On the Crustal Strain Accompanied by a Great Earthquake

by

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Abstract

In order to study the forecasting of the earthquake, the Disaster Prevention Research Institute of Kyoto University has been observing the crustal deformation with various instruments at several stations. The writer tried to study the crustal deformation before and after the Yoshino Earthquake of July 18, 1952 with the data obtained at Ide Observatory.

1. Introduction

Numerous great earthquakes have ever given a great deal of damages on human lives and properties in this country by the reason why she is called "The Nation of Earthquake." Whenever we think about the damages in the past, we can not help feeling the necessity to research and establish some preventive measures for the elimination of the damage to the minimum on the occasion of accidental earthquakes. Looking over the damages in the past, most of them have been caused by the destruction of all kinds of constructions. If we could prevent the destruction of these, the damages would be extremely eliminated. Among them, buildings are the most related to the damages of our lives and properties. Therefore it is a sine qua non to contrive to designing the aseismatic buildings. For this purpose, first thing to do will be the pervasion of earthquake-proof and fire-proof buildings, in another words, constructing the ferro-concrete buildings. To our regret, however, due to the present economical condition, the pervasion of these buildings are prevailed only on some offices, big stores, amusement facilities and a little part of apartment houses. Still we shall have to depend on the wooden houses for our dwelling for a respectably long period in future. Therefore in order to prevent our houses from earthquake damages, we must give our effort on aseismatic designing buildings not only on newly built houses but on old built houses which may well be said the most effective measures for preventing the damages. For the purpose of aseismatic designing, we should examine the criterion for earthquake-proof on houses and give some supplemental aid to strengthen on the houses economically when required. On this point of view, the writer already obtained and published the result of the examination of criterion for earthquake-proof on the wooden houses giving some vibration on them.

No matter how such an examination has been undergone, however, we with the human nature are apt to think it silly and trifle with the preventive measures with much expense against uncertain and accidental earthquake, as old saying goes like "Danger past, God forgotten." Therefore if we could foretell the location and time of the earthquake-occurrence and the scale of the earthquake we could promote the pervasion of aseismatic designing buildings and be ready for it and reduce the damage on both our material losses and mental shocks. But, it is indeed very difficult problem for us to forecast of the earthquake now that most of substances under the ground are yet scarcely explored and we can hardly foretell the earthquake-occurence theoretically. Setting the cause of the earthquake aside, the seismic vibration occurs by the occurrence of crustal destruction under the ground reaching the crustal strain to a certain limit. It is certain to be some clue for the forecasting of the earthquake to detect the crustal strain by any means around the vicinity of ground surface, as there must be some deforme on the crust before this destruction.

Thus Kenzo Sassa and Eiichi Nishimura have been observing the ground-strain and ground-tilt by use of extensometers and tiltmeters since some 20 years ago and researching the forerunning of the earthquake, the crustal strain, around the epicentre before the great earthquake. These results of research were already published frequently. The peculiar crustal deformations were detected on the occasions of the Tottori Earthquake of Sept. 10, 1943, the Tonankai Earthquake of Dec. 7, 1944, the Nanki Earthquake of Apr. 26, 1945 and the Daishojioki Earthquake of Mar. 7, 1952. The writer also has begun to observe the crustal deformation before the earthquake-occurrence since 1951 with the extensometers and tiltmeters at Ide Observatory which was reformed the adit of an abandoned copper mine located at Ide-cho, Tsuzuki-gun, Kyoto prefecture (135°49.5'E, 34°47.9'N) under the guidance of Prof. K. Sassa.

After that the earthquake called by name of Yoshino Earthquake was felt at about 1.10 on July 18, 1952 in the whole districts of Kinki, Chugoku, Shikoku, Chubu and parts of Kanto, Tohoku and Kyushu districts. Its epicentre was at southern part of Nara prefecture, 135.80° E, 34.10°N as shown in Fig. 1 and its focal depth and seismic magnitude were 70 km and 7 in Pasadena Scale respectively. But the damage was so slight as its epicentre was in mountainous area and its hypocentre was so deep in the ground. In this Observatory, where is located 100 km from hypocentre and 72 km from the epi centre, we could observe the peculiar crustal deformation before and after the earthquake-occurrence.

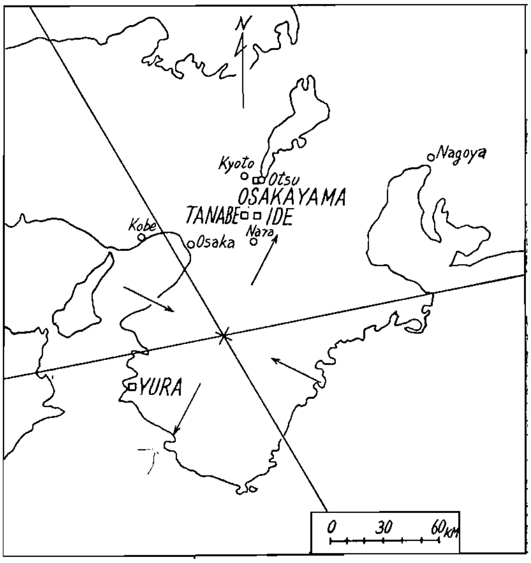


Fig. 1 Positions of the observatories and epicentre of the Yoshino Earthqnake and directions of initial ground motions in its earthquake. (The crossing full lines show the nodal line.)

