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A CONSIDERATION ABOUT THE MECHANISM OF OCCURRENCE OF LARGE-SCALE EARTHQUAKES, I.

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ABSTRACT

It is pointed out that the period of the first maximum ground-motion of *p*-waves due to a large-scale earthquake as observed at various seismological stations shows a systematic pattern of distribution concerning the azimuthal angles of the stations as seen from the origin of the earthquake. This regularity may be explained by assuming that the seismic crack composing of a series of small cracks and generating seismic waves, develops with a certain definite velocity from one end to the other along either of the nodal lines of initial motions and that the period of waves originating from the crack and propagating into various directions is modified by Doppler effect.

Further, the writer has applied the above-mentioned idea with satisfactory results to observational data for Kita-Tango (March 7, 1927), Kita-Izu (November 26, 1930), Tottori (September 10, 1943), Tônankaidô (December 7, 1944), Nankaidô (December 21, 1946), Tokachi-Oki (March 4, 1952) Earthquakes. Finally, the writer gives the result of a model experiment carried out for the purpose of testing the assumptions of his idea by glass plate.

1. Introduction

If we examine the period of the first maximum ground-motion of *p*-waves observed at seismological stations due to a large-scale earthquake, we may throw light on the physical meaning as regards the regularity of distribution of this period, by assuming that a great crack runs in a given direction along one of the so-called nodal lines of initial motions of *p*-waves and that the seismic source moves along the crack which generates the elastic waves. And if the wave source moves in an elastic medium, we might recognize the evidence of Doppler effect in the propagation of seismic waves. Based on this idea, it is possible to account for the regularity of symmetrical pattern regarding the above-mentioned time distribution in a large-scale earthquake.

It is found that the azimuthal distribution of the calculated periods of the first maximum ground-motion of *p*-waves coincides well with that of the observed periods. Thus, the writer is able to make somewhat clear the mechanism of occurrence of some remarkable earthquakes concerning the geographical or azimuthal distribution of the period of the first maximum ground-motion of *p*-waves observed at seismological stations.

2. On the Fukui Earthquake of June 28, 1948

To begin with, the writer deals with the Fukui Earthquake which occurred on June 28, 1948. The collective report on this earthquake has been already published by the authorities of the Central Meteorological Observatory and the Earthquake Research Institute (**1**). The distribution pattern showing the so-called four-quadrants type with respect to the push and pull of initial impulsive motions of p-waves was given by Dr. T. Hirono, as reproduced in Fig. 1 (**2**).

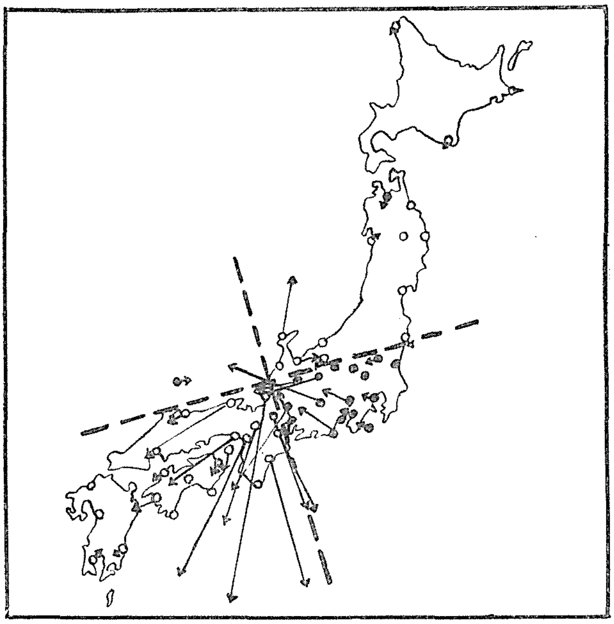

Fig. 1. The directions of initial ground-motions in the Fukui Earthquake of June 28, 1948.

Assuming that, in this Fukui Earthquake, a great crack runs horizontally from north to south along the nodal line in the direction of N 20° W at the seismic centre and considering that the seismic waves are modified by Doppler effect as the seismic source accompanied by the crack moves, the writer calculated the period of the first maximum ground-motion of p-waves observable at various stations, and compared it with that of actual ground-motion of p-waves obtained from the recorded seismogram by integration. This result will be described later.

(i) The propagation speed and length of crack

Selecting some comparatively clear seismograms from those recorded in the Fukui Earthquake at various seismological stations located within the distance of 320 km from the epicentre, the writer has calculated the period T of the first ground-motion of p-waves by integration from clear horizontal seismograms included in the above report.

