

In situ stress measurements in the Kanto-Tokai region of Japan for the prediction of earthquakes

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1. INTRODUCTION

In 1923, a major earthquake hit the Tokyo metropolitan area of Japan, killing about one hundred thousand people. Downward sliding of the Philippine-Sea plate under the North America plate (Northeastern Japan microplate) generated this Great Kanto earthquake (M 7.9) along the Sagami trough, 60 kilometers southwest of Tokyo. The Philippine-Sea plate sinks also under the Eurasian plate along the Suruga trough, 120 kilometers southwest of Tokyo. Many seismologists worry about the predicted "Tokai earthquake" along the Suruga trough where the mighty Ansei-Tokai earthquake (M 8.4) rocked the Tokai districts in 1854. Three large earthquakes of M 7, M 6.9 and 6.7, and numerous smaller earthquakes have rocked the Izu Peninsula in the eastern Tokai region since 1974. Earthquake swarms in the eastern Tokai district propagated to Izu-Oshima Island where volcanic eruptions forced temporal evacuation of ten thousand residents near the end of 1986.

The Tokai and southern Kanto districts are designated as areas of intensified observation alert to possible major earthquakes. Several governmental institutions such as the Meteorological Agency and universities have strengthened observation networks and keep watch over the seismic activity, crustal deformation, anomaly of ground water etc. in the both districts.

Knowledge of the state of stress in the earth's crust is vital for understanding the tectonic processes responsible for earthquakes. In situ stress measurements were carried out in the national research program of Japan for earthquake predictions. The National Research Center for Disaster Prevention (NRCDP) carried out the in situ stress measurements by the hydraulic fracturing technique in the Kanto and Tokai districts (Tsukahara and Ikeda,

1984). A group of researchers of Kyoto University conducted the in situ stress measurements by the overcoring method in western Japan (Tanaka et al. 1981). Another group of researchers in eastern Japan tried stress measurements by the acoustic emission method (Yoshikawa and Mogi, 1978) and by the deformation rate method (The Research Group for Crustal Stress in Eastern Japan, 1986). Besides aiding earthquake prediction research, many in situ stress measurements were also conducted in underground facilities mostly by overcoring (Kanagawa et al., 1986).

The authors, in the Geological Survey of Japan and the University of Tokyo, conducted in situ stress measurements for an earthquake prediction study in the Kanto-Tokai district (Koide et al., 1986). As deep boreholes were not available, the authors mainly used a kind of overcoring technique in a shallow drilling to measure the in situ stress (Nishimatsu et al., 1986). A borehole deformation gauge of the so-called USBM type was used to measure change in diameter of the pilot hole during overcoring. This is one of the most reliable methods for in situ stress measurement. Several other methods for stress measurements, such as the hydraulic fracturing method, were also applied in some measurement points for comparison.

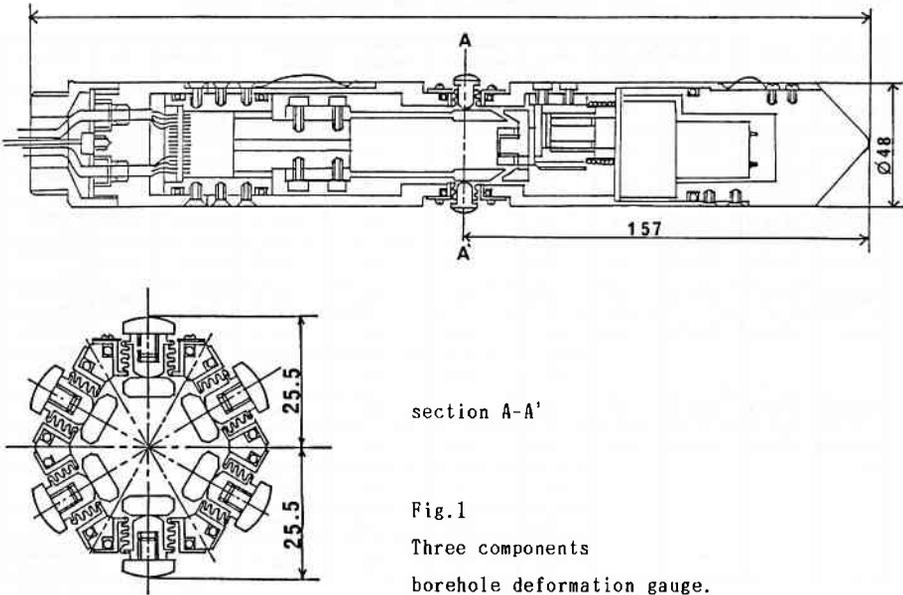
The main purpose of our study was to assess the availability of stress measurement techniques to earthquake prediction. It is probable that the measured stress at the shallow part does not necessarily indicate a state of stress in the deep source region of an earthquake, due to a topographical disturbance or to a release of overburden pressure.