The writer will report the details of the result of the observation.

2. Result of observation

In this observatory, instruments have been gradually increasing in number year after year and all kinds of instruments as shown in Table 1 arranged at present. But in those days of the Yoshino Earthquake, we had only 6 components of super-invar-bar extensometers. The result of observation with these instruments, the volume dilatation calculated from the observation with 3 components of "1", "2", "3" which are set up rectangular co-ordinate axis and the precipitation measured at Tanabe about 4 km away from this observatory are shown as in Fig. 2. Not only the variation caused by the earthquake but annual variation and the variation caused by the rainfall shoud be included in this variation. In order to find out the variation caused by the earthquake, we must eliminate the variation caused by rainfall and an annual variation. The writer will omit the method of this elimination as be already fully described in another report.

Table 1 List of instruments of Ide Observatory.

Mark	Azimuth	Sensitivity	Place
1. Super-invar-bar extensometer			
1	Vertical	(10^{-8}/mm) 5.54	O_1
2	Horizontal N88°E	4.92	O_1
3	Horizontal N 2°W	10.74	O_1
4	Dip 50° N88°E	3.46	O_1
5	Dip 66° N2°W	2.78	O_1
6	Horizontal N77°W	2.30	O_1
3′	Horizontal N2°W	6.12	O_1
2′	Horizontal N82°W	2.80	C
2. High magnification extensometer			
I	Vertical	0.329	O_1
II	Horizontal N88°E	0.492	O_1
III	Horizontal N2°W	0.892	O_1
3. Changing inductance type extensometer (Tele-metrical Extensometer)			
E_1	Horizontal N82°W	7.5	C
4. Photocell type extensometer (Tele-metrical extensometer)			
E_p	Horizontal N82°W	3.7	C

Mark		Azimuth	Sensitivity	place
5. Wire resistance strain meter (Tele-metrical extensometer)				
E_U		Horizontal N82°W	(10^{-8}/mm) 3.4	C
E_F		Horizontal N82°W	5.5	C
6. Horizontal pendulum type tiltmeter				
T.M.	A	N45°E	($10^{-2\prime\prime}$/mm) 2.0	O_1
	B	S45°E	2.0	O_1
T.M.′	A′	N45°W	3.0	O_2
	B′	N45°E	3.0	O_2
7. Photocell type tiltmeter (Tele-metrical tiltmeter)				
$T.M._P$	A'_p	N45°W	4.0	O_2
	B'_p	N45°E	4.7	O_2
8. Discharge meter				
D			(water level mm/mm) 5.3×10^{-2}	O_1
D′			1.7×10^{-2}	C
9. Thermometer				
T			0.034(°C/mm)	O_1

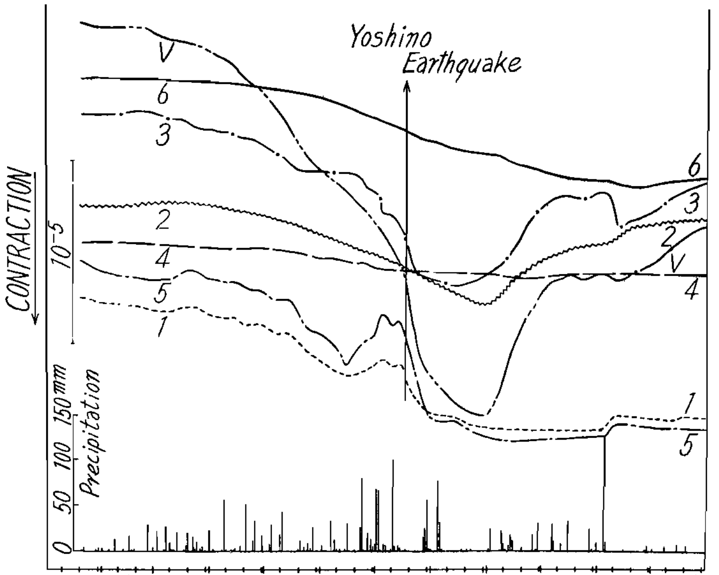


Fig. 2 Variations of linear strains observed at Ide Observatory and volume dilatation calculated from those variations and daily precipitation observed at Tanabe.