In the first place, taking the focal depth of the concerned earthquake as 33 km (**3**), we have discussed the correlation between the focal distance S to each seismological station and the period T, as given in Table I, obtaining sampling correlation coefficient r as 0.0073. Since, however, this value is less than each value in the significance level of 5% and 1% respectively, with a degree of freedom $\phi=7$, it is not significant. Also, testing the linearity of regression between S and T by means of statistic F, we have obtained the value $F=3.067$, which, however, is not significant because this value is less than either of 6.59 and 16.69 corresponding to the significance level of 5% and 1% respectively, with degrees of freedom $\phi_1=4$, $\phi_2=3$. Thus, it is difficult to assert the existence of the correlation between the focal distance S and the initial period T.

Table I
(The Fukui Earthquake)

No.	Station	T(sec)	S(km)	$\pm\alpha$
1	Abuyama	2.3	139	−0.744
2	Ôsaka	2.7	184	−0.726
3	Owashi	2.1	223	−0.923
4	Kanazawa	3.4	76	+0.520
5	Gifu	1.8	98	−0.909
6	Tsuruga	3.0	62	−0.670
7	Toyama	3.6	113	+0.303
8	Niigata	3.3	326	+0.348
6	Wajima	3.5	159	+0.724

Next, we have calculated the propagating speed v and the length l of a crack. Assuming that a crack was formed horizontally at the focus of 33 km in depth, from north to south along the N 20° W nodal line, let V be the mean velocity of p-waves originating from the crack and α be the cosine of the acute angle between the direction towards the focus from each observation station and the direction of the formation of the crack. Also, let T_p be the initial period of the seismic source at the focus.

Then by virtue of Doppler effect, we have

$$T = T_p \frac{V \pm v\alpha}{V}.$$

Inserting the values of T and α as given in Table I into this formula and taking the mean velocity V of p-waves to be 7.5 km/sec, we have calculated the propagating speed v of the crack by the method of least squares, thus obtaining

$$v = 2.1 \pm 0.3 \text{ km/sec}.$$

Further, we assume that the time of crack formation is approximately equal to the seismic duration time t, which can be calculated by the empirical formula:

$$\log t = -0.7 + M/4,$$

where M is the magnitude of an earthquake. In the case of the Fukui Earthquake, this formula gives $t=13$ sec corresponding to $M=7.2$.

Thus, the length l of the crack in the case of the Fukui Earthquake is finally estimated to be

$$l = vt = 27 \pm 4 \text{ km}.$$

(ii) The result compared with observed values

If we assume that the crack generating the seismic waves is horizontally formed at the focus along the N 20° W nodal line from north to south, with the propagating speed $v=2.1$ km/sec; that is to say, if we assume that the seismic source moves accompanying the crack, the period T' of the first maximum ground-motion of p-waves to be observed at seismological stations can be obtained according to Doppler effect as shown in Table II. This calculated value T' agrees well with the actually observed value T.

Table II
(The Fukui Earthquake)

No.	Station	T'_{cal} (sec)	T_{obs} (sec)	$\lvert \Delta T \rvert$
1	Abuyama	2.5	2.3	0.2
2	Ôsaka	2.5	2.7	0.2
3	Owashi	2.4	2.1	0.3
4	Kanazawa	3.3	3.4	0.1
5	Gifu	2.3	1.8	0.5
6	Tsuruga	2.4	3.0	0.6
7	Toyama	3.8	3.6	0.2
8	Niigata	3.3	3.3	0.0
9	Wajima	3.7	3.5	0.2

Moreover, as the limit of errors regarding the period T is estimated as 0.4 sec, the difference $|\Delta T|$ between the values T' and T seems to be unavoidable, considering the fluctuation of assumptions, for instance, the nonlinearity of the direction of crack-formation and the speciality of the crustal structure, etc.

3. Analysis of the ground-motion of the Fukui Earthquake observed at Abuyama

Fig. 2 shows the wave-form of the actual ground-motion of p-waves before the advent of the S-waves, obtained by integrating the seismograms of the Fukui Earthquake which were recorded by two Sassa-type seismographs installed at Abuyama. These are designed to record each motion of N-S and E-W; their proper periods are both 22.4 sec, and their statical magnifications are both 1, while their damping ratios are 2.6 and 1.6 respectively.

Besides, Fig. 3 shows the wave-form projected to the vertical plane containing the direction which combines the Abuyama seismological station with the focus of the Fukui Earthquake. Here, the writer comprehends that wave-form is composed of three small cracks. Generally speaking, when the n sine waves of the same periods and amplitudes pass through a certain station with the phase difference φ, the resultant amplitude S of superposed waves, at any time t between $(n-1)\varphi$ and $n\varphi$, can be represented by

$$S = \sum_{i=1}^{n} \sin \omega(t-\overline{i-1}\varphi)\ ,$$

where the maximum amplitude of each wave has been taken as unity.

