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Estimation of Efficiency of the Modern and Planning Optimal Network of Seismic Stations within the Vietnam Territory

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Abstract—Efficiency of the modern network of seismological observations in Vietnam is estimated, and an optimal design of planning network, consisted of 14 seismic stations is proposed. At the same sensitivity of network, but with a less number of stations, the new network would enable to determine hypocenter parameters in a more precise at a more uniform distribution of errating band within observation area.

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Key words: seismic stations, efficiency of observation network, experiment planning.

INTRODUCTION

Currently, modernization of Vietnam's seismic network is planned on the basis of 20 broadband seismic stations. In this relation, the problem is arise how to locate these stations optimally within the territory in order to predict earthquakes and to study the Earth's crust and upper mantle beneath Vietnam. Rapid development in electronics and computer science stimulates perfection of seismological observation networks worldwide and, in particular, in Vietnam. However, increase in sensitivity of seismic stations does not mean yet, that observation system, equipped with such stations, will be efficient. In this relation, estimation in efficiency of seismic stations network for the territory of Vietnam is an important problem, having a great value, because an optimal network enables to implement a sufficiently reliable determination of main parameters of earthquakes hypocenters at a minimal number of recording stations.

The basis for study of a region's seismicity is a set of data on main parameters of earthquakes sources (hypocenter coordinates, magnitude), occurred within a studied territory. Precision of earthquakes hypocenters parameters determination in a great degree depends on mutual position of seismic stations and their position in relation to hypocentral zone. In this relation, there is a need of efficiency estimation and optimization of seismic stations network.

Problems in estimation of efficiency and optimal planning network of seismic stations had been considered by various authors [3–6, 8, 9, 12–14, 19–22, 24–27]. Optimal planning network of seismic stations in Vietnam had been considered in [10, 17].

It was implied in [17] that there are N_0 seismic stations within the S area and errors in determination of earthquakes sources parameters, recorded by these stations, exceeds a set level. To perfect the present network of seismic stations, first of all, it was need to determine subregion s_i ($i = 1, 2, ..., m$) within S region, where there is a possibility to place additional stations. Problem was to determine in s_i N_1 observation points, which would supplement the existing network in an optimal way. On the basis of "planning of regressive experiment" theory, a problem of optimal additional N_1 stations comes to a problem of meansquare error minimization in parameters of earthquakes hypocenters. Choice of additional stations minimal number is implemented on the basis of comparison in a needed error level with errors in parameters of earthquakes hypocenters, with the use of N_1 additional seismic stations. As a result, 15 points within the territory of Vietnam were selected, where additional seismic stations should be placed.

In [10] the problem had been considered concerning determination of optimal placement of additional seismic stations within the territory of Northern Vietnam and adjacent areas. As a result, optimal locations of additional seismic stations had been determined for this territory.

For the whole territory of Vietnam, the problem of seismological network optimization has not been studied up to the present. However, as had been shown in [16], there is a lack of data on earthquakes in some of its parts, related to absence of recording stations. However, if to see at the map of Vietnam (see Fig. 1), it is easy to note, that it is impossible to design a united and optimal observation network due to a great oblongness of territory from north to south. Any seismological observation network for such territory in