Although overcoring at a depth of several hundred meters is technically possible, obtaining in situ stress measurements by overcoring in deep boreholes is difficult. The hydraulic fracturing technique is often applied for deep stress measurements. This technique, however, only allows us a rough estimation of state of stress, because the orientation of a new fracture is statistically uncertain regardless of the anisotropy in rock or in a section of bore hole.

In several places, stress was measured by a few different methods in a single bore hole or in nearby holes. The results of this study suggest that even shallow stress measurements reflect the tectonic stress to some extent and are useful for detecting areas with an abnormal state of stress.

2. IN SITU STRESS MEASUREMENTS

Sites of tectonic disturbance related to active faults draw our interest to



the purpose of earthquake prediction. However, a rock body tends to be intensely fractured at the sites of tectonic disturbance. Stress measurements are extremely difficult in fractured rock mass. We have very few chances to find the outcrop of rock in underground tunnels in such a tectonically disturbed area. Usually, we are forced to measure the state of stress in a shallow vertical borehole drilled from the ground surface.

A three components borehole deformation gauge originally developed by K. Suzuki et al. (1970) was inserted into a pilot hole of about 50mm diameter and overcored with an overcoring bit larger than 150mm diameter. This deformation gauge (Fig.1) is of the so-called USBM type and water-proofed for use in a water-filled vertical drill hole (Nishimatsu et al, 1986).

During the overcoring, the change in diameter of the pilot hole is measured with an accuracy of $\pm 2\mu\text{m}$ with sets of electric resistance strain gauges bonded onto cantilevers which apply a negligibly small load on the wall of the pilot hole. The mechanical situation for this measurement is very close to the ideal boundary conditions for which analytical solutions can be obtained. We can estimate the relieved stress during overcoring precisely with this deformation gauge. Results of measurements are summarized in Table 1 and Fig.2.

At the Tanzawa site, 30km east of Mt. Fuji, comparison was made by another kind of overcoring technique which used a borehole deformation gauge of the

Table 1 Results of stress measurement in the Kanto-Tokai region

Test Site	Latitude	Longitude	Elevation (m)	Depth (m)	Maximum Horizontal Stress (MPa)	Minimum Horizontal Stress (MPa)	Azimuth of Maximum Horizontal Stress	Rock type	Year	Technique
Tanzawa (A)	35° 28' N	139° 4' E	500	5.73	11.7	3.2	N 7° E	Quartz Diorite	1978.11	Deformation Gauge
Tanzawa (B)	35° 28' N	139° 4' E	500	14.89	7.5	2.6	N 9° E	Quartz Diorite	1978.12	Inclusion
Tanzawa (E)	35° 28.5' N	139° 5.5' E	900	11.25	12.3	4.5	N 27° E	Quartz Diorite	1979.11	Deformation Gauge
Shioda (K)	34° 40.5' E	138° 56.5' E	12	19.0	4.0	2.0	N 20° W	Porphyrite	1981.3	Deformation Gauge
Tsukuba (I)	36° 11' N	140° 5.5' E	40	16.20	1.0	0.9	N 66.5° W	Granite	1982.3	Deformation Gauge
Tanzawa (F)	35° 28' N	139° 4' E	500	12.78	6.9	1.8	N 30° E	Quartz Diorite	1983.2	Deformation Gauge
Toi (J)	34° 54' N	138° 50' E	12.50	350	4.7	2.1	N 0° W	Diorite	1983.12	Deformation Gauge
350				7.6	5.1	N 0° W	Hydraulic Fracturing			
Nankai (K)	35° 07' N	138° 30' E	20	14.25	1.1	0.0	N 65° W	Andesite	1984.3	Deformation Gauge
Shibahawa (L)	35° 17' N	138° 33' E	299	10.93	2.3	0.0	N 21° W	Andesite	1985.3	Deformation Gauge
				10	---	0.4	N 0° W			Hydraulic Fracturing
				31.85	1.9	1.35	N 27° W			Stress Fracturing
				19.0	2.0	0.0	N 31° W			Differential strain curve