Therefore,

$$S = \frac{\sin(\omega t-\omega\varphi\overline{n-1}/2)\sin(n\omega\varphi/2)}{\sin(\omega\varphi/2)}\ .$$

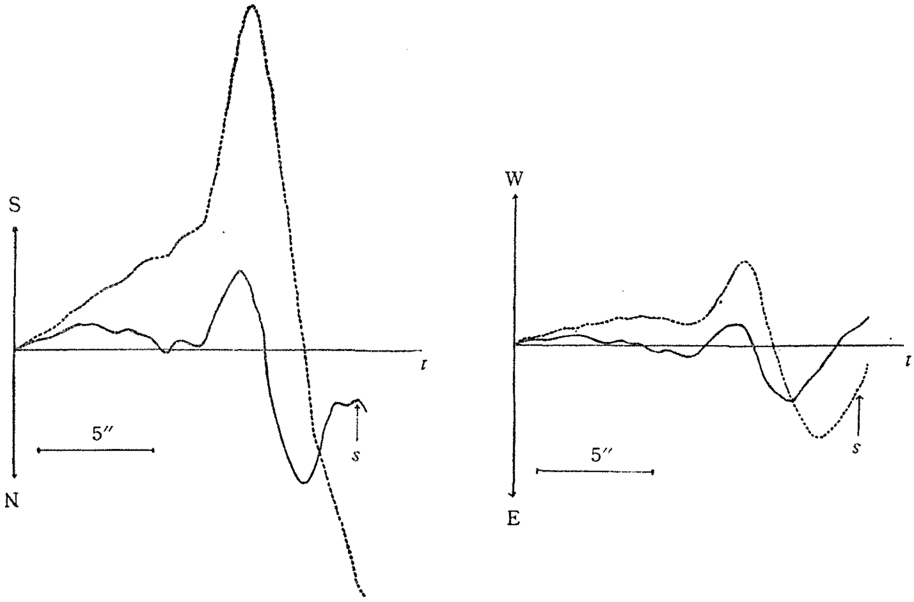

Fig. 2. The unbroken curves represent the horizontal seismograms of *p*-waves observed at Abuyama, and the dotted curves represent the horizontal ground-motions (determined by integration) connected with them.
(The Fukui Earthquake)

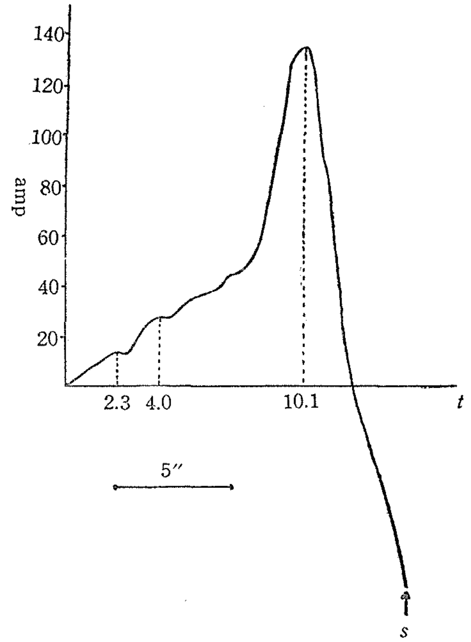

Fig. 3. The horizontal component of the ground-motion projected to the vertical plane containing the direction which combines Abuyama station with the epicentre of the Fukui Earthquake.

When n cracks generate successively at equal time-intervals of t_0 sec and equal distance-intervals of x_0 km, the phase difference φ_i among n waves arriving successively at the observational station is given by

$$\varphi_i = t_0 - \frac{x_0}{V}\cos\theta_i\,,$$

where V is the velocity of p-waves, v is propagating speed of each crack and θ_i is the acute angle between the direction of propagation of the crack and the line connecting the observation point and the starting point of each crack.

In the present case, we have $\theta_i \fallingdotseq \theta$, $\varphi_i \fallingdotseq \varphi$, so that the following formula for the angular velocity ω is obtained:

$$\omega = 2\pi \Big/ T_0\left(1-\frac{v}{V}\cos\theta\right) \qquad \text{rad./sec.}$$

