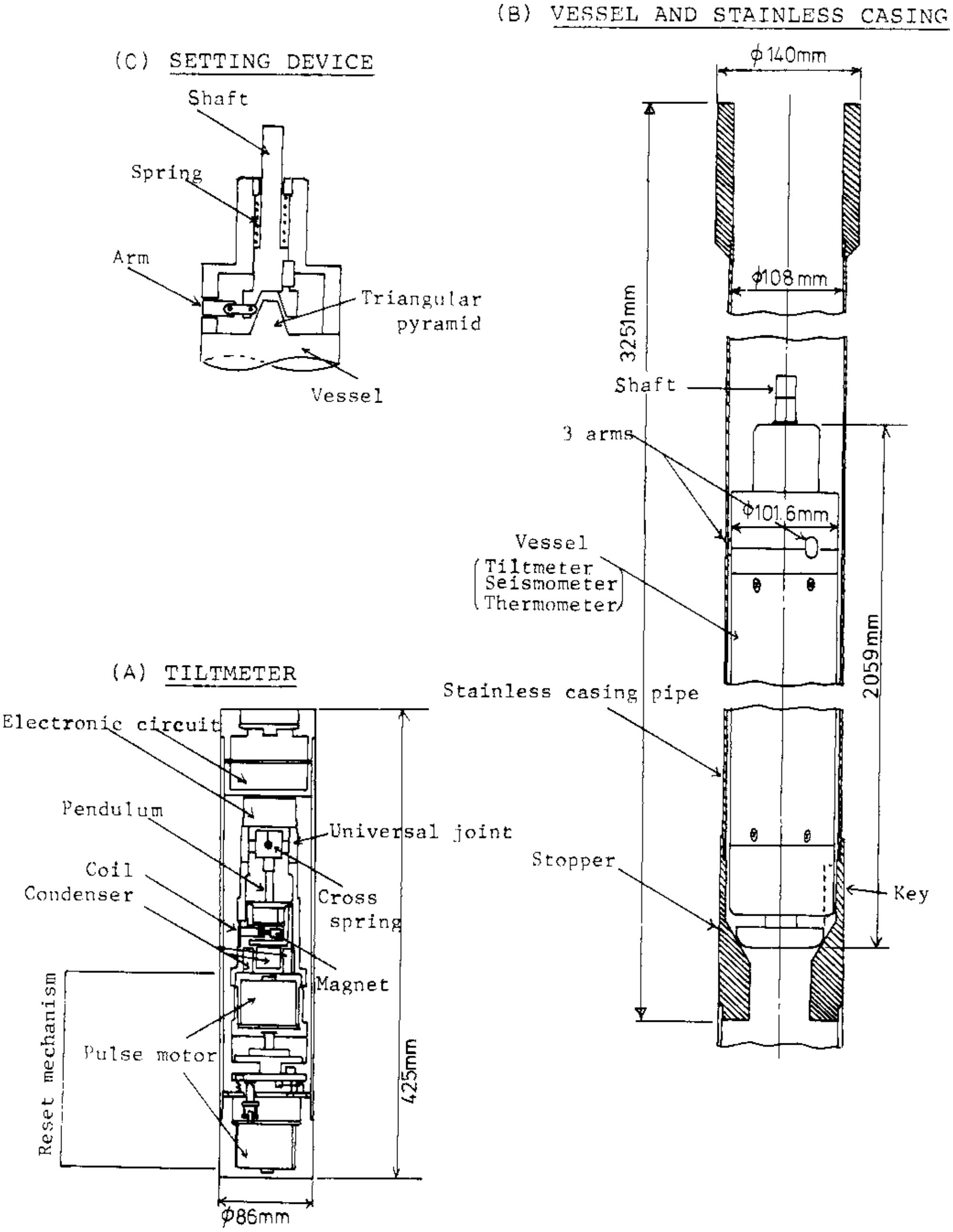


Fig. 11. Force balanced pendulum tiltmeter (Sato and Takahashi, 1978).

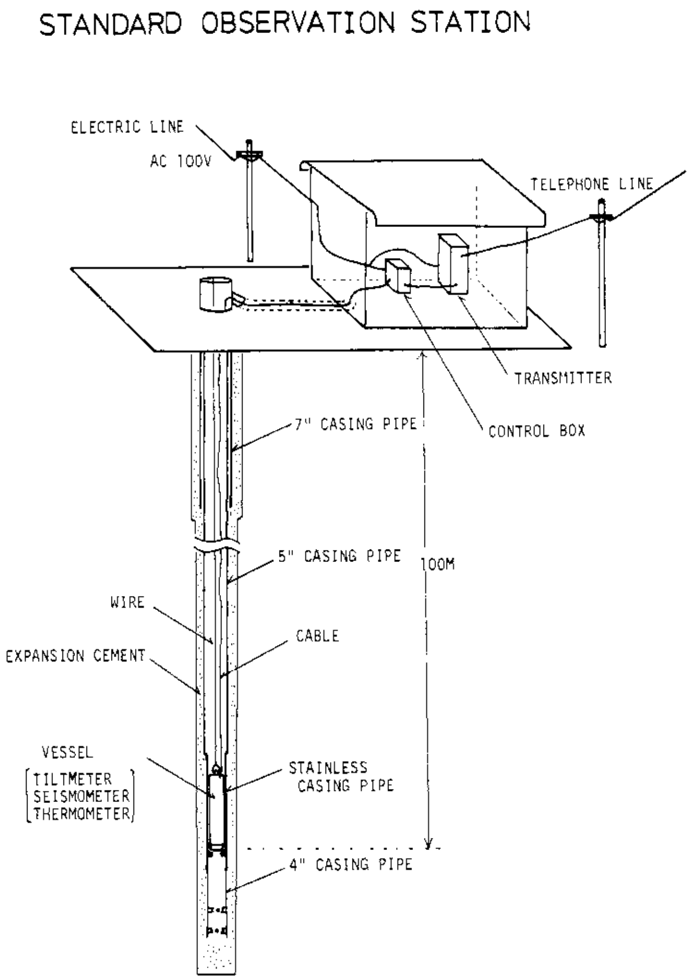


Fig. 12. Standard observation station.