Table 2 Three dimensional stress in the Seikoshi mine, Toi.

Stress	Borehole deformation method (MPa)	Hydrofracturing method (MPa)
σ_1	17.4 (N 4° W 72°)	12.3 (N 10° E 50°)
σ_2	3.5 (S 12° E 17°)	5.8 (S 58° E 17°)
σ_3	2.1 (S 78° W 2°)	3.4 (S 44° W 35°)
σ_x	2.17 (4.55)*	5.30 (4.05)
σ_y	4.67 (3.74)	7.70 (6.52)
σ_z	16.17 (3.35)	8.86
τ_{xy}	-0.36 (1.94)	-1.81 (6.96)
τ_{yz}	-3.82 (1.89)	-3.92
τ_{zx}	0.22 (1.89)	-1.31

* Orientation or standard deviation are given in ()

$\sigma_1, \sigma_2, \sigma_3$: Principal stresses

x: east-west, y: north-south, z: vertical axes.

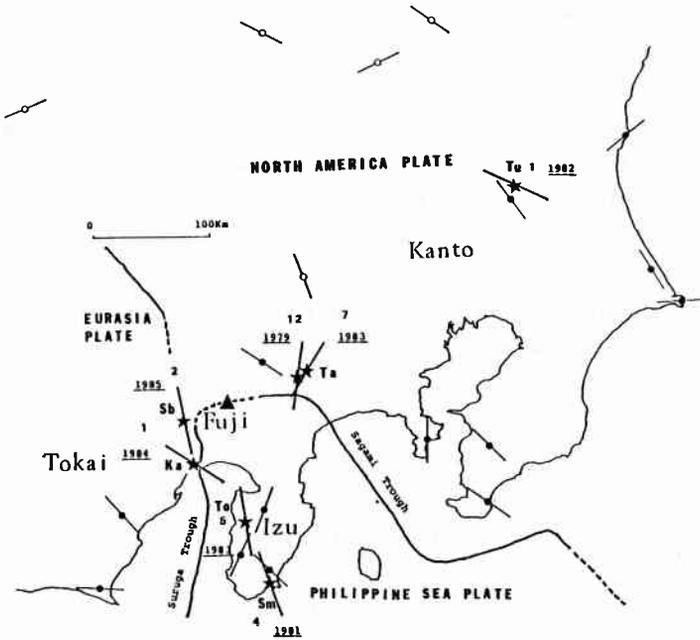


Fig.2 Direction of horizontal maximum compression in the Kanto-Tokai region. Short bars indicate the measured directions of the maximum horizontal compression. Large stars are the results of the stress relief method in this study with the value of the maximum horizontal compression (in MPa) and the measured years.

Open circles are other results of the stress relief method (Koide et al., 1986). Closed circles are the results of the hydrofracturing technique by N.R.C.D.P. (Tsukanara and Ikeda 1984). Tu: Tsukuba, Ta: Tanzawa, To: Toi, Sm: Shimoda, Sb: Shibakawa, Ka: Kanbara.

inclusion type. In this technique, a multi-component strain cell is cemented into a pilot hole and grouted with cement paste (Kanagawa et al., 1986). At Tanzawa, the maximum stress measured with the inclusion type strain cell was smaller than that measured with the deformation gauge at Tanzawa A and E boreholes, but similar to the value measured at Tanzawa F borehole.