Each time t_i which determines the maximum value of the resultant amplitude of the observed ground-motion of p-waves during the time between $(n-1)\varphi$ and $n\varphi$ is induced as below: Now, we measure the time t from the arrival instant of the first motion of p-waves and we consider the resultant amplitude S as the one-valued continously differentiable function of t. Thus, each time t_i above-mentioned is obtained by differentiating S once or twice associated with t, i. e., from

$$\frac{dS}{dt} = 0, \quad \frac{d^2S}{dt^2} < 0,$$

we have

$$t_i = \frac{mT_0}{4}\left(1-\frac{v}{V}\cos\theta\right) + \frac{n-1}{2}\left(t_0-\frac{x_0}{V}\cos\theta\right),$$

$$\text{for } m = 1,\ 3,\ 5, \cdots\cdots\cdots .$$

In the Fukui Earthquake, by analyzing the wave-form of the actual ground-motion of p-waves observed at Abuyama, we shall find it composed of three sine waves. Thus, we may consider that three horizontal cracks were generated successively at the intervals of the distance $x_0 = 9$ km and of the time $t_0 = 3.5$ sec in the focal region from north to south very closely along the N 20° W nodal line.

In the present circumstances, we have $\cos\theta = 0.744$, $V = 7.5$ km/sec, $v = 2.1$ km/sec, $T_0 = 4T_p = 12.2$ sec, so each t_i which fixes the first, second and third maximum parts of the superposed wave-form can be calculated as 2.4 sec, 4.0 sec and 10.4 sec, respectively. Although these times approximately correspond to the actual ones given in Fig. 3, we find that the ratios of resultant amplitudes corresponding to each maximum part of ground-motion are quite different from those of the actual ground-motion given in Fig. 3, as will be easily understood by a simple calculation.

But, if only we assume that each crack is made at different intervals of time t_0 and distance x_0 and we determine their suitable values, the ratios of the resultant amplitude among the maximum parts considerably resemble the actually observed ones as in the following explanation. In other words, we suppose that the first, second and third cracks occurred in the focal region from north to south very closely along the N 20° W nodal line with such intervals of distance x_0 and time t_0 as given by

$$x_{(12)},\ x_{(23)}\ ;\ t_{0(12)},\ t_{0(23)},$$

wherein suffix (ij) shows the notation of the number of cracks formed in these turns. When the maximum amplitudes of the three fundamental sine waves composing the wave-form of the actual ground-motion observed at Abuyama are denoted by a_1, a_2, a_3, respectively, the resultant amplitudes S obtained by superposing the three sine waves are represented by

$$S = a_1 \sin \omega t + a_2 \sin(\omega t - \omega\varphi_1) + a_3 \sin(\omega t - \omega\varphi_1 - \omega\varphi_2) .$$

Now, when we have

$$x_{(12)} = 4\,\text{km}, \qquad x_{(23)} = 6\,\text{km} ;$$
$$t_{0(12)} = 3.0\,\text{sec}, \qquad t_{0(23)} = 4.0\,\text{sec} ;$$
$$a_1 : a_2 : a_3 = 1 : 2 : 12 ;$$
$$\omega\varphi_1 = 1.684\,\text{rad.}, \qquad \omega\varphi_2 = 2.202\,\text{rad.},$$

the ratios among resultant amplitudes S_1, S_2, S_3, corresponding to each time which determines the positions of the first, second and third maximum parts of the ground-motion are calculated as follows:

$$S_1 : S_2 : S_3 = 1 : 2.1 : 10.2 .$$

The times showing each maximum part of the ground-motion are given as 2.4 sec, 9.5 sec. These values as well as the ratios of resultant amplitudes approximate to those actually observed as shown in Fig. 3.

Judging from the accuracy of present seismograms and from the assumption that the fundamental waves are composed of the sine waves having the same periods, the discordance of such a degree may be unavoidable.

Moreover, if the times T_1, T_2, T_3 required for the formation of each crack are proportional to the square roots of maximum amplitudes a_1, a_2, a_3 of the fundamental sine waves corresponding to each crack, i. e., if we have

$$T_1 : T_2 : T_3 = \sqrt{a_1} : \sqrt{a_2} : \sqrt{a_3} ,$$

using the value $t = 13$ sec as given in the foregoing § 2 (i), the times T_1, T_2, T_3 are calculated as follows:

$$T_1 = 2\,\text{sec}, \qquad T_2 = 3\,\text{sec}, \qquad T_3 = 8\,\text{sec}.$$

By combining the above-stated values with the intervals of distance and time of each crack, the distance between the starting point of the first crack and the terminal point of the third crack, the time and the mean velocity necessary for crack-formation are calculated to be 26.8 km, 15 sec and 1.8 km/sec, respectively. This mean velocity of crack-formation coincides with the above-mentioned value of 2.1 km/sec within the limit of errors. Therefore, in the Fukui-Earthquake, it would be safe to say that one great crack was horizontally formed in the focal region with the velocity of 2.1 km/sec from north to south along the N 20° W nodal line. Taking for granted, however, that the mechanism of occurrence of a large-scale earthquake is understood in such a way as to be composed of a series of small cracks, we may just as well deal with them as one crack, if only we determine suitable intervals of distance and time. As a matter of fact, however, judging from the stand-point of the mechanism of elastic wave occurrence accompanying the crack, we may arrive at a rational conclusion by regarding it as composed of three cracks.