This area has been of particular interest for earthquake and crustal movement investigations for many years. Tiltmeter studies, telluric cureent measurements, magnetometer studies, geodimeter measurements, tellurometer measurements, gravity studies, creepmeter studies, strong motion instrumentations and microearthquake studies are vigorously performed in the area(Bacon, et al., 1975). The crustal tilt observation is performed mainly by U. S. Geological Survey(USGS), California Institute of Technology(CALTEC) and California Division of Mines and Geology(CDMG). A typical installation is illustrated in Fig. 10. The tilt signals from the borehole sites are transmitted by a telemetering system using telephone lines to the Office of Earthquake studies of USGS in Menlopark and the Seismological Laboratory of CALTEC in Pasadena. The tiltmeter sites of USGS along the San Andreas fault are shown in Fig. 13.

It was reported that several tiltmeters recorded anomalous changes prior to the earthquake of November 28, 1974(M=5.2) near Holister in central California(Mortensen and Johnston, 1976). Raw records are shown in Fig. 14. According to Johnston and Mortensen(1974), the tiltvector changed its orientation preceding earthquakes as illustrated in Fig. 15. It should be noted however that most of the premonitoring earthquake signals are buried in local meteorogical noise, such as the influence of rainfall on the tilt data(Wood and King, 1977).

Site selection is found to be a crucial factor in the shallow borehole installation. Sites selected on bases of radial symmetry, homogeneity of material, and remoteness from the topographical changes show reportedly no apparent diurnal temperature effects or ground loading effects due to rainfall at a resolution of 10^{-7} radians(Mortensen and Johnston, 1975). Several bubble tiltmeters were imported from the U.S.A. and used for the crustal tilt observation in Japan. Some of them are still operating in vaults,offering good and stable records, but those which are installed in shallow holes of 2 m depth suffer from the influence of temperature changes and rainfall(Hamada, 1978; Sato and Takahashi, 1978; Harrison and Herbst, 1977). This shows a limitation of the borehole-type tiltmeter installed in shallow

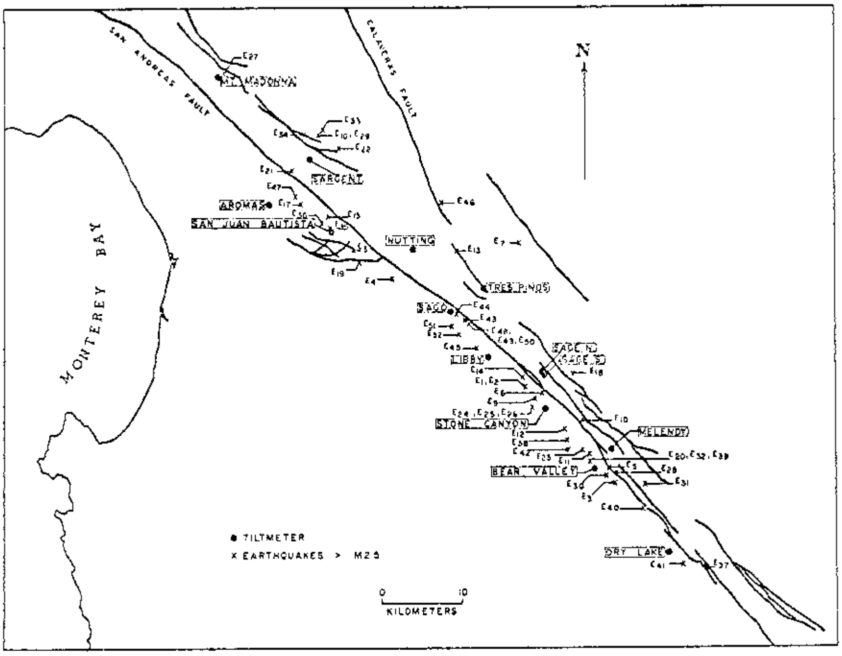


Fig. 13. Tiltmeter sites (circles) along an 85km section of the San Andreas fault in California and earthquakes (x's) of M> 2.5, which have occured near the instrument sites in the interval from July, 1973 to June, 1974 (Mortensen and Johnston, 1975).

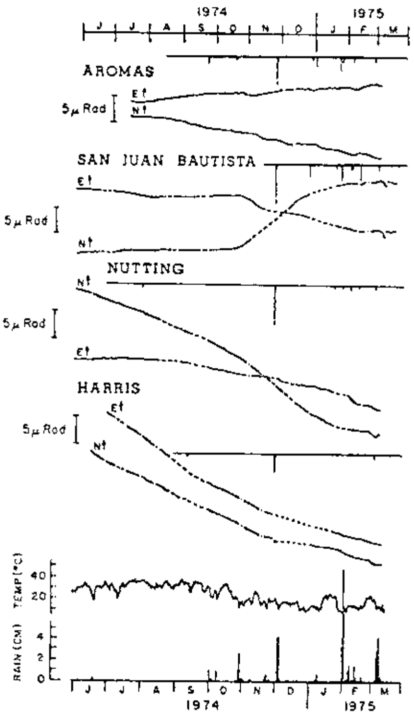


Fig. 14. Raw records for the four operational tilt sites nearest to the epicenter of the earthquake (November 28, 1974). Local earthquakes near each site are plotted above each record as vertical lines of length proportional to source dimension, depth and inverse distance. Rainfall and temperature in the area of the tilt array are shown in the bottom plot (Mortensen and Johnston, 1976).