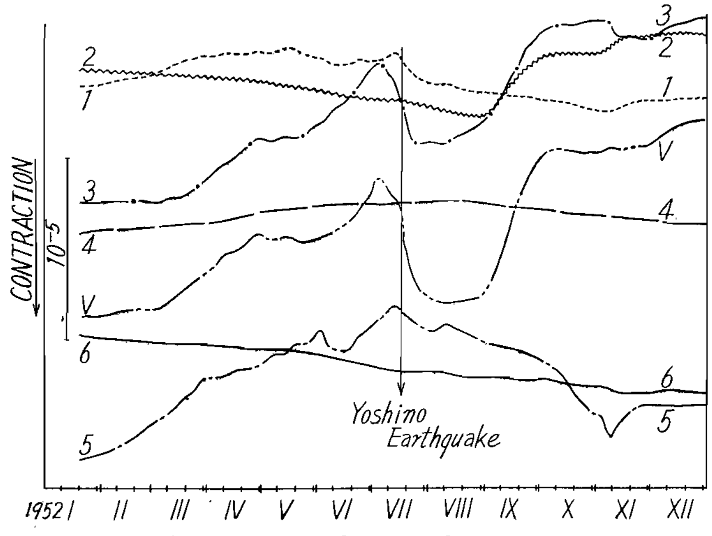


Fig. 3 Variations of linear strains and volume dilatation of which eliminated annual variations at Ide.

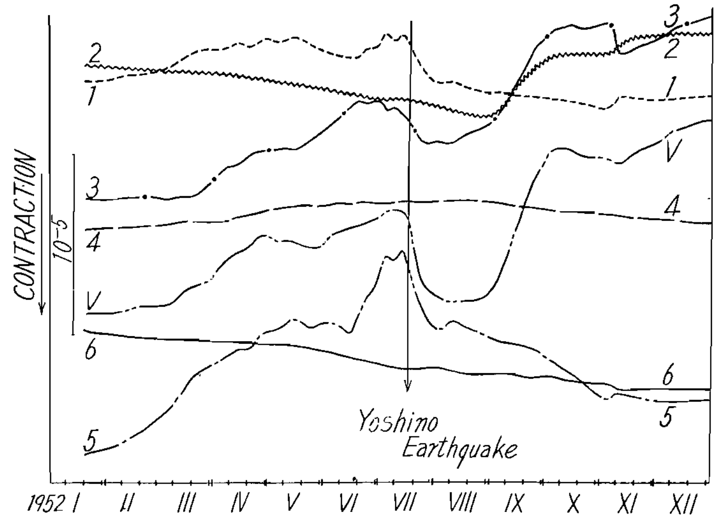


Fig. 4 Variations of linear strains and volume dilatation of which eliminated annual variations and variations caused by rainfall at Ide.

First of all the result of the elimination of annual variation from the variation obtained by the observation is shown in Fig. 3. And then the result of the elimination of the variation caused by the rainfall from the variation on components "1", "3", "5" which were influenced greatly by rainfall is shown in Fig. 4. On this eliminating adjustment, we used the effective curve obtained from the precipitation as we had not yet set up the discharge meter of water in the adit. Therefore the variation of Fig. 4 can be esteemed the crustal deformation related to the earthquake at this observatory before and after the Yoshino Earthquake. As this figure apparently shows us, we find the peculiar variation several months before the earthpuake-occurrence. The writer already found and published the peculiar variation several weeks before the occurrence of rock-falling in a part of adit of this observatory. Anyway though they are differed in scale, whether earthquake or rock-falling are the same phenomena of rock-breaking. Accordingly, there must be stored the strain energy which is necessary for the break of rock in the neighbourhood of that rock and it is considered that the deformation which is epuivalent to the energy comes into being on the crust.

3. Study and examination on the result of observation

Being the directions of extensometers "2", "3", "1" the axis of x, y, z

of Cartisian rectangular co-ordinate, as three components of these extensometers are set up rectangular direction on another, and postulating the components of displacement of a particle at $P(x, y, z)$ as u, v, w, the linear strains ε_x, ε_y, ε_z, the shearing strains ψ_{yz}, ψ_{zx}, ψ_{xy} and the rotating strains ω_x, ω_y, ω_z are given by following formulas.

$$\varepsilon_x=\frac{\partial u}{\partial x},\quad \varepsilon_y=\frac{\partial v}{\partial y},\quad \varepsilon_z=\frac{\partial w}{\partial z},$$

$$\psi_{yz}=\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y},\quad \psi_{zx}=\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z},\quad \psi_{xy}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x};$$

$$\omega_x=\frac{1}{2}\left(\frac{\partial w}{\partial y}-\frac{\partial v}{\partial z}\right),\quad \omega_y=\frac{1}{2}\left(\frac{\partial u}{\partial z}-\frac{\partial w}{\partial x}\right),\quad \omega_z=\frac{1}{2}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right).$$

(Instead of the suffixes of x, y, z, each component's number 2, 3, 1 of extensometers shall be converted hereafter.)