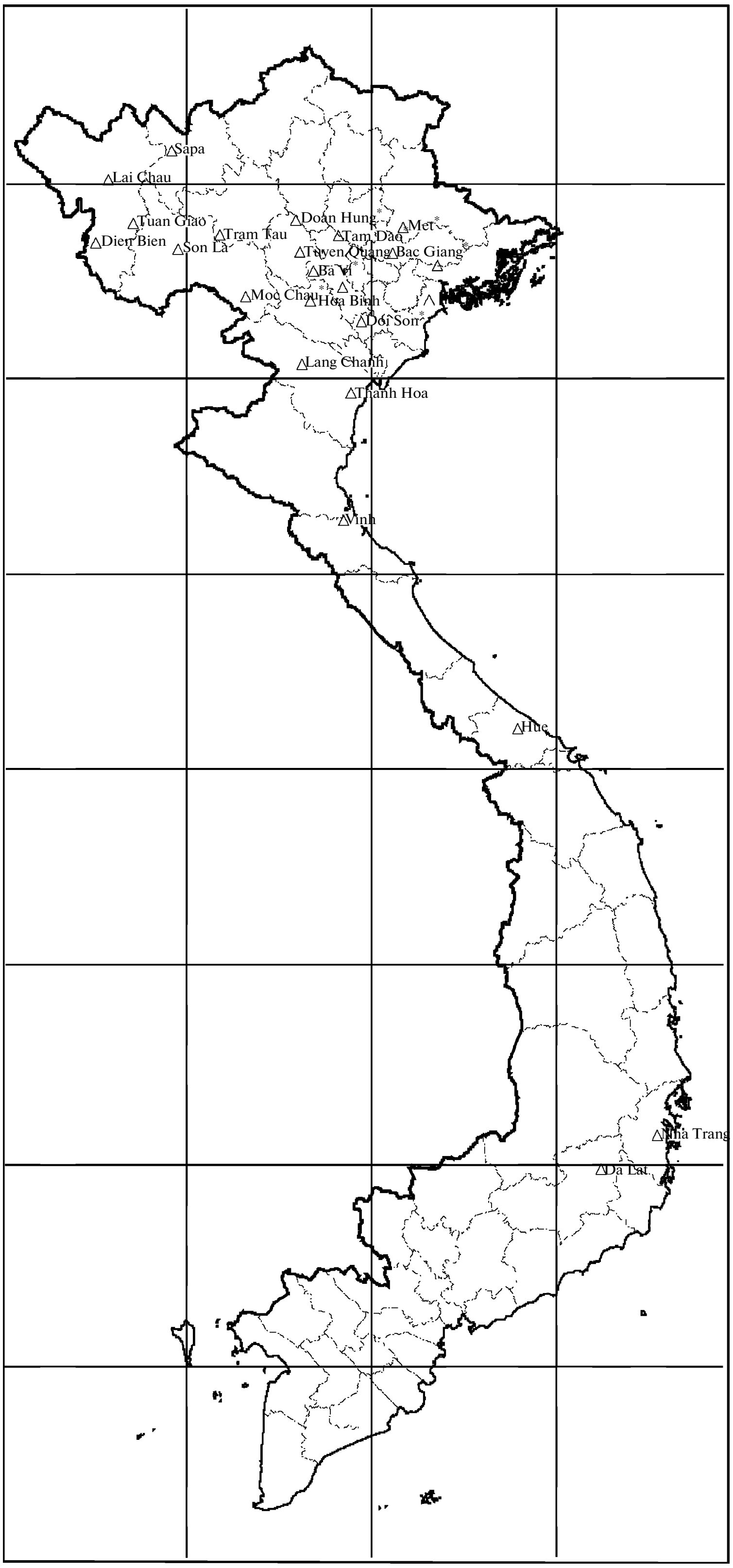

Fig. 1. Scheme of seismic stations network in Vietnam.

whole would be non-optimal. In this case we can say only about optimization of local observation networks for particular regions, such as north, center, and south of Vietnam.

In the present work, the estimation is given concerning efficiency of seismic stations network in the north of Vietnam on the basis of calculation of maximal errors in determination of main parameters of earthquake hypocenters.

To estimate efficiency and to design an optimal network of seismic stations in the study area, we use the approach, proposed in [6–8]. Let us consider in brief its main points.

SYSTEMS OF LINEAR EQUATIONS, CONNECTING HYPOCENTER COORDINATES OF HOLLOW EARTHQUAKES AND SEISMIC STATIONS AT VARIOUS INITIAL DATA

Let us consider the system of equations, connecting coordinates of earthquakes hypocenters and coordinates of recording seismic stations, on assumption that surface The Earth is flat, and observation points are situated on the day surface

$$(X - x_i)^2 + (Y - y_i)^2 + H^2 = v_i^2(\tau_i - \tau_0)^2, \qquad (1)$$

where X, Y, H and τ_0 are coordinates of hypocenter and origination time of earthquake (time in a source); x_i, y_i, and τ_i are coordinates of seismic stations, recorded earthquake, and arrival times of seismic waves to these stations ($i = \overline{1, n}$); v_i is efficient velocities of seismic waves propagation, numerically equal to relation of straight-line distance from i station until hypocenter to travel time of seismic wave along a ray.

If X, Y, H and τ_0 are unknown, then, introducing the variable $\eta = X^2 + Y^2 + H^2 - v^2\tau_0^2$ and assume $v_i = v = \text{const}$, we come to the system

$$Xx_i + Yy_i + \tau_0 v^2 \tau_i + 0.5\eta = f_i, \qquad (2)$$

where $i = 1, 2, \ldots, n \geq 4; f_i = 0.5(x_i^2 + y_i^2 - v^2\tau_i^2)$.

Let us write the system of linear equations, connecting coordinates of earthquake hypocenter, velocity of seismic waves propagation, and time in a source in a matrix form

$$\mathbf{Kp} = \mathbf{f}, \qquad (3)$$

where $\mathbf{K} = \{k_{ij}\}$ is system matrix, that is mathematical model of studied relation; $\mathbf{p}^{\mathrm{T}} = \{p_j)$ is column vector of seek parameters; $\mathbf{f}^{\mathrm{T}} = \{f_i\}$ is column vector of observed values; $i = 1, 2, \ldots, n; j = 1, 2, \ldots, m; n \geq m$.