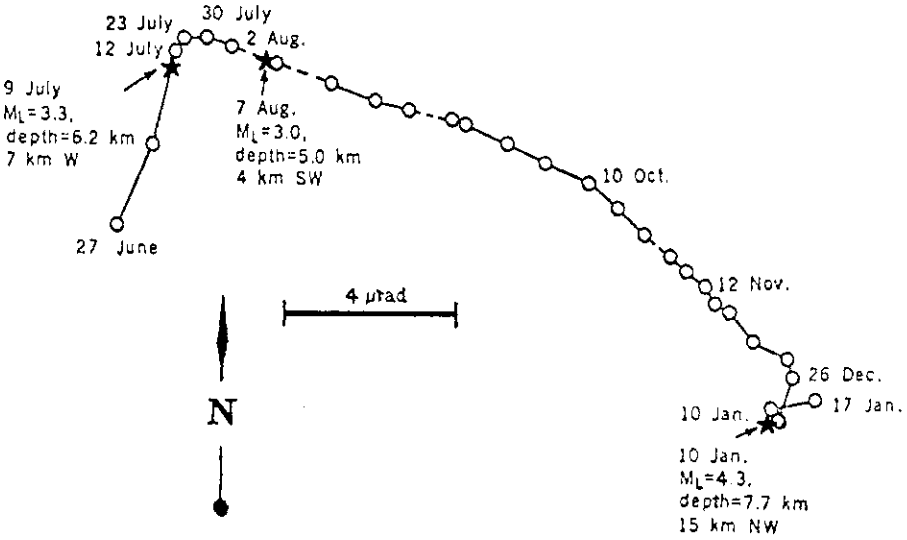


Fig. 15. Cumulative weekly mean tilt vectors (circles) from June, 1973 to January, 1974 for the Nutting site 7km south of Hollister. The tilt vector changed its orientation preceding earthquakes (Johnston and Mortensen, 1974).

holes. Since there is a lot of rain in Japan, shallow borehole observation is not so appropriate.

In Japan, borehole-type tiltmeters have been developed with zeel since the Matsushiro earthquake swarm, 1965-1967(Okada, et. al., 1975; Akashi and Fukuo, 1977).

Hereafter, the crustal tilt observation using the force balanced pendulum tiltmeter is described. National Research Center for Disaster Prevention(NRCDP) has not only developed the force balanced pendulum tiltmeter itself but has improved borehole drilling techniques and installation methods for the crustal tilt observation.

NRCDP has performed crustal tilt observation at the Iwai-kita and the Iwai-minami stations, the southern part of the Boso peninsula, since 1973(Suzuki, 1978). The locations are shown in Fig. 24. An active fault, the Iwai fault, is located between the two stations, of which the distance is about 2 km. The depths of the two boreholes located in Tertiary formation are 50 m. The tilt data recorded are shown in Fig. 16. Rainfall seems to affect the local ground tilt as shown in Fig. 16. Long term drift has been about 0.4- 2.2 arc second per year for the past five years. Figs.16(A) and(B)show difference between the long term drift before and after October, 1975, when the tiltmeters were installed again in the boreholes. This means that the tiltmeter undergoes drift movements probably because of the instability of the vessels in the boreholes.

A crustal tilt observation with an array of borehole-type tiltmeters(4 stations) was started at Okabe-machi, Shida-gun, Shizuoka-ken in February, 1978. The area was selected for observation because a large earthquake is anticipated in the Tokai area because of various kinds of scientific data, some of which will be mentioned in the following section. The object of this small aray observation is to detect precisely the local crustal tilt changes, which can not be observed by a single sensor. The geology of the observation area is in the Setogawa group of Paleogine as shown in Fig. 17.

The force balanced pendulum tiltmeters are installed at the bottom of the boreholes, of which the depths are 102m(Okabe station), 54m(Chikamata station) and

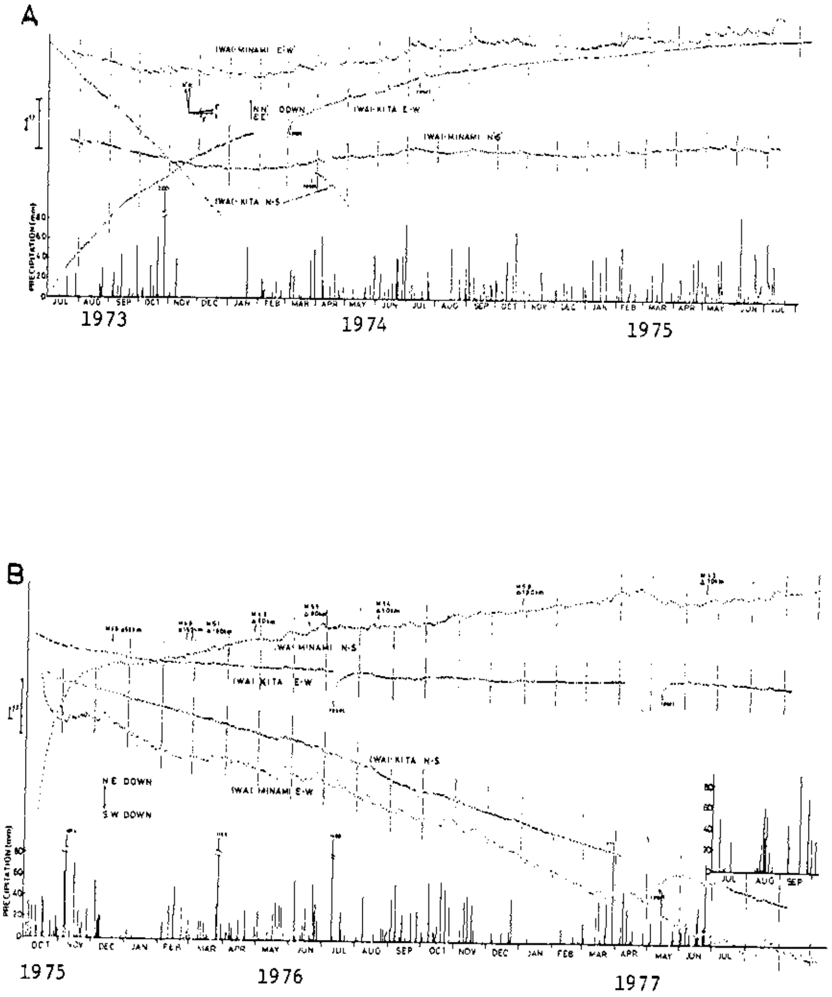


Fig. 16. Tilt data obtained at the Iwai—minami and the Iwai—kita stations. Precipitation is plotted in the bottom. Tiltmeters are installed again at October, 1975. A. From July, 1973 to July, 1975. B. From October. 1975 to September, 1977. (Suzuki, 1978).