The variations of linear strins ε_1, ε_2, ε_3 are already illustrated with the mark "1", "2", "3" in Fig. 4 at Ide Observatory. And the variation of linear strains before and after the Yoshino Earthquake observed at Osakayama Observatory about 20 km awy from Ide Observatory is shown in Fig. 5. In comparing both variations observed at Ide and Osakayama Observatories, among the extensometers the components which are set up to the similar direction are as follow. The components "3" (N2°W) of the former and N2°W of the later, "2" (N88°E) of the former and N86°E and N76°W of the later. The variations of the later, are illustrated as they are observed with the instruments without eliminating the annual variations which are not known because of this short history, though the one obtained at Ide are adjusted on the annual variations and the effects caused by rainfall. Therefore it is rather unnatural to compare these variations, but the variations due to meteorological effects being very small at Osakayama where the observing

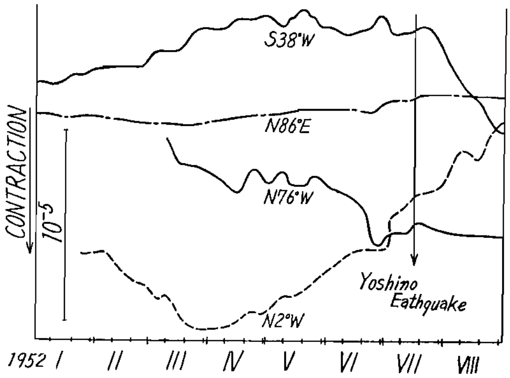


Fig. 5 Variations of linear strains observed at Osakayama Observatory. The variation of component S38°W is eliminated annual variation. (by I. Ozawa.)

room is very deep under the ground, with the exception of component N86°E at Osakayama, the variations of component "3" at Ide and N2°W at Osakayama similarly extended from around March and, on the contrary, the variations of "2" and N76°W contracted. And the variation of component S38°W at Osakayama shown in Fig. 5 is eliminated the annual variation, same one as at Ide. The variations on this component and the component "3" at Ide which is set up to the rather similar direction of the former began to extend from around March and contracted from the beginning of July before the earthquake-occurrence. Next on obtaining the ground-tilt it is presumed and obtained by rotating strains, as the tiltmeter was not set up in those days. On the variation of ground-tilt caused by the occurrence of rock-falling, the writer had ever tried to compare with the result of observation with tiltmeter and the result obtained roughly by rotating strains under such assumption that the origin of rectangular co-ordinate axis, i. e. the point of intersection of both components "1", "2", "3" is kept immovable and found they were almost resembled each other as shown in Fig. 6. Therefore, under the assump-

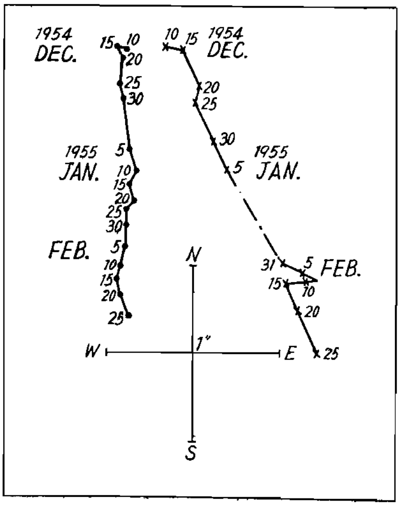


Fig. 6 Comparison of both variations of ground-tilt observed with tiltmeter and presumed from variation of linear strains.

×: ground-tilt observed with tiltmeter,
●: ground-tilt calculated from linear strains.

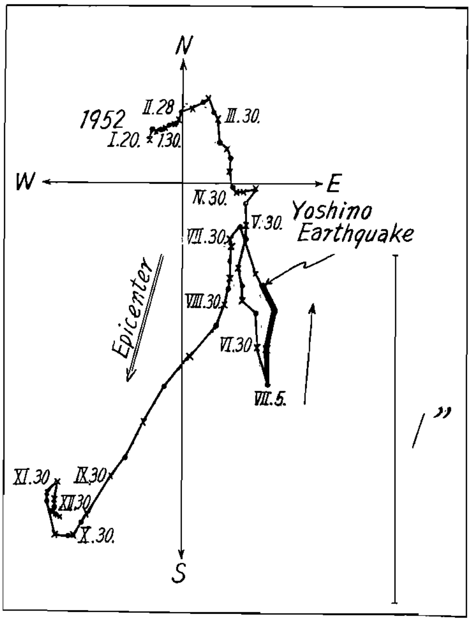


Fig. 7 Variation of ground-tilt at Ide (presumed from variations of linear strains).