Solution of equation (3) is found by the least-squares procedure and presented by the formulae

$$\mathbf{P} = \mathbf{K}^{+}\mathbf{f},$$

where $\mathbf{K}^{+}$ is generalized inverted matrix, equal to $\mathbf{K}^{+} = (\mathbf{K}^{\mathrm{T}}\mathbf{K})^{-1}\mathbf{K}^{\mathrm{T}}$.

Depth H of earthquake hypocenter is not determined directly by solution of the systems (2), but can be done from correlation:

$$H^2 = \eta - X^2 - Y^2 + v^2\tau_0^2. \qquad (4)$$

MAJORANT ESTIMATIONS OF ERRORS IN DETERMINATION OF HYPOCENTER COORDINATES OF HOLLOW EARTHQUAKES AND THEIR PROPERTIES

Let vector of free terms **f** and matrix **K** from the system of equations (2) are given with errors $\Delta\mathbf{f} \neq 0$ and $\Delta K \neq 0$. in this case, for error of **p** vector we have equation [9]

$$\Delta\mathbf{p} = \Delta\mathbf{f} - \Delta\mathbf{K}\mathbf{p}.$$

Solution of this equation is determined by the least-squares procedure

$$\Delta\mathbf{p} = \tilde{\mathbf{K}}^{+}(\Delta\mathbf{f} - \Delta\mathbf{K}\mathbf{p}).$$

For errors of particular components Δp_i of **p** vector we obtain the following relations:

$$\Delta p_i = \tilde{\mathbf{k}}_j^{(+)}(\Delta\mathbf{f} - \Delta\mathbf{K}\mathbf{p}), \quad j = 1, 2, \ldots, m,$$

where $\tilde{\mathbf{k}}_j^{(+)}$ is vector-line of $\tilde{\mathbf{K}}^{+}$ matrix.

Using the Cauchy-Bunyakowsky inequality, for majorant assessment of erro Δp_j we will obtain the following relation:

$$|\Delta p_i| = |\tilde{\mathbf{k}}_j^{(+)}(\Delta\mathbf{f} - \Delta\mathbf{K}\mathbf{p})| \leq \|\tilde{\mathbf{k}}_j^{(+)}\| \times \|\Delta\mathbf{f} - \Delta\mathbf{K}\mathbf{p}\|, \qquad (5)$$

where $\| \bullet \|$ is Euclidean norm.

For vector error $\Delta\mathbf{p}$ we have

$$\|\Delta\mathbf{p}\| \leq \|\tilde{\mathbf{K}}_j^{(+)}\| \times \|\Delta\mathbf{f} - \Delta\mathbf{K}\mathbf{p}\|. \qquad (6)$$

Let us consider now the system of linear equations (2). Assume that errors in determination of stations coordinates are negligibly small, and arrival times of seismic âîëí are determined with precision $|\delta\tau_i| = \rho_i|\Delta\tau|$, $\rho_i \geq 0$. Weighting coefficients ρ_i are chosen in accordance with value and character of $|\delta\tau_i|$ values.

Except accidental mistakes in determination of arrival times of seismic waves at station, values $|\delta\tau_i|$ and, consequently, ρ_i, can reflect deviation of observed travel time of seismic waves, propagating in a real non-uniform 3D media from travel time of waves in a media with relation of velocity change, accepted in interpretation. Thus, weighting coefficients ρ_i reflect both measurement unequality at stations and systematical deviations in determination of τ_i, related with non-uniformity of real medias.

Let us consider the system of linear equations (2). In this case, time in a source is unknown, but values of v_i are known and estimations of (5) are enabled, because it is followed from (2) and (6) that $\Delta \mathbf{K} \neq 0$, $\Delta \mathbf{f} \neq 0$. and, so,

$$(\Delta \mathbf{f} - \Delta \mathbf{K}\mathbf{p})_i = - v_i^2 \tau_i \delta\tau_i - [0\ 0\ V_i \delta\tau_i\ 0](X\ Y\ \tau_0\ h)^{\mathrm{T}}$$

$$= - v_i^2 \tau_i \delta\tau_i + v_i^2 \delta\tau_i t_i = -v_i^2(\tau_i - \tau_0)\delta\tau_i = v_i R_i \delta\tau_i,$$

$$|\Delta p_j| \leq \sum_{i=1}^{n} \left|\tilde{k}_{ji}^{(+)} R_i v_i \rho_i\right| \times |\Delta\tau|.$$

For a norm of vector error $\Delta \mathbf{p}$, the following estimation is true

$$\|\Delta \mathbf{p}\| = \left\{\sum_{i=1}^{n} |p_i|^2\right\}^{1/2} \leq \left\|\tilde{\mathbf{K}}^{+}\right\| \times \|\mathbf{R}\mathbf{v}\rho\| \times |\Delta\tau|, \qquad (7)$$

where $\|\mathbf{R}\mathbf{v}\rho\| = \{\sum_{i=1}^{n} |R_i v_i \rho_i|^2\}^{1/2}$.