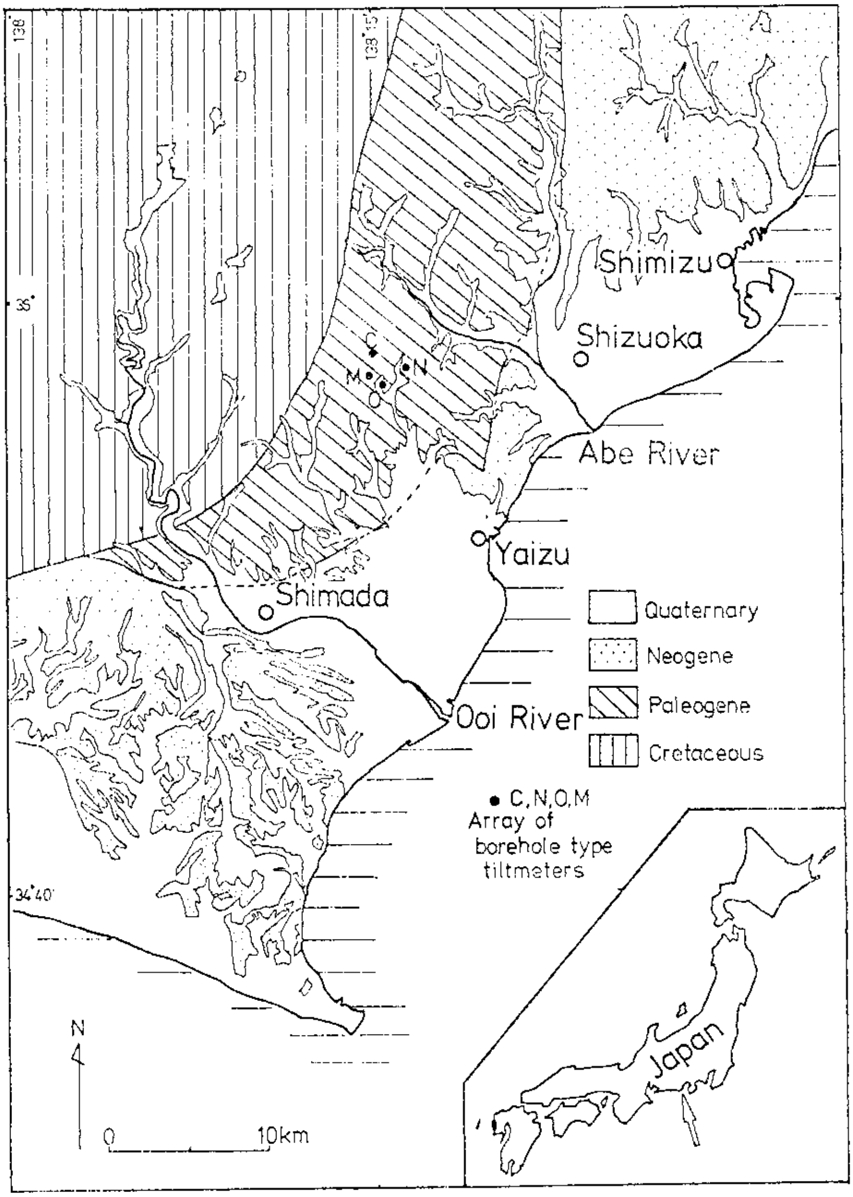


Fig. 17. Geology in Shizuoka-ken(Shizuoka Univ., 1973).

53 m(Nodazawa station). The boreholes are located on the apexes of an equilateral triangle of about 2.5 km in length as illustrated in Fig. 18. The bubble tiltmeters are installed in shallow holes(Matozawa station) for experimental purpose. Seismometers, thermometers, a rain gauge and a barometer are installed to support the crustal tilt observation. All the signals are transmitted by the telemetering system (Pulse code modulation method)using telephone lines to NRCDP at Tsukuba and monitored there(Sato and Takahashi, 1978). The telemetering system and the recording system are illustrated in Fig. 19. The tilt data observed are shown in Fig. 20. From the array observation during about half a year, the following are concluded: Long term drift of each component is less than about 0.1 arc second per month. Short period tilt changes of day order at the three stations are well correlated. The influence of rainfall is clear in the data obtained at the Chikamata station. There is little correlation between tilt and barometric changes. Small tilt steps take place occasionally caused by strong earthquake shocks.

The force balanced pendulum tiltmeter can be installed in a borehole as deep as about 100 m, so that site selection is easier than the one for the bubble tiltmeter. At those depths, the force balanced pendulum tiltmeters show no apparent diurnal temperature effects, but, some of them located near rivers or ponds show ground loading effects due to the rising of the water level of rivers or ponds owing to rainfall. Therefore, we have to select the site apart from rivers and ponds, and install the tiltmeter deep in sound rock as much as possible.

The long term drift of the force balanced pendulum tiltmeter is about a few arc second per year, one order larger than that of water-tube tiltmeters. Inspite of the long term drift, the force balanced pendulum tiltmeter is expected to be very effective to detect anomalous short term tilt changes of the order of 0.1 arc second or larger prior to the occurence of large earthquakes.

NRCDP is completing three deep borehole observatories around Tokyo, the capital of Japan, and the crustal tilt and the microearthquake observation started at the Iwatsuki observatory(3510 m depth) in 1970 and the Shimohsa observatory (2300 m