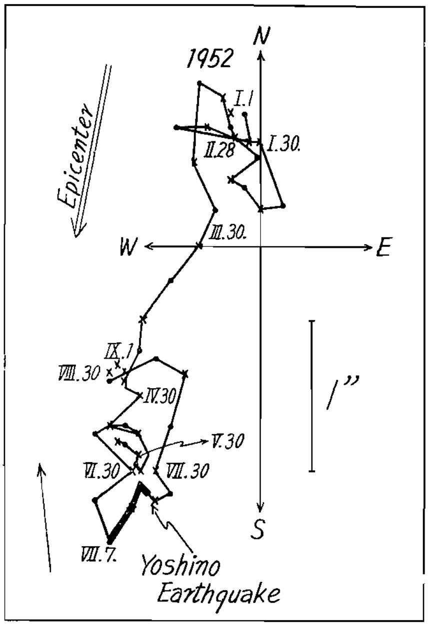


Fig. 8 Variation of ground-tilt observed at Osakayama Observatory (by I. Ozawa).

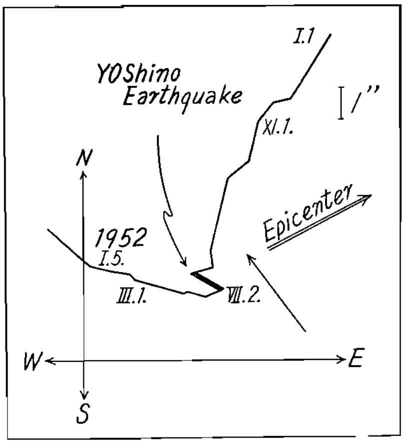
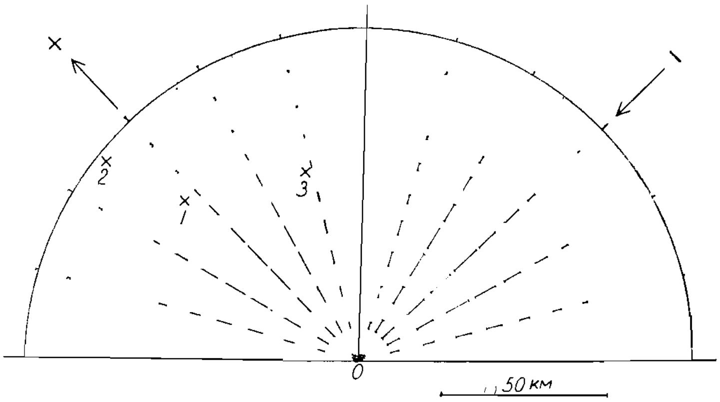
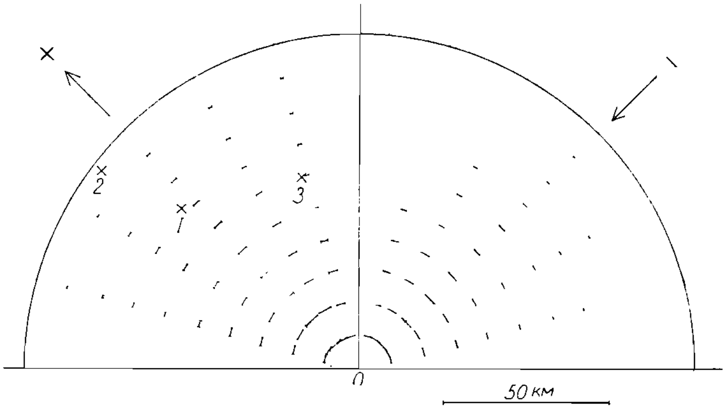


Fig. 9 Variation of ground-tilt observed at Yura Observatory (by K. Hosoyama).

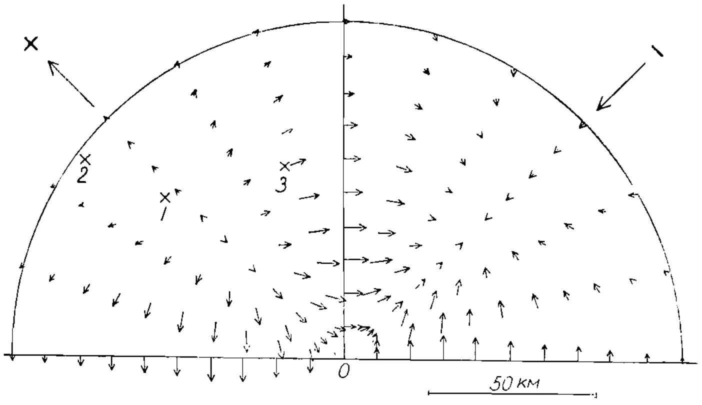
tion as mentioned above, the vector diagram of tilting motion of ground in Fig. 7 obtained roughly by rotating strains is presumed almost similar with the actual variation of ground-tilt at Ide. Now in looking over this variation together with the variations of ground-tilt, illustrated in Fig. 8 and Fig. 9, observed by I. Ozawa at Osakayama Observatory and K. Hosoyama at Yura Observatory, every one of them continued their downward tilting in the direction of the epicentre until the beginning of July and turned their tilting direction to N at Ide and Osakayama and to N-W at Yura on almost same day without much difference of the date (Ide on 5 July, Osakayama 7 July and Yura 2 July). In 1935 F. J. W. Whipple calculated elastico-dynamically the value of deformation on the surface of elastic body that will be deformed by the nucleus of seismic force which is equivalent to the crack-model studied by the late T. Shida. By these ways, the distribution of the strains on the ground surface on the occasion of the Yoshino Earthquake is obtained as shown in Fig. 10. On the other hand, the distribution of initial motion of P-wave on the occasion of the Yoshino Earthquake is shown in Fig. 1 as already drawn, and as three observatories, Ide, Osakayama and Yura, are included into the push zone and also the epicentre distances are 72 km,



(A) Radial strain.