CONSIDERATION OF ERRORS IN STATEMENT OF VELOCITY MODEL OF MEDIA

In the case when velocities distribution in an elastic media is given with errors δv, estimation of (7) becomes false. Indeed, in this case, hypocentral distances $\tilde{R}_i = R_i + \delta R_i$ are determined incorrectly by the given travel times of seismic waves, and, consequently, efficient velocities $\tilde{v}_i = v_i + \delta v_i = R_i/t_i$.

Let us write errors in determination of vector **f** and matrix **K**. After appropriate transformations we obtain

$$\Delta f_i = - \nu_i(\tau_i^2 + \tau_0^2)\delta\nu_i - \nu_i^2 \tau_i \delta\tau_i,$$

$$(\Delta \mathbf{K}\mathbf{p})_i = - 2\nu_i \tau_i d\nu_i - \nu_i^2 \tau_0 \delta\tau_i.$$

As a result, we can write

$$(\Delta \mathbf{f} - \Delta \mathbf{K}\mathbf{p})_i = -(\tau_i - \tau_0)^2 v_i \delta v_i$$

$$- (\tau_i - \tau_0) v_i^2 \delta\tau_i = - R_i^2 \frac{\delta v_i}{v_i} - R_i v_i \delta\tau_i.$$

It is easy to ascertain that time incursion from an error in setting of efficient velocity v_i, is

$$\delta\tau_{v_i} \approx \frac{R_i}{\tilde{v}_i} - \frac{R_i}{v_i} \approx R_i \frac{\delta v_i}{v_i^2}.$$

Taking into account the last relation, we can finally write

$$(\Delta \mathbf{f} - \Delta K \mathbf{p})_i = -R_i v_i(\delta\tau_i + \delta\tau_{vi}).$$

As a result, we obtain the relation

$$|\Delta p_j| \leq \left\|\tilde{\mathbf{k}}_j^{(+)}\right\| \times \|\mathbf{R}\mathbf{v}(\delta\tau_t + \delta\tau_v)\|$$

and, correspondingly,

$$\|\Delta \mathbf{p}\| \leq \left\|\tilde{\mathbf{K}}^{+}\right\| \times \|\mathbf{R}\mathbf{v}(\delta\tau_t + \delta\tau_v)\|. \qquad (8)$$

Let us estimate contribution of δv error in a general error. Assume that $v \approx 6.0$ km/sec, $\delta v \approx 0.1$ km/sec, $\delta\tau_t \approx 1.0$ sec. Then $\delta\tau_t$ and $\delta\tau_v$ become comparable at hypocentral distances $R = \frac{\delta\tau_t}{\delta v} v^2 \approx 360$ km.

AN OPTIMAL SYSTEM OF SEISMOLOGICAL OBSERVATIONS

Estimation (8), being a majorant one, gives a guaranteed precision in determination of hypocenter parameters of hollow earthquakes. If to vary coordinates of observation points, then it is possible to choose such their location, at which estimation (8) would obtain its minimal value. So, the problem in determination of optimal geometry of observation system can be considered as problem of minimization of objective function $J = \left\|\tilde{\mathbf{K}}^{+}\right\| \times \|\mathbf{R}\mathbf{v}\rho\|$, or, in a more precise, of a functional from objective function J. Let us introduce such a functional.

Let us consider inside the Earth a hypocentral area Θ, in which earthquake hypocenters are distributed in accordance with a law $\rho(X, Y, H)$, and set an area Ω at the Earth's surface, within which we should place seismic stations to regicster earthquakes from Θ area. Ω area is to be called planning area of seismological experiment. It is clear that Θ area is three-dimensional and Ω area is two-dimensional. It is corresponded to the real conditions of seismological observations, at which seismic stations are located at the day surface. Projection of Θ area to the day surface, called epicentral zone, we will mark as Θ'.

We will say that problem of seismic experiment planning is to place seismic stations in Ω area in a way that function

$$F = T + \alpha\Phi[J(X, Y, H, x_i, y_i)],$$

called loss function, possessed the minimal value. Here the functional $\Phi[J(X, Y, H, x_i, y_i)]$ characterizes the precision of determination in parameters of hypocenters; α is normalizing factor; T value determines a total cost for experiment, expresses, for instance, in monetary units.

It is obvious that such a statement of problem implies determination of both optimal design of stations network and number of stations in Ω area. Statements of more particular problems are also possible. For instance, there are observation points already located in Ω area. There is a need to determine optimal addition for network up to $n + m$ points within Ω (probably, number m of additional points as well) in the sense of criterion, mentioned above, using the given law $\rho(X, Y, H)$.