Only at the Toi site in the western Izu Peninsula, we measured the in situ stress by drilling from an underground gallery of the Seikoshi mine of a vein-type gold deposit. The three dimensional state of stress was measured by overcoring with a borehole deformation gauge and by hydraulic fracturing in three boreholes which were perpendicular to each other (Table 2). The difference

between the results of the two methods is within the standard deviation except for the vertical stress. The large standard deviation is due to heterogeneity of rock. The large vertical stress by overcoring is derived from the steep topography. At the Shibakawa site, 20km west of Mt. Fuji, vertical drilling from the ground surface was made to measure stress by overcoring, by hydraulic fracturing, by the diametral deformation method (sleeve fracturing) and by the differential strain curve method. The diametral deformation method and the deformation rate method have just been recently developed, and therefore, have not yet been sufficiently established technically or theoretically.

In the diametral deformation method, fluid pressure is applied through a flexible sleeve to the wall rock of a borehole (Kikuchi et al. 1987).

The differential strain curve method is not an in situ stress measurement in the narrow sense, but the method for measuring pre-existing stress which was developed by Yamamoto et al. (1986). Cores taken from drilled Shibakawa boreholes were compressed in the laboratory to estimate the memorized stress in the cores from the stress-strain curves.

Estimated values and orientation of maximum horizontal stress by overcoring, by the diametral deformation method (sleeve fracturing) and by the differential strain curve method are virtually equivalent, although the discrepancy among values of the minimum horizontal stress arises from the smallness of the measured values.

3. STRESS IN THE KANTO-TOKAI REGION

The stress field estimated from in situ stress measurements in the Kanto-Tokai region (Fig.2) is generally consistent with the plate tectonics model in spite of all possible measurement errors and topographical disturbances. The generality of the east-west horizontal compressions in the northern part of the Kanto region suggests the effect of a pinching of the Northeastern Japan microplate between the Pacific plate and the Eurasia plate.

The northwest-southeast or north-south horizontal compressions are distinguished in the southern Kanto and Tokai areas. The nearly north-south compressions are observed in some measurement points relatively close to the plate boundaries. The measured state of stress is rather abnormal in the sites where a nearly north-south compression is observed. The abnormally high horizontal compression in the nearly north-south direction which was measured in the shallow borehole in the Tanzawa area coincides with geologic structures such as the east-west trending anticlines and thrust faults. The result of stress

measurement strongly supports the concept from plate tectonics that the rapidly uprising Tanzawa mountain is the area of stress concentration due to the collision of the Philippine Sea plate into the North America plate.

On the other hand, the abnormally lower compressive stress in the horizontal east-west direction rather than in the vertical direction indicates the horizontal extensional state of stress in the Toi area of the northwestern Izu Peninsula. The east-west horizontal extension in the northwestern Izu Peninsula, which is also indicated by north-south trending normal faults and tension fractures in the gold-bearing vein systems of the Seikoshi mine, is the effect of a bending of the Philippine Sea plate which is sinking under the Eurasia plate along the Suruga trough (Nakamura, 1981).

The stress is rather low at the Shibakawa site, west of Mt. Fuji., which is located on the crest just over a northeast-southwest trending active thrust fault with left-slip component, which is one of the northern extensions of the Suruga trough.

The results of in situ stress measurements suggest that the general orientation of maximum horizontal compression is northwest-southeast in the southern Kanto and Tokai regions, but that the stress field is disturbed to form areas of stress concentration or stress release, where the horizontal maximum compression tends to be nearly north-south.

Disastrous major earthquakes occur along the plate boundaries in the southern Kanto and Tokai regions such as the Great Kanto earthquake along the Sagami trough and the suggested Tokai earthquake along the Suruga trough. The area of stress disturbance, where the direction of horizontal maximum stress is nearly north-south, are directly affected by the plate interaction and possibly make the most sensitive and critical areas (so called "Tsubo" in Japanese) for prediction of major earthquakes in the Kanto-Tokai region.

4. STRESS CHANGE MONITORING

As an abnormally high compression of the north-south trend was detected in Tanzawa, a stress change meter was inserted at a depth of 14.89m in the Tanzawa D borehole after the measurement of absolute stress by overcoring (Fig.3) This stress change meter is a cylinder of neat cement which contains four displacement meters of electric resistance strain gauges. The stress change meter is inserted into the borehole and grouted with the same kind of cement paste.