(B) Tangential strain.



(C) Tilt.

Fig. 10 Distributions of surface strains calculated theoretically on the occasion of the Yoshino Earthquake.

+←— : Push zone, ——→ : Pull zone, O : Epicentre,

—— : Extension, ├—┤ : Contraction, ←— : Tilting direction.

1 . Ide Observatory, 2 : Osakayama Observatory, 3 : Yura Observatory.

98 km and 60 km respectively (and the forcal distances are also 100 km, 120.5 km and 92 km), the calculated tilting directions accompanied by the earthquake at these observatories should be the directions indicated by arrow marks in Fig. 7, 8 and 9. In these variations observed at these three observatories, the tilting directions are noticed to be changed to the direction theoretically calculated from the beginning of July about 10 days before the earthquake-occurrence. The results of a few observation as mentioned above may be not sufficient to deduce the crustal deformation before and after the earthquake-occurrence, but the ground seems to continue its downward tilting in the direction of the epicentre for a pretty long term before the earthquake-occurrence and also turn its tilting direction towards the direction of which movement will be accompanied by the earthquake and at the time of the earthquake and right after it, it seems to tilt greatly to that direction.

In comparing with the distribution of strain and the result of observation, though we have only two data observed at Ide and Osakayama, each component of extensometer shows the specific variation before the earthquake-occurrence, but these are not so regular variations as the ground-tilt. Especially on checking the variation observed at Ide only, it was extended to the radial direction of "3" until the beginning of July but it began to contract several days before the earthquake-occurrence. On the contrary, it was contracted to the tangential direction of "2" until the beginning of July and though it was slight change, but anyhow extended after then. On the other hand from the distribution of strain calculated about the model of the earthquake, it should extend to the direction of "3" and contract to the direction of "2". They have been changing the same way as the strain distribution until about 2 weeks before the earthquake-occurrence, but began to move opposite after then. On this point the variation of ground-strain was greatly different from the variation of ground-tilt.

Secondary, the shearing strains were obtained as shown in Fig. 11.

It is assumed that the earth's crust is homogeneous and isotropic elastic body, the principal stresses σ_1, σ_2 and σ_3 and principal shear stresses τ_{12}, τ_{23} and τ_{31} are formed as follows;

$$\sigma_1=\frac{E}{1+\nu}\left\{\varepsilon_1+\frac{\nu}{1-2\nu}e\right\},\quad \sigma_2=\frac{E}{1+\nu}\left\{\varepsilon_2+\frac{\nu}{1-2\nu}e\right\},\quad \sigma_3=\frac{E}{1+\nu}\left\{\varepsilon_3+\frac{\nu}{1-2\nu}e\right\},$$

$$\tau_{12}=G\cdot\psi_{12},\quad \tau_{23}=G\cdot\psi_{23},\quad \tau_{31}=G\cdot\psi_{31},$$

where $e=\varepsilon_1+\varepsilon_2+\varepsilon_3$ and also stand for the volume dilatation, and E, G and

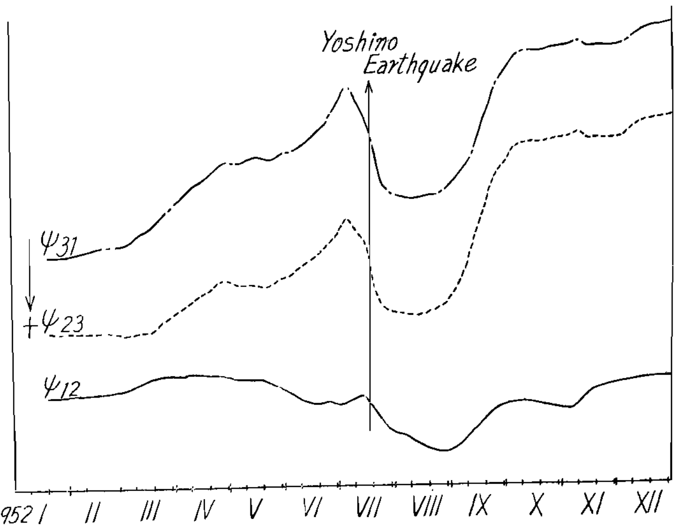


Fig. 11 Variations of shearing strains at Ide.