ESTIMATION IN EFFICIENCY OF SEISMOLOGICAL OBSERVATION SYSTEMS

Optimal networks of seismological observations enable to determine earthquake hypocenter parame-

Table 1. Averaged relation of characteristic periods on epicentral distance for *P* waves

D, km	<100	<300	<1000	<2500	>2500
$\log(T, s)$	$0.19\log\Delta - 1.08$	$1.97\log\Delta - 4.63$	0.245	$0.98\log\Delta - 2.71$	$0.03\log\Delta - 0.53$

ters with minimal errors. The existing local and regional networks of seismic stations, for some reasons, sometimes have not an optimal design. It is natural in these cases to estimate how effective an observation system.

Let seismic stations are placed in points with coordinates $M_i = (x_i, y_i)$ $i = 1, 2, ..., n)$ for recording earthquakes in Θ area. Then, on the basis of the $\rho(X, Y, H)$ distribution law, earthquake hypocenter in Θ area, the value of functional $\Phi = \Phi[J(X, Y, H)]$ can be calculated; this functional characterizes precision in determination of hypocenter coordinates for Θ area in general for the given observation system. It is obvious that it is possible to determine an optimal observation system for the given function $\rho(X, Y, H)$, and such system would be characterized with a value of functional $\Phi_0 =$ $\Phi_0 = \min\limits_{\Omega}\Phi\,[J(X, Y, H, x_i, y_i)]$. It is natural to estimate quality of observation system with relation

$$q_C = \Phi_0/\Phi.$$

Due to $\Phi \geq \Phi_0$, then it is obvious that $0 \leq q_C \leq 1$. q_C parameter enables to estimate quality of observation system in general from the viewpoint of maximal errors in determination of hypocenter coordinates.

CALCULATION OF RECORDING DISTANCE FOR SEISMIC STATIONS IN ESTIMATION OF OBSERVATION NETWORK EFFICIENCY

It is obvious that efficiency of observation network depends not only on number of stations, mutual location of stations and the whole network relatively to hypocenter, but also on power of earthquake.

If magnitude of earthquake is small, then distant seismic stations or stations with a low magnification would not record it. As a result, hypocenter parameters would not be determined by the data of entire network of stations, but its part. To take into account in calculation of objective function the stations, which do not register weak signals, we should have criteria, which would enable to exclude such stations from calculations. Depending on initio\al information, there are various approaches are possible.

The first approach is to use directly the fact that values of minimal magnitudes are depended on epicentral distances for every single station.

The second approach implies to use functional relation of $m_{\min}$ values of minimal magnitudes for earthquakes, which are recorded by this seismic station, on epicentral distances. Here is the formulae proposed in [2] to determine $m_{\min}$

$$m_{\min} = \log(\gamma a_n/VT) + \delta(\Delta, h, s(T, \omega)) - \Delta m.$$

In this formulae, γ parameter is minimal possible relation of useful signal amplitude to a noise level, sufficient for its extraction (it is assumed in practice that $\gamma \approx 1.5$); a_n is noise amplitude at seismogram in mm; V is multiplication of an instrument in thousands. It is usual at seismic stations, that multiplication is chosen that a_n is to be about 1 mm.

There is no multiplication of an instrument in a digital recording. In this case, ground motions (in meters) in a maximum region of amplitude-frequency characteristic for electrodynamic seismic receivers would determine by the formulae

$$A = \frac{a_n}{V} = \frac{u_{ADC}a_{ADC}}{2\pi f a_{\max}SK},$$

where a_{ADC} is value of signal in outgoing recordings of analog-digital converter (ADC); $a_{\max}$ is range of ADC in reading (it is determined by capacity of ADC); f is frequency of signal in Hz; S [V sec/m] is electromechanical coupling coefficient (ECC); K is amplification coefficient for recording channel; u_{ADC} is working range of ADC in volts. So, for minimal magnitudes we obtain

$$m_{\min} = \log\left(\frac{\gamma a_{ADC}u_{ADC}}{2\pi a_{\max}SK}\right) + \delta(\Delta, h, s(T, \omega)) - \Delta m.$$

Here a_{ADC} is value of microseism signal in recordings.

For a priori estimate of $m_{\min}$, as T period or f frequency of signal we should use some characteristic

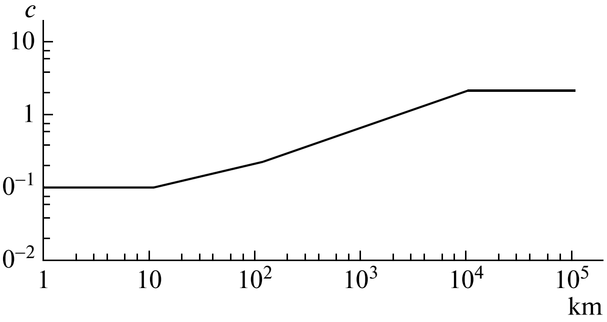

Fig. 2. Dependence of characteristic periods of seismic waves on epicentral distances.