4. Other large-scale earthquakes

The writer has applied the above-mentioned idea to the following remarkable earthquakes, i. e., Kita-Tango (March 7, 1927), Kita-Izu (November 26, 1930), Tottori (September 10, 1943), Tônankaidô (December 7, 1944), Nankaidô (December 21, 1946), Tokachi-Oki (March 4, 1952) earthquakes.

Picking up some comparatively clear seismograms, the writer has calculated the time T' which indicates the maximum part of initial ground-motion observed at seismological stations due to each earthquake, according to his idea already described. It is very interesting to notice that the above values of T' are in satisfactory agreement with the observed ones represented by T, as given in Tables III~VIII. The figures corresponding to these tables are shown in Figs. 4~9. In these figures, each short arrow shown by the dotted line along the unbroken nodal line represents the direction of crack-formation in the focal region.

Table III
(The Kita-Tango Earthquake)

No.	Station	T' (sec)	T (sec)	$\pm\alpha$
1	Kyôto	0.8	0.7	-0.982
2	Kôchi	1.4	1.6	-0.515
3	Kôbe	0.8	0.6	-0.921
4	Sumoto	1.0	0.9	-0.819
5	Sendai	2.1	2.0	+0.087
6	Tôkyo	1.5	1.7	-0.431
7	Numazu	1.3	1.6	-0.588
8	Hamada	2.2	2.1	+0.174

Further, each value of the crack-length relative to each earthquake taken up here is estimated as follows:

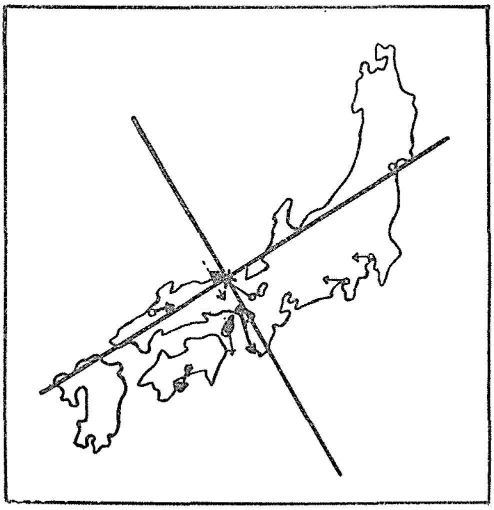

Fig. 4. The directions of initial ground-motions in the Kita-Tango Earthquake of March 7, 1927. The crossing unbroken lines show the so-called nodal lines, and arrow drawn with dotted line along one of them represents the direction of cracking.

Kita-Tango Earthquake	34 ± 5 km	($M = 7.6$)	
Kita-Izu Earthquake	28 ± 4 km	($M = 7.3$)	
Tottori Earthquake	29 ± 4 km	($M = 7.4$)	
Tônankaidô Earthquake	42 ± 6 km	($M = 8.0$)	
Nankaidô Earthquake	46 ± 7 km	($M = 8.2$)	
Tokachi-Oki Earthquake	49 ± 7 km	($M = 8.2_5$)	(4)

Table IV
(The Kita-Izu Earthquake)

No.	Station	T' (sec)	T (sec)	$\pm\alpha$
1	Akita	2.1	2.0	+0.998
2	Ôsaka	0.9	1.0	−0.292
3	Kumagaya	2.1	1.9	+0.982
4	Sionomisaki	0.6	0.5	−0.629
5	Hachijojima	0.4	0.4	−0.917
6	Hikone	1.1	0.9	−0.070
7	Maebashi	2.1	2.3	+0.997
8	Misima	0.6	0.6	−0.725
9	Mera	1.0	0.9	−0.276
10	Wajima	1.8	1.7	+0.713

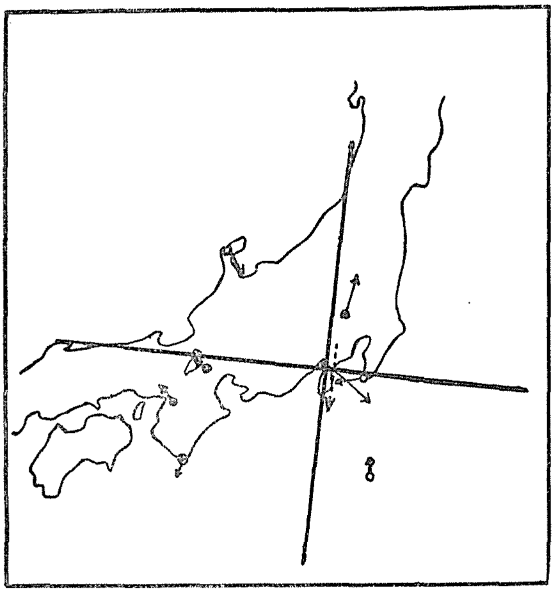

Fig. 5. The directions of initial ground-motions in the Kita-Izu Earthquake of November 26, 1930. The crossing unbroken lines and arrow are the same as those in Fig. 4.