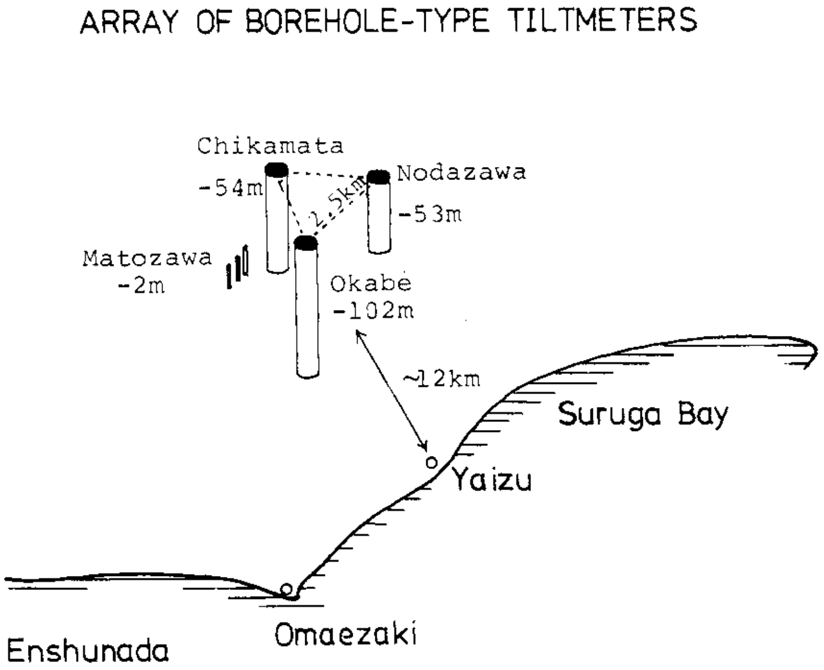


Fig. 18. Array of borehole–type tiltmeters at Okabe–machi.

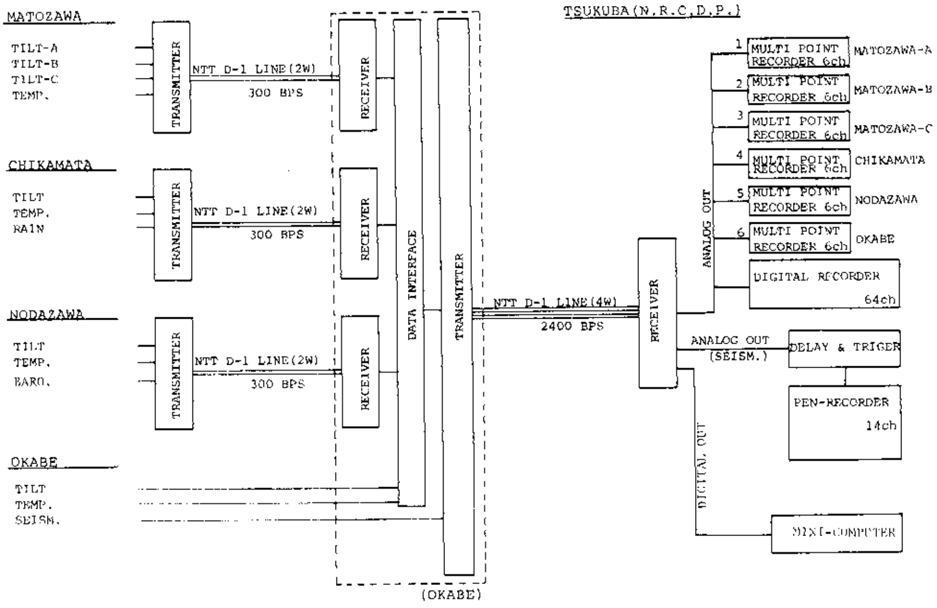
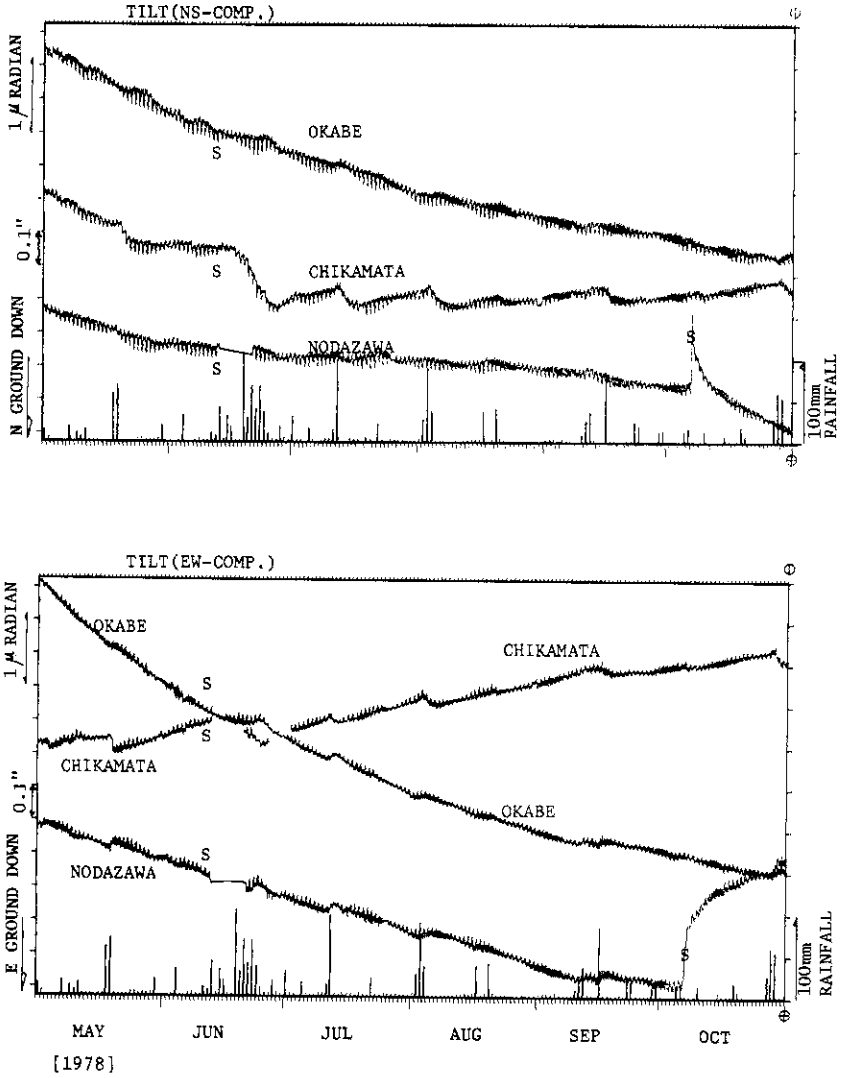


Fig. 19. Telemetering and recording system.



S: step caused by earthquake shock is corrected.