As this stress change meter can practically be considered a uniform cylindrical inclusion of neat cement in rock, the stress change in rock can be

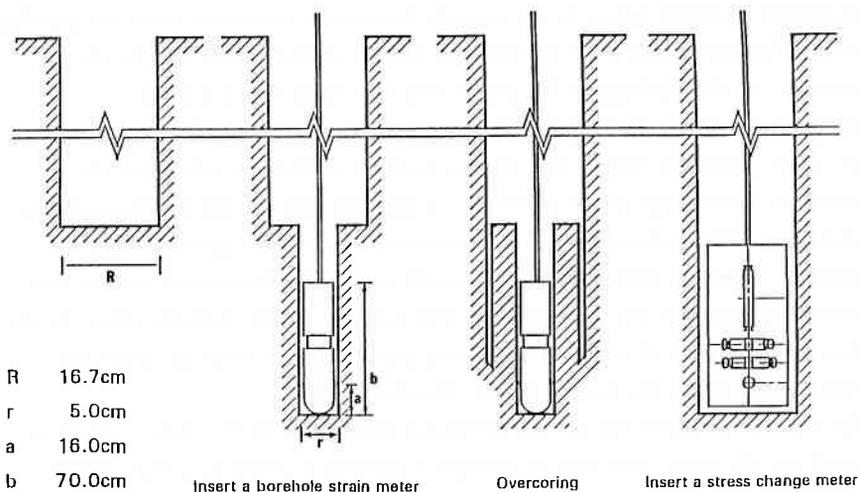


Fig.3 Inserting of a stress change meter after the measurement of absolute stress by overcoring.

calculated from the strain of inclusion if the elastic moduli of rock and inclusion are known.

The maximum shear stress in the horizontal plane (that is a half of maximum horizontal deviator stress) gradually increased after a large earthquake (M6.7) which occurred 63km south of measurement site at the end of June, 1980 (Fig.4) After the shear stress increased more than 100 kPa, many small earthquakes occurred in the Tanzawa area. The largest earthquake in this swarm of activity marked M 4.5 in April, 1981. This observation indicates the significance of stress change monitoring for earthquake predictions.

5 CONCLUSION

Improvements should still be made on many points about the techniques for stress measurements of the earth's crust. Different methods for stress measurement indicate similar stress orientation and the same type of stress state. The measured state of stress usually agrees with the tectonically suggested state of stress. The stress measurement in the Kanto-Tokai region indicates the interaction of lithospheric plates.

Although the measured absolute value of stress is uncertain, the stress measurement technique can allow us to detect areas with an abnormal state of stress. Such a tectonically disturbed area is important for the prediction of

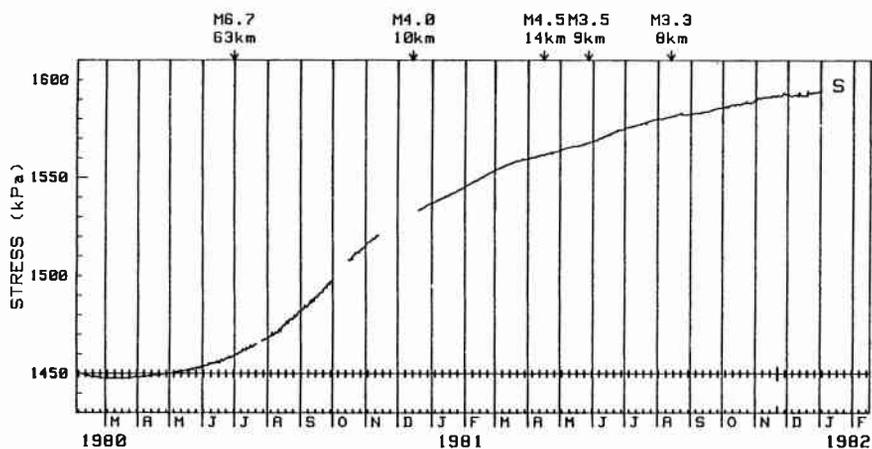


Fig.4 Change of maximum shear stress in the horizontal plane in Tanzania. Magnitude of earthquakes and distances from the measurement point are shown.

earthquakes. The monitoring of stress change is also effective for detecting a build-up of tectonic stress which may cause earthquakes.

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