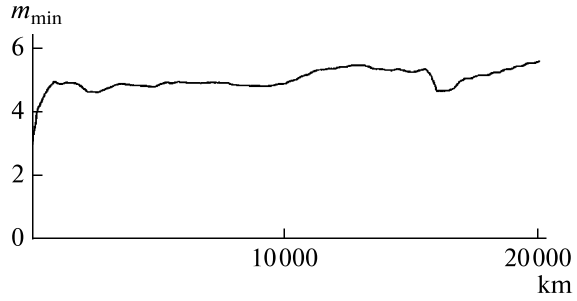

Fig. 3. Dependence of m_{min} values on epicenter distances for seismic stations with multiplication $V \sim 40000$.

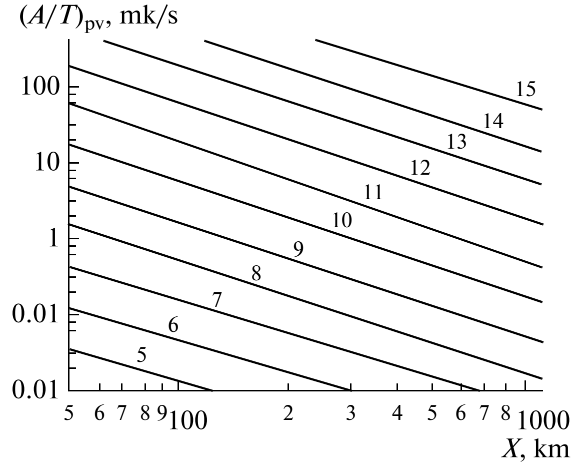

Fig. 4. Nomogram for determination of energy classes K for earthquakes in Sakhalin and Kurile Islands.

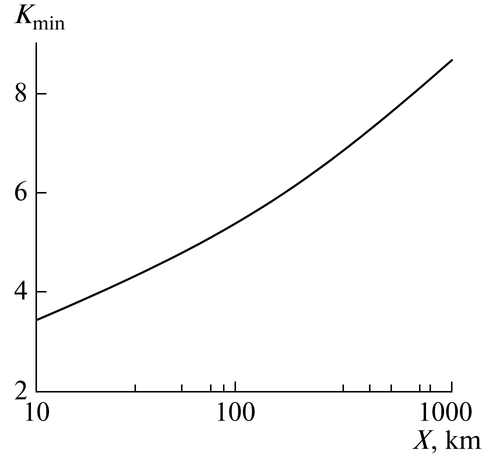

Fig. 5. Calibration curve for seismic station with multiplication $V \sim 40000$.

periods. Spectrum of signal, recorded by a seismic station, depends on several factors, first of all, on epicentral distances, because, as is known, a high-frequency part of seismic wave fades faster than a low-frequency one. Moreover, spectral compound of seismic record is influenced by installment type in a station and earthquake power, i.e. its magnitude. The averaged relation of characteristic periods on epicentral distance for magnitudes of about m_{min} in respect to broadband installment for P-waves, obtained on the basis of study in experimental dependences of seismic waves dynamics [2], is presented in the Table 1.

At $\Delta < 10$ km, the value of $T \approx 8 \times 10^{-2}$ sec.

The graph of this dependence in a logarithmic scale is presented at the Fig. 2.

Gage function $\delta(\Delta, h, s(T, \omega))$ is well studied. For various types of installment and different regions of CIS for hollow and far zones, the values of gage functions are presented in the Instruction on industrial procedure and observations processing at seismic stations UNSO USSR [11].

The graph of magnitude values m_{min} dependence on epicentral distance for seismic stations with multiplication at $V = 40000$ ($\Delta m = 0$) is presented at the Fig. 3. We used the averaged calibration curve [11], values of characteristic periods were taken in accordance with dependence mentioned above. Values of Δm for different regions are presented, for instance, in [2]. Usually $|\Delta m| < 0.25$.

It is usual that regional dependences of minimal magnitudes on epicentral distances are built for regional and local seismic networks. For territory of former USSR, the energy characteristics is so called "class", which are decimal logarithms of earthquake energy (in ergs). There were not works on making dependences of minimal magnitudes on epicentral distances implemented for the territory of Vietnam. So, for calculation of minimal magnitudes, it is logical to use data on the region, similar in structure and seismicity, for instance, those on Far East of Russia. We also can use dependence of minimal energy classes on distances, and then come to magnitudes. Relation between energy class K and magnitude m is given by correlation [23] $K = 1.2 + 2m$.