Fig. 20. Tilt date obtained at the Chikamata, the Nodazawa and the Okabe station, in which force balanced pendulum tiltmeters are installed. Precipitation is plotted in the bottom.

depth) in 1978(Takahashi and Hamada, 1975). Another deep borehole observatory will be completed in a few years at Fuchu, western part of Tokyo. The force balanced pendulum tiltmeters are successfully in much deeper boreholes down to a few kilometers. The deep borehole observatories are free from the heavy noises on the ground surface, and are expected to provide the most essential data of the crustal activity in the metropolitan area. Long term drift of the tiltmeter is about 1 arc second per month at the Iwatsuki observatory probably because of high temperature at the bottom, 86°c. However, short term stability of the tiltmeter is satisfactory.

6. Crustal activity observation program in the Kanto-Tokai area by NRCDP

The Kanto and the Tokai areas are very important in Japan from the social, cultural, industrial and economical points of view. These areas also have a huge population. A large earthquake is anticipated in these areas according to various kinds of geophysical data. The south part of the Kanto area and the Tokai area have been appointed to "the area of intensified observation" by Coordinating Committee for Earthquake Prediction(CCEP) as illustrated in Fig. 21. The Philippine Sea plate faces the Eurasian plate off the Pacific coast of Japan and the root of the Izu peninsula. Large earthquakes have occurred in those areas in historical times along the Nankai trough and the Sagami trough, which are the plate boundaries, as shown in Fig. 22. Recently, it has been reported that anomalous vertical movement occurred in the Tokai area from the precise levellings as illustrated in Fig. 23.

Vigorous geophysical research studies on these areas have been exerted by governmental and municipal agencies and universities. Repetition of precise levelling, triangulation and geodimeter survey, gravity surveys, tide gauge installations, borehole-type tiltmeter installations, borehole-type strainmeter installations, in-situ stress measurements by hydro-fracturing, geochemical observation of ground water and monitoring of the ground water level, measurements of seismic wave

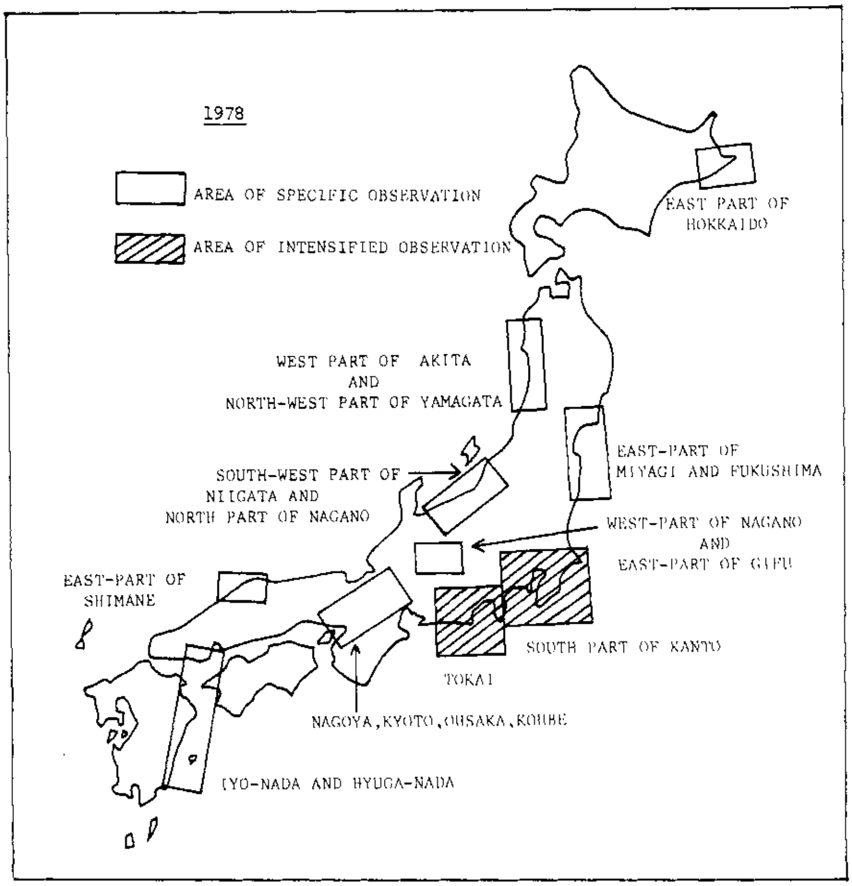


Fig. 21. Disignation of the area of special attention by the Coordinating Committee for Earthquake Prediction.

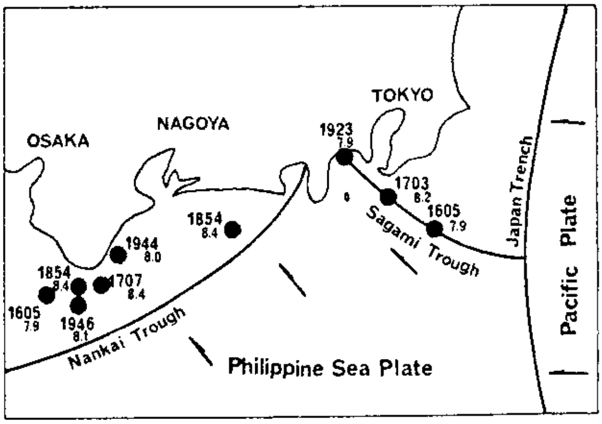


Fig. 22. Plates, troughs and a trench off the Pacific coast of Honshu, Japan. The arrows show the direction of plate motion. Epicenters of extremely large earthquakes since 1600 are indicated in the figure along with their year of occurrence and magnitude (Rikitake, 1976).

