A NUMERICAL METHOD FOR DETERMINING THE AVERAGE CHARACTERISTICS OF THE EARTH’ S CRUST FROM SEISMOGRAMS OF DISTANT EARTHQUAKES

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A NUMERICAL METHOD FOR DETERMINING THE AVERAGE CHARACTERISTICS OF THE EARTH' S CRUST FROM SEISMOGRAMS OF DISTANT EARTHQUAKES

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The information provided by seismograms of distant earthquakes is currently used in the method of transmitted converted waves (MTCW) to study the structure of the crust and upper mantle ($^{1-3}$). Based on the extraction of weak useful waves in the presence of more intense noise, using the only exact polarization criteria available in this method for identifying MTCW waves, it gives sufficiently well-founded results only with respect to sharp boundaries between the sedimentary cover and the crystalline basement. As for deep boundaries, including the Mohorovičić discontinuity, the MTCW results are subject to strong fluctuations depending on the distance of the earthquake, its azimuth relative to the station, and the form of the impulse at the source. Estimates of the intensities of deep converted waves obtained by MTCW contradict theoretical estimates, and structural results often contradict the data of the DSS method and the method of profile seismological observations. In this connection, the problem of developing physically more justified and stable methods for studying the crust from distant earthquakes is of current importance.

To solve this problem, as an admissible idealization of the real structure of the medium, in accordance with the concepts existing in seismology and DSS concerning the M surface as the sharpest and most regular boundary in the crust and upper mantle, one may take a model of a layer with properties varying smoothly with depth, lying on a homogeneous mass of rocks of the upper mantle. Interference wave processes in such a system, for conditions of oblique incidence from the lower half-space of a plane wave, can be exhaustively described by numerical methods. Using the program available in work (^{4}) for calculating oscillations of an inhomogeneous layer, the main regularities in the formation of complete seismograms of the vertical and horizontal components of oscillations of the ground surface were analyzed. From theoretical calculations it followed that, for velocity values within the limits actually admissible for the crust and for angles of incidence on the lower boundary less than 40°, the structure of the seismograms has a stable character. The principal energy contribution to both components is made by the direct wave P. If the maximum amplitude of the P wave on the vertical component is taken as 100%, then the amplitudes of the remaining waves are estimated as follows: the P wave on the horizontal component, 10-15%; the PPP wave (a double wave in the crust) on the vertical component, 15-25%, on the horizontal component, 2-5%; the PS wave on the horizontal component, 7-15%; the summed wave $(PPS + PSP + SPP)$ has, on the X-component, a maximum amplitude of 6-12%; the summed wave $(PSS + SPS + SSP)$ on the X-component, 6-10%. The remaining waves do not exceed a few percent in amplitude. An example of theoretical seismograms is given in Fig. 2.

The structure of real seismograms from distant earthquakes in open regions, on the basis of numerous studies carried out

in recent years with the aid of large seismic arrays is represented in the following form ($^{5-8}$). At the very beginning of the record (the first 2-4 sec), the primary signal is recorded. This is the P-wave, polarized in the plane of incidence and kinematically satisfying the Jeffreys—Bullen hodograph. In the subsequent part of the record, the energy is dominated by low-velocity near-surface waves arising at topographic irregularities of the ground surface and block structures of the upper part of the crust. It is important to emphasize that the spatial organization of these waves (azimuth of propagation, apparent velocity, polarization) differs from that of the P-wave and of intracrustal converted and multiple waves, which are polarized in the same plane as the P-wave and have the same apparent velocity. The latter property can be used to "clean" seismograms of "lateral" waves.

Let us now consider the problem of numerically determining the parameters of such a model of crustal structure, which gives the best agreement of the experimental seismograms with the theoretical seismograms simultaneously for the vertical and horizontal components among all models of the class considered by us. The solution algorithm consists in carrying out the following operations. First of all, in order to improve the signal-to-noise ratio, the initial seismograms of distant earthquakes were transformed by means of the polarization operator proposed in (^{9}). The filtering actions of the operator are based on the difference in the spatial organization of the useful crustal waves and the interfering lateral waves. It is essential that, for implementation of this filter, observations from an ordinary three-component instrument installation are sufficient. As a result of the transformation, at the output we obtained seismograms $Z(t)$ and $X(t)$ cleaned of lateral waves, which subsequently served as the observed wave field.

In the quantitative description of the crustal model adopted above, the following were taken as variable parameters: v_1—the velocity of longitudinal waves at the top of the layer, v_2—the velocity of longitudinal waves at the bottom of the layer, and H—the thickness of the layer. The velocity within the layer varies according to a linear law. The remaining characteristics of the medium required

Fig. 1

Figure 1: Fig. 1

for solving the direct problem are considered known from other geophysical data. In particular, from the results of processing nearby earthquakes and large industrial explosions, for the Altai–Sayan region it was accepted that $v_p/v_s = 1.75$ and that the velocity in the upper mantle is $v_M = 8.1$ km/sec. The density distribution in the crust and the top of the mantle was taken according to Bullen' s model.