Here is the nomogram [1] presented at the Fig. 4, for energy classes of Sakhalin and Kurile Islands, which would allow to draw a dependence graph of minimal classes' values on epicentral distance.

Here is calibration curve presented at Fig. 5, which is semi-logarithmic scale for energy classes for a seismic station with multiplication $V = 40000$ ($\Delta m = 0$), built using this nomogram. This calibration curve is well approximated by power function: $K_{min} = 2.2X^{0.2}$.

Table 2. Parameters of seismic stations

No.	Name of station	Code of station	Longitude (N deg) min	Latitude (E deg) min	Altitude, m	Ground	Equipment	Year of starting
1	Ba Vi	BVV	21 06.13	105 22.12	182	Sandstone	L-4C-1D	1995
2	Bac Giang	BGV	21 17.41	106 13.65	15	Sandstone	L-4C-1D	1962
3	Chua Tram	HNV	20 56.29	105 41.33	50	Limestone	L-4C-3D	1995
4	Doan Hung	DHV	21 37.61	105 11.03	70	Aleurolite	L-4C-1D	1995
5	Tuyen Quang	TQV	21 17.65	105 13.72	10	Quartzite	Does not work	
6	Doi Son	DSV	20 35.13	105 53.24	70	Quartzite	L-4C-1D	1999
7	Met	MTV	21 32.88	106 20.52	30	Quartzite	L-4C-1D	1999
8	Phu Lien	PLV	20 48.36	106 37.81	90	Quartzite	L-4C-1D	1923
9	Tam Dao	TDV	21 27.88	105 38.74	1200	Sandstone	L-4C-1D	1995
10	Yen Tu	YTV	21 09.42	106 43.02	900	Sandstone	L-4C-1D	2001
11	Sapa	SPV	22 20.30	103 50.11	1550	Aleurolite	L-4C-3D	1975
12	Lai Chau	LCV	22 02.32	103 09.26	1100	Aleurolite	L-4C-3D	1990
13	Dien Bien	SBV	21 23.38	103 01.10	480	Clay-sale	L-4C-3D	1990
14	Tuan Giao	TGV	21 35.39	103 25.09	400	Aleurolite	L-4C-3D	1997
15	Son La	SLV	21 20.03	103 54.30	700	Aleurolite	L-4C-3D	1997
16	Tram Tau	TTV	21 28.36	104 21.66		Aleurolite	L-4C-3D	2002
17	Moc Chau	MCV	20 50.65	104 38.13		Limestore	L-4C-3D	2002
18	HoaBinh	HBV	20 47.77	105 20.32	80	Sandstone	L-4C-3D	1970
19	Lang Chanh	LAV	20 09.19	105 14.85		Sandstone	L-4C-3D	2002
20	Thanh Hoa	THV	19 51.05	105 46.92		Limestone	L-4C-3D	2002
21	Vinh	VIV	18 32.88	105 42.00	5	Quartzite	L-4C-3D	1990
22	Hue	HUV	16 25.01	107 35.13	8	Aleurolite	L-4C-3D	1995
23	Nha Trang	NHA	12 18.30	109 05.62	80	Quartzite	L-4C-3D	1957
24	DaLat	DLA	11 57.91	108 28.89	1550	Aleurolite	L-4C-3D	1977

Table 3. Parameters of the used velocity model

Depths (km)	0–2	2–7	7–12	12–18	>20	>40
Velocity of P wave, km/sec	5.17	5.73–5.93	5.93–6.13	6.13–6.37	6.82	8.04

DETERMINATION OF MINIMAL MAGNITUDES AND ERRORS IN DETERMINATION OF EARTHQUAKE HYPOCENTER COORDINATES FOR THE MODERN AND OPTIMAL NETWORKS OF SEISMOLOGICAL OBSERVATIONS IN NORTHERN VIETNAM

First, let us estimate efficiency of the existed network, and then construct an optimal one for seismic stations of Vietnam. Let us calculate errors in determination of earthquake hypocenter parameters, which can be recorded by the modern network of Vietnam. As was said above, the seismic network of Vietnam in general is a fortiori non-optimal, so calculations are made for the northern part of Vietnam only. Parameters of all seismic stations in Vietnam are listed in the Table 2.