Table V
(The Tottori Earthquake)

No.	Station	T' (sec)	T (sec)	$\pm\alpha$
1	Ôsaka	1.6	1.8	−0.515
2	Kôbe	1.7	1.9	−0.407
3	Sumoto	1.8	1.5	−0.105
4	Takamatsu	2.1	2.0	+0.454
5	Hikone	1.4	1.3	−0.887
6	Murotomisaki	2.1	2.0	+0.358
7	Yonago	2.4	2.6	+0.970

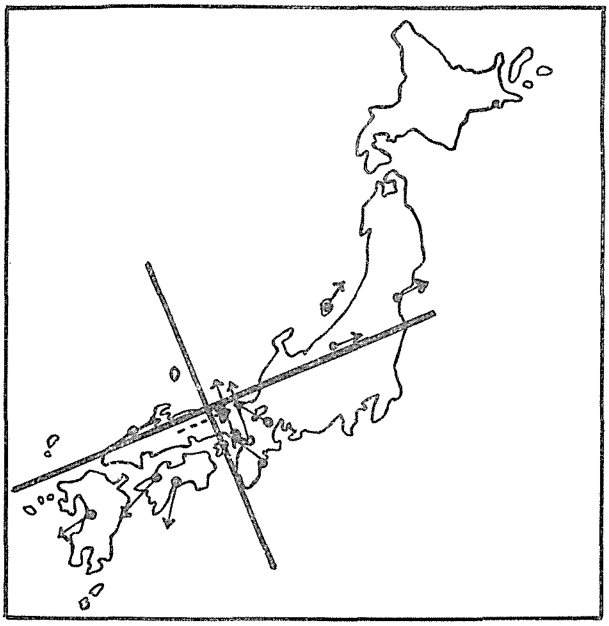

Fig. 6. The directions of initial ground-motions in the Tottori Earthquake of September 10, 1943. The crossing unbroken lines and arrow are the same as those in Fig. 4.

Table VI
(The Tônankaidô Earthquake)

No.	Station	T'(sec)	T(sec)	$\pm\alpha$
1	Owashi	1.6	1.3	−0.848
2	Kyôto	2.0	2.0	−0.682
3	Sionomisaki	1.6	1.7	+0.927
4	Nara	1.6	1.7	−0.656

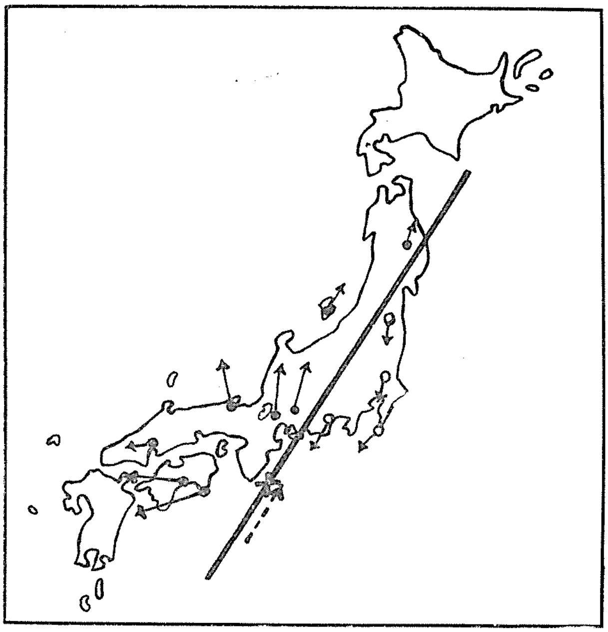

Fig. 7. The directions of initial ground-motions in the Tônankaidô Earthquake of December 7, 1944. The unbroken line and arrow are the same as those in Fig. 4.