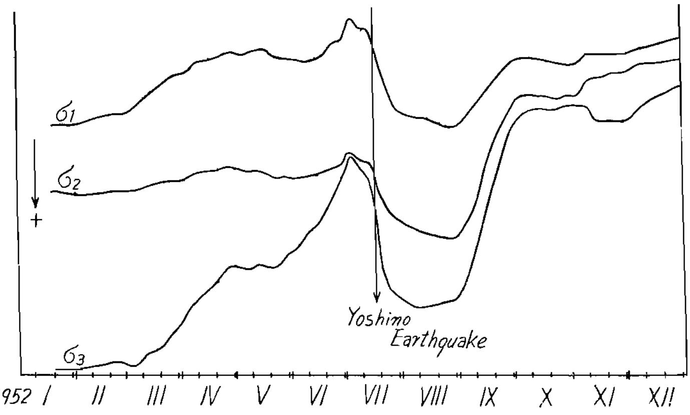


Fig. 12 Variation of principal stresses at Ide.

ν are Young's modulus, modulus of rigidity and Porsson's ratio respectively.

In the special case in which $\nu=\frac{1}{4}$, the variation of principal stresses is obtained from the variation of linear strains as shown in Fig. 12 and the graph of the variation of principal shear stresses also does same in Fig. 11. Anyhow the great specific variation is observed before the occurrence of earthquake.

Finally let us presume the energy of this earthquake from the result of observation. Keeping the eyes on that the variation became great suddenly from around March 1952 and it stopped at the beginning of July and then the reverse change was observed, it is assumed that the main energy of this earthquake has direct relation to the amount of strain observed during the period from 1 March to 7 July, however, it does not seem to store up the whole energy of the earthquake for like these short period. The variations of strains during this period became $\varepsilon_1=+1.2\times10^{-6}$, $\varepsilon_2=-1.5\times10^{-6}$ and $\varepsilon_3=+7.3\times10^{-6}$ (+ : extension). The strain energy E stored up within a unit volume of rock is formed as follows;

$$E=G\left[\frac{1-\nu}{1-2\nu}(\varepsilon_1+\varepsilon_2+\varepsilon_3)^2-2(\varepsilon_2\varepsilon_3+\varepsilon_3\varepsilon_1+\varepsilon_1\varepsilon_2)\right].$$

In the case in which Lame's constant $\lambda=\mu$, so that $\nu=\frac{1}{4}$, using $\lambda(=\mu)=10^{10}$ (This value was obtained by the observation of strain caused by the full water in the Sabo-dum near this observatory.), it becomes $G=10^{10}$ and $E=0.836$. (Hereafter, all the numerical quantities will be expressed in C.G.S. system.)

On the other hand, the variations of strains at Ide and Osakayama were great as described above from around March 1952 until the beginning of July. Therefore it is to be supposed that the two have some relation with each other. In order to compare these variation quantities of strain, calculating the variation quantity of strain on the azimuth of N38°E at Ide which is the same azimuth of extensometer at Osakayama, it is obtained as 5.0×10^{-6} from the result of observation on the components "2", "3", "6" which are set up to different azimuth one another. I. Ozawa had ever tried to obtain the value of $\lambda(=\mu)$ of the rock near the Osakayama Observatory which was obtained by the strain caused by the earth tide. And its value was about 10^{10}. It is much the same as the value the writer obtained at Ide. Therefore the relation between strain and epicentral distance is obtained as follow from each variation of strain of N38°E direction at Ide and Osakayama as 5.0×10^{-6}, 3.1×10^{-6} and epicentral distances of both observatories as 100 km and 120.5 km respectively.

$$\frac{5.0\times10^{-6}}{3.1\times10^{-6}}=\left(\frac{120.5}{100}\right)^n,$$

$$n=2.55.$$

The directions of N38°E at these observatories are nearly the directions towards epicentre both. From the result above mentioned, the variation of horizontal strain in the direction of the epicentre is in inverse proportion to the epicentre distance r to the 2.5th. For the purpose of simplification of calculation, we will proceed our discussion under the following assumption, namely the material within the sphere of radius r_0 of the focus (Let us call this sphere the "earthquake nucleus".) will be strained until the stored strain energy within a unit volume of rock reaches the maximum energy x to be stored up within it. At the time of earthquake-occurrence, the stored energy is sent out from the earthquake nucleus by some kind of mechanism or other and the strain energy stored up within a unit volume of rock without the earthquake nucleus is in inverse proportion to the epicentre distance r to the 5th.

