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Abstract

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GEOFYSICS

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ON THE POSSIBILITY OF ESTIMATING THE EXTENT OF AN EARTHQUAKE SOURCE FROM KINEMATIC DATA

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An earthquake is a complex process of rupture of the continuity of the earth's crust or mantle, extended in time and in space. Depending on the strength of the earthquake and the character of the destruction, focal regions may be of quite large size, reaching several hundred kilometers. Nevertheless, the coordinates of an earthquake source as presently determined represent it as a point hypocenter, while the time in the source is understood as the moment of occurrence of the earthquake. This circumstance greatly limits ideas about seismicity and the seismic regime and the possibility of solving a number of problems connected with earthquake prediction.

The improvement of seismic observations and hodographs of seismic waves has made it possible to ensure a sufficiently high accuracy in determining epicenters, estimated in a number of cases as ± 5 -10 km. In determining the coordinates of strong earthquakes there have been systematic discrepancies between determinations of epicenter coordinates from nearby and distant stations. On the one hand, this was a consequence of insufficiently complete observation systems (especially near the focal region); on the other hand, of an internal inconsistency of the data. For example, earlier arrivals were observed on seismograms (by 8-10 sec), which could not be correlated with the data of other stations and were automatically excluded from the general summary processing. Analysis of the causes of these systematic residuals made it possible to obtain data on the presence of several points of disturbance within a single focal region.

Different points of disturbance are formed during propagation of a rupture of the continuity of the earth's crust as a result of an earthquake. In order to determine these points of disturbance, it is necessary to divide the data of the overall observation system into several sets internally consistent with one another.

For separating observation systems, a method is proposed based on analysis of the residuals of the times of first arrivals of seismic waves f_i for different hypocenters

Fig. 1. Graphs of individual measurements of the quantities δ_i as a function of focal depth. a –epicenter No. 1, b –No. 2; f_i'' –residual for epicenter No. 1 ($h = 0$)

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$$f_i = t_p - t_p^*, \quad (1)$$

where t_p is the observed travel time of seismic waves, and t_p^* is the travel time according to the averaged Jeffreys-Bullen hodograph.

It is not the residual values themselves that are considered, but their ratios to the value of the residual corresponding to any hypocenter within the focal region. For this purpose, for possible hypocenters the residual values were calculated for all stations, and the data obtained were compared with one another. In addition, supplementary calculations are made of station residuals for different focal depths and of the values of the ratios δ_i

$$\delta_i = |f_i' / f_i''|, \quad (2)$$

where f_i' and f_i'' are residuals for two different hypocenters.

The quantity δ_i determines the character of the behavior of the station residuals of the entire system as a whole and makes it possible to establish the validity of the hypocenters from the point of view of minimization of residuals.

Fixing different depths, each time the value δ_i is estimated for the individual stations of the system under consideration. If all stations of the system recorded first arrivals emitted from one and the same point of the focal region, then for one of the hypocenters all station values δ_i will be less than or equal to 1. If, however, the stations recorded

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first arrivals emitted from different points of the focal region, then the station values δ_i will turn out to be inconsistent; namely, it will be impossible to determine a single hypocenter for which all $\delta_i \leq 1$. The stations will have $\delta_i \leq 1$ for different hypocenters. For one and the same

hypocenter, for some stations δ_i will be $\ll 1$, while for others δ_i will be greater than 1. Thus, depending on the value of δ_i , it is possible to distinguish systems of stations that give consistent data on the times of the first arrivals of seismic

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

waves. This procedure can be applied to any observation system including both near and distant stations, sufficiently uniformly distributed in azimuth.

Unique material from instrumental observations for the Indian earthquake in Koyna (10 XII 1967), in the range of epicentral distances from 0° , 1 to 100° , made it possible, by means of this procedure, to determine two internally consistent observation systems: a system of near ($\Delta < 20^\circ$) and a system of distant ($\Delta > 20^\circ$) stations (see Fig. 1).

Fig. 2. Diagram of the location of epicenters Nos. 1 and 2. a —earthquake epicenter; b —seismic stations; v —confidence ellipse of errors

Figure 1 gives the individual values of δ_i , calculated for two possible hypocenters. As can be seen from Fig. 1a, observations of waves at distances $\Delta < 20^\circ$ give minimum values of δ_i , and, consequently, of the residuals, for depths less than 10 km. From Fig. 1b it is seen that the smallest value of δ_i for a large number of distant stations corresponds to depths of 60–80 km. The points on the Earth's surface corresponding to these hypocenters proved to be displaced relative to one another (Fig. 2).