Table VII
(The Nankaidô Earthquake)

No.	Station	T'(sec)	T(sec)	$\pm\alpha$
1	Ôsaka	2.5	2.4	−0.814
2	Kameyama	2.4	2.3	−0.980
3	Kôchi	3.5	3.8	+0.242
4	Kyôto	2.5	2.4	−0.871
5	Hikone	2.4	2.4	−0.943

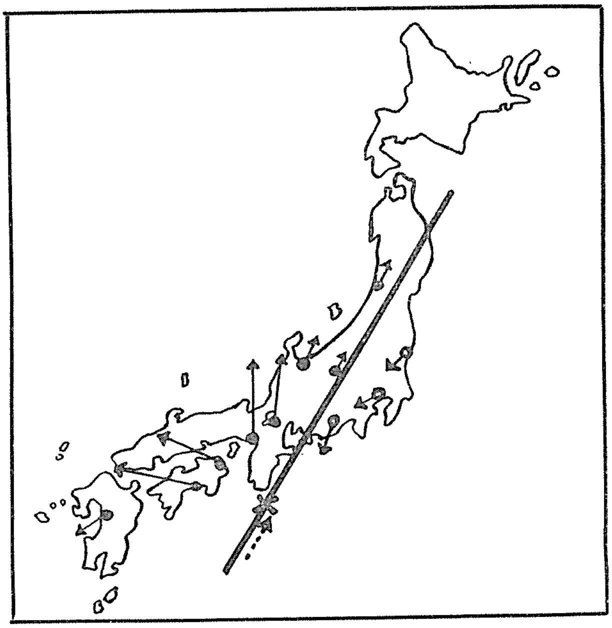

Fig. 8. The directions of initial ground-motions in the Nankaidô Earthquake of December 21, 1946. The unbroken line and arrow are the same as those in Fig. 4.

Table VIII
(The Tokachi-Oki Earthquake)

No.	Station	T' (sec)	T (sec)	$\pm\alpha$
1	Aomori	0.9	1.0	−0.771
2	Obihiro	1.4	1.2	+0.528
3	Kushiro	1.5	1.7	+0.891
4	Sapporo	1.2	1.2	+0.086
5	Sendai	0.8	0.8	−0.990
6	Tsukubasan	0.8	0.8	−0.988
7	Hachinoe	0.9	0.9	−0.907
8	Miyako	0.9	0.8	−0.928
9	Wakkanai	1.4	1.4	+0.640

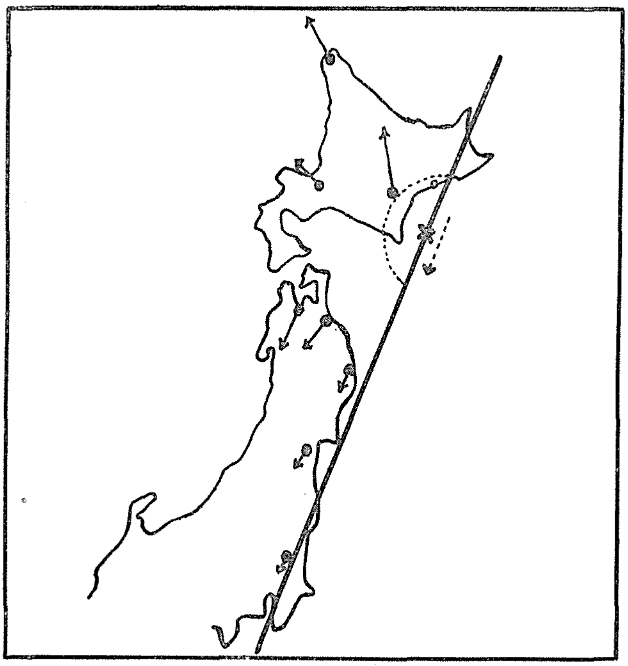

Fig. 9. The directions of initial ground-motions in the Tokachi-Oki Earthquake of March 4, 1952. The unbroken line and arrow are the same as those in Fig. 4.

When we consider the mechanism of occurrence of seven foregoing remarkable earthquakes which showed distinct nodal lines in connection with the regularity of the geographical or azimuthal distribution as regards the period of the first maximum ground-motion of each earthquake, it is of great interest to notice a satisfactory coincidence of the calculated period with the observed one, if only we apply Doppler effect to the generated waves, assuming that the crack is formed along the nodal line and the elastic waves accompany the crack. In other words, if we consider the physical meaning of the geographical or azimuthal distribution with regard to the above initial period from the stand-point of the movement of the seismic source accompanying the formation of the crack, we shall be able to give a new phenomenological explanation to the mechanism of occurrence of large-scale earthquakes.

5. A model experiment

In order to establish the validity of the writer's assumptions, the following simple experiment with glass plate was tried. First, let us describe an outline of this experiment. As shown in Fig. 10, the rectangular glass plate abcd (21 cm × 31 cm × 0.2 cm) is stuck to the square glass plate ABCD (61 cm × 61 cm × 0.2 cm) with a binding agent, for instance, cellophane tape, and all the plates are supported on the stay at its gravity-centre.