As the form of the pulse incident on the bottom of the layer, we took the first wave train, most clearly distinguished on the filtered seismogram $Z(t)$. With the known form of the signal, the direct problem was solved in the following range of variation of the medium parameters being varied: $v_1 = 5.5 \div 6.4$ km/sec with a step of 0.1 km/sec; v_2—$6.0 \div 8.0$ km/sec with a step of 0.2 km/sec; $H = 30 \div 60$ km with a step of 3 km in the first variant, and $H = 35 \div 50$ km with a step of 1 km in the second variant. In this, combinations with $v_1 > v_2$, i.e., models with waveguides, were excluded.

The best agreement between theoretical and observed seismograms is understood in the sense of the root-mean-square measure of their deviation

$$\chi^2(v_1, v_2, H) = \frac{1}{2N}\left\{\sum_{i=1}^{N} \left|X(i \cdot \Delta t) - X\left(i \cdot \Delta t\right)\right|^2 + \sum_{i=1}^{N} \left|Z(i \cdot \Delta t) - Z\left(i \cdot \Delta t\right)\right|^2\right\},$$

where N is the total number of points of the discrete seismogram (we took $N = 300$); Δt is the spacing of the tabulated data (0.1 sec).

To find the minimum of the function of three variables $\chi^2(v_1, v_2, H)$, we applied the method of simple enumeration of values, which gives the most reliable results in the case of multimodal surfaces.

To obtain experimental data, in the summer of 1966 special expeditionary observations were carried out in the Gorny Altai region for recording distant earthquakes at short station spacings, using stations equipped with identical apparatus: SKM-III seismographs and GK-7 galvanometers. The drum recording speed was 240 mm/min.

Fig. 1. Original seismogram of the earthquake of 28 VIII 1966, Solomon Islands region. $\Delta = 82^\circ$, $h = 477$ km, s. st. Ust-Kan

An example of processing, according to the scheme presented, of the distant earthquake of 28 VIII 1966 is shown in Figs. 1 and 2. The corresponding optimal section is determined by the parameters: $v_1 = 5.9$ km/sec, $v_2 = 7.6$ km/sec, $H = 44$ km. It is interesting to note that calculation of this same earthquake for another signal length, equal to the total oscillation $(P + P_{cP})$,

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

gave a close velocity section: $v_1 = 5.7$ km/sec, $v_2 = 7.6$ km/sec, $H = 42$ km. This example, as well as the results of processing other earthquakes, show the stability of the re-

Fig. 2. 1 –seismograms filtered in the directions of the SV- and P-waves; 2 –theoretical seismograms corresponding to the optimal section: $v_1 = 5.9$ km/sec; $v_2 = 7.6$ km/sec, $H = 44$ km; 3 –correlation function expressing the correlation of the signal with the remaining part of the record

Fig. 3. Optimal velocity sections of the Earth' s crust. Distances between stations: Ust-Kan –No. 1, 1.5 km; Ust-Kan –No. 2, 1.5 km; Ust-Kan –No. 3, 4 km; Ust-Kan –No. 4, 7 km; Ust-Kan –No. 5, 19 km; Ust-Kan –No. 6, 12 km. 1 –Aleutians, 22 VII; 2 –Banda Sea, 23 VII; 3 –Aleutians, 7 VIII ($h = 120$ km); 4 –Japan, 20 VIII ($h = 150$ km); 5 –Philippines, 30 VIII; 6 –India, 15 VIII; 7 –Hindu Kush, 22 VIII ($h = 177$ km); 8 –Taiwan, 15 IX; 9 –Solomon Is., 28 VIII ($h = 477$ km); 10 –Philippines, 21 VIII ($h = 70$ km)

of solving the inverse problem with respect to the choice of the shape of the incident impulse.

The final justification of the proposed approach to the study of the structure of the earth' s crust from distant earthquakes may be the agreement of the results of processing different earthquakes recorded by one station, and of the same earthquake recorded at nearby stations (Fig. 3). The stability of the results for the seismic station Ust-Kan (Gorny Altai), where the largest number of determinations was made, is characterized by the following values of the parameters and their root-mean-square deviations: $v_1 = 5.8 \pm 0.15$ km/sec, $v_2 = 7.3 \pm 0.3$ km/sec, $H = 43 \pm 2$ km.

The proposed method permits automation of the processing of primary seismic information on an electronic computer. The convenience of its use and the accuracy of the results can be substantially increased through the use of digital seismic stations.

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Note: Figure translations are in progress. See original paper for figures.