The accuracy estimated by procedure (1) and shown in Fig. 2 in the form of confidence ellipses of errors indicates that this discrepancy is not caused by errors in determining the coordinates of the epicenters. The existing discrepancies in the epicenter coordinates may be explained by the horizontal extent of the focal region in the direction from southwest to northeast by 20–25 km. The discrepancy of the hypocenters indicates a vertical extent from depths of 0–10 km to 60–70 km. Figure 3 shows a diagram of the focus of the Koyna earthquake.

Fig. 3. Diagram of the focus of the earthquake in Koyna

The character of the displacement in the focus may be described as slip along a rupture plane situated almost vertically from the surface to a depth of 60–70 km. The apparent rupture velocity, determined on the basis of the difference in location and time of occurrence of the initial and final disturbances, proved to be ~ 3 km/sec, which agrees well with the data (²⁻⁴).

The following dynamic factors testify to the depth of the focus of the Indian earthquake:

1. The ratio of the maximum values of the oscillatory velocity in body and surface waves, obtained on the basis of the determination of M_{pv} and M_{LH}

Fig. 4

Figure 4: Fig. 4

in accordance with (8), showed that the depth of hypocenter No. 2 is 60 ± 5 km.

2. Analysis of the seismograms of 16 stations of the USSR, located at epicentral distances of $25-60^\circ$ in various regions of the USSR (Central Asia, the Caucasus, Turkmenia, platform areas), made it possible to detect a wave sP , reflected near the epicenter, at a focal depth $h = 64$ km.
3. The ratio between the different frequencies in the spectrum of the P wave, from records of the Obninsk seismic station (SKD-type apparatus), determined by calculating the value α —the angle of inclination of the envelope of the spectral function—in accordance with the work ⁽⁶⁾, indicates a focal depth $h = 60-70$ km.

The extent of the focal region is indicated by the directivity of surface-wave radiation. Figure 4 shows a polar diagram of the location of the seismic stations for which it proved possible to determine the magnitude from surface waves. From data from 23 stations, the mean magnitude was determined; it proved to be 6.4 ± 0.4 . The deviations of the observed magnitude values for individual stations from the mean value were then calculated (on the scale shown in Fig. 4).

Fig. 4. Diagram of the directed radiation of surface waves $\delta M_i = M_i - \overline{M}_{av}$. Positive values of these deviations are indicated by arrows in the direction toward the stations; negative values, in the direction away from the stations.

1 —Goris, 2 —Bakuriani, 3 —Baku, 4 —Kyzyl-Arvat, 5 —Frunze, 6 —Sochi, 7 —Simferopol, 8 —Lvov, 9 —Tbilisi, 10 —Makhach-Kala, 11 —Yerevan, 12 —Pulkovo, 13 —Sverdlovsk, 14 —Semipalatinsk, 15 —Tiksi, 16 —Magadan, 17 —Yakutsk, 18 —Przhevalsk, 19 —Vladivostok, 20 —Alma-Ata, 21 —Yuzhno-Sakhalinsk, 22 —Tashkent

In the north-northeast direction the surface waves prove to be more intense, whereas in the westward direction they are substantially weakened.

The results obtained provide instrumental confirmation of the explanation, proposed in ⁽⁵⁾, of the macroseismic manifestation of the Koyna earthquake on the Earth' s surface. The macroseismic manifestations on the Earth' s surface correspond neither to the effect expected from a surface, nor to that expected from a deep shock; the isoseists have an irregular character, and specifically the principal macroseismic effect was caused by the region of initial disturbance, located near the surface.

A system of closely spaced stations (No. 1) made it possible to determine the hypocenter of this initial disturbance. The point on the Earth' s surface corresponding to this hypocenter coincides with the region of maximum destruction.

The end of the process in the focal region (hypocenter No. 2), accompanied by a large release of energy, in connection with propagation to a depth of 60–70 km, could have produced an effect on the Earth's surface of no more than intensity 6. However, this effect substantially disturbed the pattern of the earthquake manifestation on the surface, characteristic of a shallow focus (⁷).

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