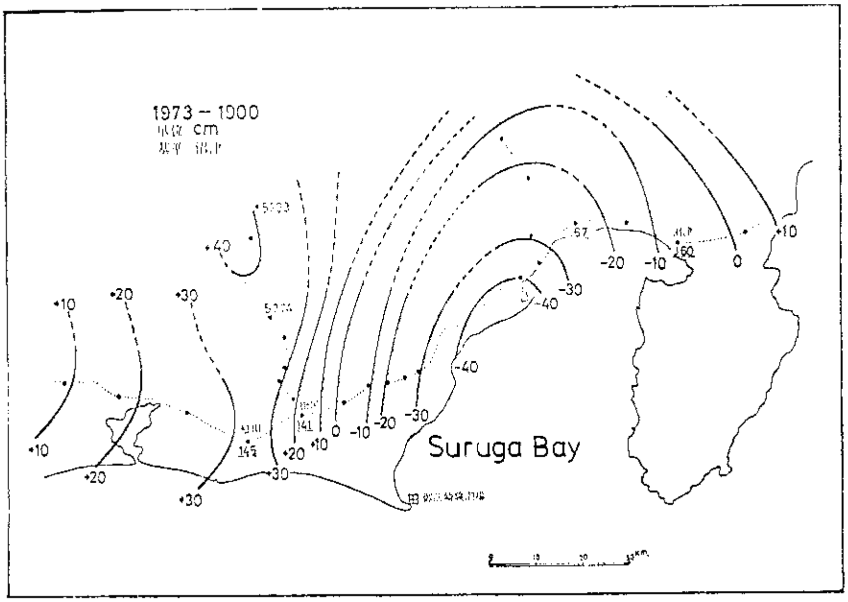


Fig. 23. Vertical movement in the Tokai area (GSI, 1978).

velocity changes by explosions and natural earthquakes, microearthquake observations, geological surveys of active faults, surveys of submarine topography, etc. have been performed. Borehole-type tiltmeter installations have been conducted mainly by NRCDP.

Now, NRCDP is going to construct 50 crustal activity observation stations in the Kanto - Tokai area in the coming 5 years. According to our plan, high sensitive seismometers are installed at all the 50 stations, among which 17 stations are equipped with the borehole-type tiltmeters. Distribution of the crustal activity observation stations are illustrated in Fig. 24. A standard observation station is illustrated in Fig. 12. All the signals are transmitted by the telemetering system using telephone lines to NRCDP at Tsukuba and recorded by the analog and the digital recording systems, as illustrated in Fig. 25.

The new observation network monitoring the micro-seismicity and the crustal movement, especially the crustal tilt, will contribute to earthquake prediction in the area. It is expected that some of these crustal activity observation stations will detect anomalous tilt changes or anomalous seismicity prior to the coming large earthquakes.

Ackowledgements

The author would like to express his thanks to Mr. H. Takahashi who kindly gave him instruction on borehole construction for the crustal tilt observaton and also to Dr. K. Hamada who informed him of the crustal movement studies in the U.S.A.. The author is also grateful to Mr. M. Takahashi, Mr. H. Suzuki and Mr. K. Kasahara for kind instruction on the crustal tilt observation at the Iwai-minami, the Iwai-kita and the Iwatsuki observatories, and to Miss. M. Tatsukawa who is engaged in analysis of the crustal tilt data. The author wishes to thank Dr. T. Rikitake, from whose publication "Earthquake Prediction" many references are taken, and also to Mr. M. Ohtake for careful reading of this manuscript.

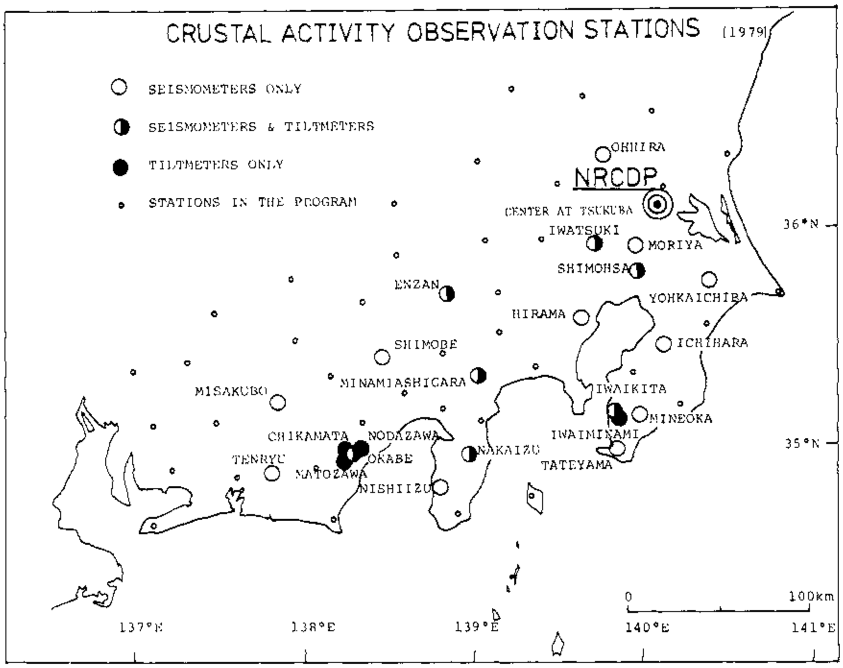


Fig. 24. Crustal activity observation stations in the Kanto—Tokai area in the program of NRCDP.

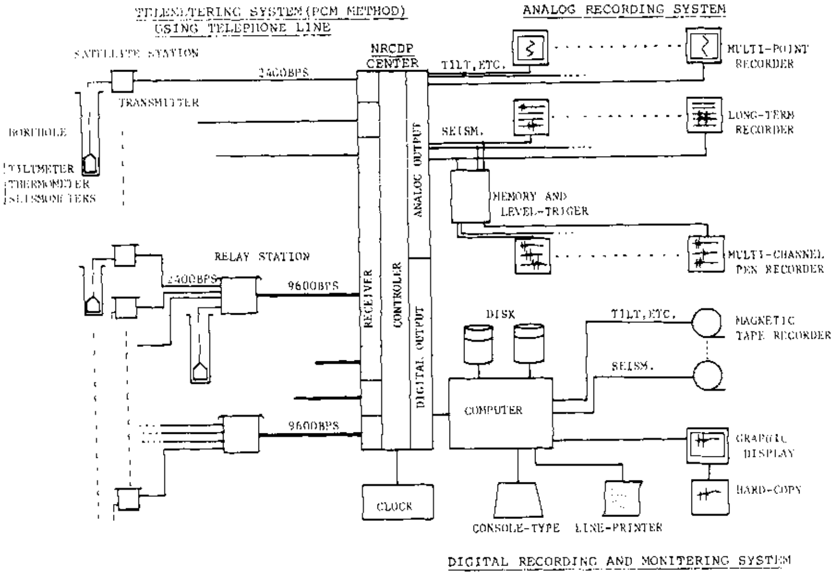


Fig. 25. Telemetering and recording system of NRCDP.