Thus, let us look at Fig. 10. (i) When we strike the glass plate at the point 0, and (ii) when the crack runs through the plate abcd, from e to g along the line ef, the moving coils which are set up at the positions marked with the signs ①, ②, ③ on the glass plate ABCD, catch tremors propagating through the glass plate in the cases of (i) and (ii), respectively.

In this manner, the tremors caught by moving coils at the positions ①, ②, ③ are optically recorded on the roll paper set up in the oscillograph. In the case of (ii), however, the plate abcd is previously damaged by a diamond pencil for the purpose of inducing the crack along the line ef on the plate abcd.

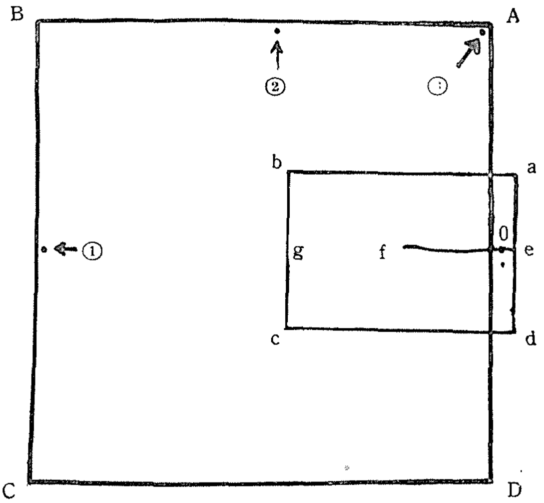

Fig. 10. The rectangular glass plate abcd is previously damaged by a diamond pencil for the purpose of inducing the crack along the line ef, and is stuck to the square glass plate ABCD as shown in this figure.

When we heat the plate abcd near the point e with the flame of an alcohol lamp a crack will run through the plate abcd from e to g along the line ef on it.

Judging from the result of such an experiment as shown in Fig. 11, we may distinguish the period of the first maximum motion of tremors caught at the positions ①, ②, ③ in the case (ii) from that in (i).

Thus, applying the writer's idea to the result as described in Table IX concerning the case (ii), we shall have the propagating speed of the crack in the glass plate as follows:

$$1.5_2 \pm 0.0_4 \text{ km/sec},$$

wherein the velocity of p-waves propagating through the glass plate is taken as 4.0 km/sec.

In consequence of this simple model experiment using a glass plate, it seems valid and adequate to recognize the following two facts, i. e., the facts that elastic waves are always generated on the occasion of the crack formation and that azimuthal distribution concerning the period of their first maximum parts is regular.

Admitting of these facts derived from this very simple model experiment, we may grasp from the view-point of the movement of seismic source accompanying the

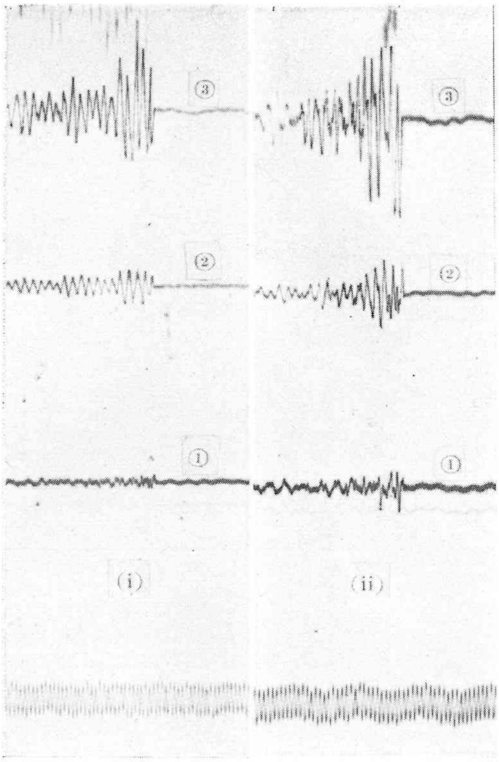

Fig. 11. A pair of records of tremors caught at the positions ①, ②, ③ on the plate ABCD shown in Fig. 10. Records marked with the sign (ii) show the tremors when we strike the plate at the point 0, and those shown in (ii) represent the tremors accompanying the crack which runs through the plate from e to g along the line ef (in Fig. 10). (Period of tuning fork is 1/100 sec.)

Table IX

Position	T' $\times 100^{-1}$sec.	T $\times 100^{-1}$sec.	$\pm\alpha$
①	0.36	0.34	-1.000
②	0.41	0.42	-0.731
③	0.55	0.54	-0.104

formation of the crack along the nodal line, the regularity of geographical or azimuthal distribution regarding the initial period of the maximum ground-motion of *p*-waves due to a remarkable earthquake.

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