Under the assumption as mentioned above, the strain energy Er_0 that is to be stored within the earthquake nucleus is given by

$$Er_0=\frac{4}{3}\pi r_0{}^3 x\ ,$$

where x may be taken to be $3\times10^3\sim2\times10^4$. And at $r>r_0$ without the earthquake nucleus, the strain energy within a unit volume of rock forms the following formula.

$$E=\frac{k}{r^5}\ .$$

If we put $E=0.836$ and $r=100\,\text{km}$ at Ide Observatory in this formula,

$$k=0.836\times10^{35}$$

is obtained. If we take $x=3\times10^3\sim10^4$, the radius r_0 of the earthquake nucleus

$r_0=1.94\times10^6\sim1.53\times10^6$ $(=19.4\,\text{km}\sim15.3\,\text{km})$ are obtained. And the strain energy Er_0 stored within the earthquake nucleus

$$Er_0=8.8\times10^{22}\sim14.3\times10^{22}$$

are obtained. On the other hand, the strain energy E_∞ that is to be stored in the body outside the earthquake nucleus are obtained as follows;

$$E_\infty=\int E\,dV=4\pi k\int_\infty^{r_0}\frac{dr}{r^3}=2\pi k r_0{}^{-2}=14.0\times10^{22}\sim22.5\times10^{22}.$$

It is to be supposed that the earth's material is strained due to some force applied to the earthquake nucleus and the distribution of the strain above mentioned comes into being in the crust. Thus the amount of energy given by some force within the earthquake nucleus would be the same as that of energy given by the same force in the body outside the earthquake nucleus. But, in comparison of both values Er_0 and E_∞, the value of E_∞ is far larger than the value of Er_0.

Generally, if the case is one in which the force is applied to a certain part of the elastic body, the energy E_0 stored is

$$E_0 = E_s + E_w,$$

where E_s is the energy that is dissipated for the work in neutralizing the strain stored in the body and E_w is the energy that is dissipated as elastic waves energy, in the release of the force.

On the other hand, as shown in Fig. 4 the variations of linear strains become great suddenly from around Mar. and show the monotonous variation until the beginning of July about 10 days before the earthquake-occurrence. But the reverse change was observed from the beginning of July and this variation stopped towards the middle of Aug. and then afterwards another variation began. We suppose that the variations of linear strains from the beginning of July until the middle of Aug. show the strains resumed due to the earthquake-occurrence, in other words, the release of the force.

Then, as above-mentioned, the amounts of strain energy E_∞ stored before the earthquake-occurrence in the body outside the earthquake nucleus are

$$E_\infty = 14.0 \times 10^{22} \sim 22.5 \times 10^{22},$$

and taking $\varepsilon_1 = -2.0 \times 10^{-6}$, $\varepsilon_2 = -1.0 \times 10^{-6}$ and $\varepsilon_3 = -4.5 \times 10^{-6}$ as the amount of strain resumed after the earthquake-occurrence, the strain energy E_∞' resumed in the body outside the earthquake nucleus will be $8.9 \times 10^{22} \sim 14.3 \times 10^{22}$.

Looking the both values, E_∞ and E_∞', we can find out that 63.6 % of the amount of strain energy stored in the body outside the earthquake nucleus before the earthquake-occurrence is equal to the amount of strain energy resumed after the earthquake-occurrence. This is meant that 63.6 % of the amount of strain energy stored in the earthquake nucleus is dissipated for the work in neutralizing the strain energy stored in the body outside the earthquake nucleus due to the earthquake-occurrence and the remainder, 36.4 % of the amount of strain energy stored in the earthquake nucleus is dissipated as elastic wave energy then.

Therefore the energy E of the earthquake, that is the energy of the elastic wave are obtained as follows;

$$E = E_w = Er_0 \times \frac{E_\infty - E_\infty'}{E_\infty} = 0.364 \times Er_0 = 3.2 \times 10^{22} \sim 5.2 \times 10^{22}.$$

On the other hand, according to the 1956 formula of B. Gutenberg and C. Richter, the energy E of an earthquake is related to its magnitude M as follows;

$$\log E = 1.5M + 11.8.$$

If we put $M=7$ into this formula, which is the magnitude of this Yoshino Earthquake,

$$E = 2.0 \times 10^{22}$$

is obtained which value is smaller than any of the values $3.2\times10^{22} \sim 5.2\times10^{22}$ estimated by the present writer. But both values may be said to be in concordance with each other considering the nature of the problem of this kind.

In 1954, T. Utsu and A. Seki published an interesting article in which they studied the relation between the aftershock area A and the magnitude M of the main-shock. They obtained a formula as follows,

$$\log A = M + 6.$$

The aftershock area A is the horizontal area in which aftershocks of a large earthquake take place.

If we put the magnitude $M=7$ of the Yoshino Earthquake into this formula,

$$A = 10^{13}$$

is obtained. If the aftershock area A is the earthquake nucleus projected on the earth's surface, which assumption appears to be a reasonable one,

$$A = 10^{13} = \pi r_0^2$$

or $$r_0 = 1.8\times10^{6} \ (=18\,\text{km}).$$

This value agrees almost with the values $r_0 = 19.4\,\text{km} \sim 15.3\,\text{km}$ estimated by the writer.

4. Conclusion

As the writer tried to study the problem under several assumptions mentioned above, the peculiar change of the crustal strain before the great earthquake does not appear lawlessly, but it may be said to have close relation with the earthquake as the phenomena forerunning earthquake.

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