REFERENCES

Allen, R. V., A borehole tiltmeter for measurements at tidal sensitivity, Bull. Seism. Soc. Am., 62, 815-, 1972.

Allen, R. V. et al., Some instruments and techniques for measurements of tidal tilt, Phil. Trans. Roy. Soc. London A, 274, 219-, 1973.

Akashi, K. and N. Fukuo, Borehole seismometer and strainmeter, Seimitsu Kikai, 43, 111-, 1977.

Bacon, C. F. et al., Crustal movement studies near Parkfield, California, California Geology, September, 202-, 1975.

Castle, R. O. et al., Elevation changes preceding the San Fernando earthquake of February 9, 1971. Geology, 2, 61-, 1974.

Dambara, T., Crustal movements before, at and after the Niigata earthquake, Rep. Coord. Comm. Earthquake Prediction, 9, 93-, 1973.

GSI(Geographical Survey Institute), Crustal movements in the Tokai district, Rep. Coord. Comm. Earthquake Prediction, 19, 96-, 1978.

Hamada, N., Personal communication, 1978.

Harrison, J. C., Tilt observations in the Poorman Mine, near Boulder, Colorado, J. Geophys. Res., 81, 329-, 1976.

Harrison, J. C. and K. Herbst, Thermoelastic strains and tilts revisted, Geophys. Res. Let., 4, 535-, 1977.

Johnston, M. J. S. and C. E. Mortensen, Tilt precursors before earthquakes on the San Andreas fault, California, Science, 186, 1031-, 1974.

Johnston, M. J. S., Testing the physical parameters of short baseline tiltmeters intended for earthquake prediction, US Geological Survey Open-File Report, 76-556, Menlo Park, Callifornia, 1976.

Kasahara, K., Tiltmeter observation in compliment with precise levelings, J. Geod. Soc. Japan, 19, 93-, 1973.

Kinemetrics Inc., Catalog of Biaxial tiltmeter TM-1, California, U. S. A., 1975.

Mortensen, C. E. and M. J. S. Johnston, The nature of surface tilt along 85km of the San Andreas fault- Premonitary results from a 14 instrument array, Pure & Appl. Geophys., 113, 237-, 1975.

Mortensen, C. E. and M. J. S. Johnston, Anomalous tilt preceding the Holister earthquake of November 28, 1974, J. Geophys. Res., 81, 3561-, 1976.

Okada, Y. et al., Observation of crustal deformation at the Fujigawa observatory, Central Honshu, Japan (I), J. Geod. Soc. Japan, 21, 179-, 1975.

Ostrovsky, A. E., On changes in tilts of the earth's surface before strong near earthquakes. In: M. A. Sadvosky(Editor), Physical Bases of seeking methods of Predicting earthquakes, Acad. Sci. U.S.S.R., Moscow, 152-, 1970, Translated in English from Russian.

Rikitake, T., Earthquake Prediction, Elsevier Scientific Publishing Company, New York, 1976.

Sassa, K. and E. Nishimura, On phenomena forerunning earthquakes, Trans. Am. Geophys. Union, 32, 1-, 1951.

Sato, H. and H. Takahashi, An array system for observation of the crustal tilt(I), Report of the National Research Center for Disaster Prevention, 20, 39-, 1978.

Shizuoka Univ., Geological map of Shizuoka prefecture, 1973.

Suzuki, H., Tilt observations at Iwai-kita and Iwai-minami observation wells, Boso penisula, Rep. Coord. Comm. Earthquake Prediction, 19, 42-, 1978.

Takahashi, H. and K. Hamada, Deep borehole observation of the earth's crust activities around Tokyo, Pure & Appl. Geophys., 113, 311-, 1975.

Tsubokawa, I., et al.,Crustal movements before and after the Niigata earthquake, J. Geod. Soc. Japan, 10, 165-, 1964.

Wood, M. D., and N. E. King, Relation between earthquakes, weather and soil tilt, Science, 197, 154-, 1977.

Research Notes of the N. R. C. D. P., No. 34, March 1979

Yamada, J., A water-tube tiltmeter and its applications to crustal movement studies, Spec. Bull. Earthquake Res. Inst., Univ. Tokyo, 10, 1-, 1973.

(Manuscript received February 19, 1979)

ボアホール型傾斜計と地震予知

佐藤春夫

国立防災科学技術センター第２研究部

地震に先行して，異常な傾斜変動が観測されたという報告は現在まで数多くある．地殻傾斜の連続観測は，地震予知のための最も有効な手段の一つと考えられている．この１０年間，ボアホール型傾斜計が精力的に開発され，かつ，地殻傾斜観測に使用されるようになってきた．水管傾斜計や水平振子傾斜計は設置のために横坑を必要とするが，ボアホール型傾斜計設置のための観測井は，その建設費が横坑に比較して安価であること，また，平野部にも建設可能な事など、観測点の面的配置を考えた時，好都合である．ボアホール型傾斜計として力平衡型振子式傾斜計が日本で，気泡型傾斜計が米国で熱心に開発されてきた。

国立防災科学技術センターは，力平衡型振子式傾斜計を開発してきたが，同時に観測井の作井方法及び傾斜計の観測井内設置方法を工夫・改良してきた．深度５０～１００ｍ程度の観測井に設置された力平衡型振子式傾斜計は，安定した記録を提供しており，そのドリフトは２～３秒／年程度である．このドリフト量は，横坑内に設置された水管傾斜計のそれよりも約１ケタ大きいが，大地震に先行してあらわれるであろう０.１秒以上の大きな短期的異常傾斜変化をとらえるには，充分役立つと考えられるようになってきた．

現在，国立防災科学技術センターは，大地震の発生が懸念されている関東・東海地域に５０点の地殻活動観測施設及びそのテレメーター網を建設している．全５０点に高感度地震計を配備し，内１７点に力平衡型振子式傾斜計を併設する計画である．この観測網によって，大地震に先行するであろう地殻傾斜の異常変動やサイスミシティの変化を検知することが可能になるであろう．