As was shown in [15], sources of most earthquakes within the territory of Vietnam are located

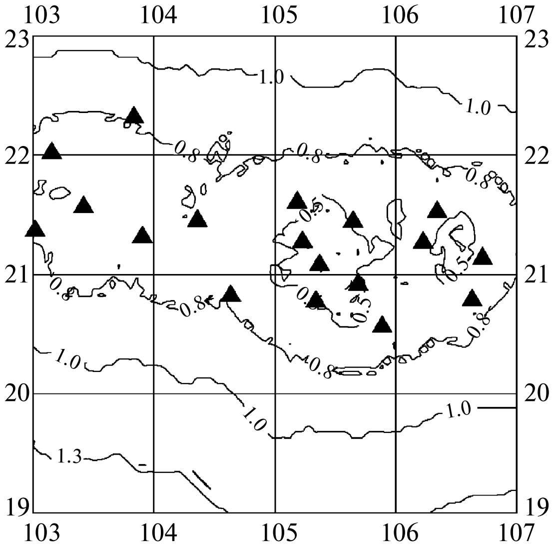

Fig. 6. Distribution of minimal magnitudes for the modern network in Northern Vietnam.

mostly at the depths $h = 0–50$ km. In this relation, depth of earthquake source for determination of errors and minimal magnitudes is assumed at 30 km.

Today, in determination of hypocenter parameters of earthquakes the velocity model of the Earth's crust is used, obtained in [18] (Table 3). The same model was applied as velocity model of the Earth's crust in Vietnam for calculation of errors and minimal magnitudes of earthquakes. It is supposed that error in determination of velocity of seismic waves propagation is 0.1 km/sec, and error in measurement of arrival times of seismic waves $\Delta t = 0.1$ sec.

Here are isolines at the Figs. 6 and 7 presented for minimal magnitudes and errors in determination of earthquake hypocenter coordinates for the modern observation network of Northern Vietnam. At that, X axis is directed to the east, Y axis is to the north, and Z axis to the center of the Earth, and increasing in number of seismic stations was assumed at 40,000. In the north of Vietnam, northwards from 19-th parallel, 19 seismic stations are established, while working ones are 18. the characteristic feature of the network is its oblongness in east-west direction. As a consequence of such configuration, there is asymmetry in determination of hypocenter parameters for recorded earthquakes. It is followed from the Fig. 6 that in the square (19,103)°, (23,107)° at multiplication of instruments at 40,000, the network reliably records events with

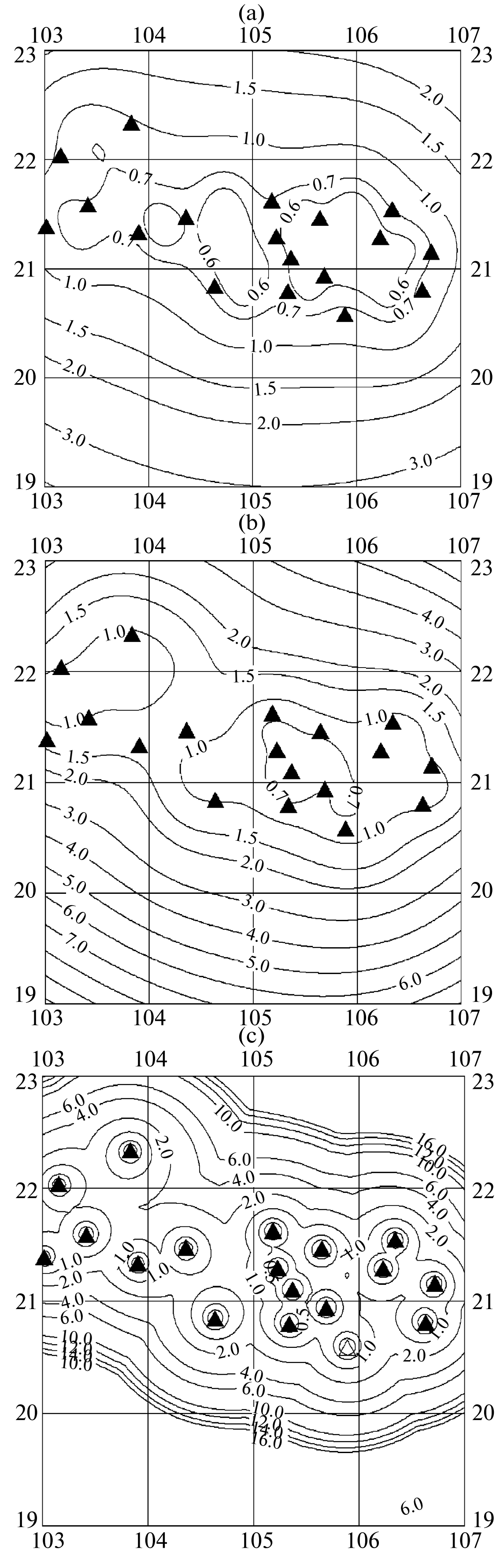

Fig. 7. Errors distribution in determination of X (a), Y (b), Z (c) coordinates in determination of hypocenter coordinates for the modern network in the north of Vietnam.

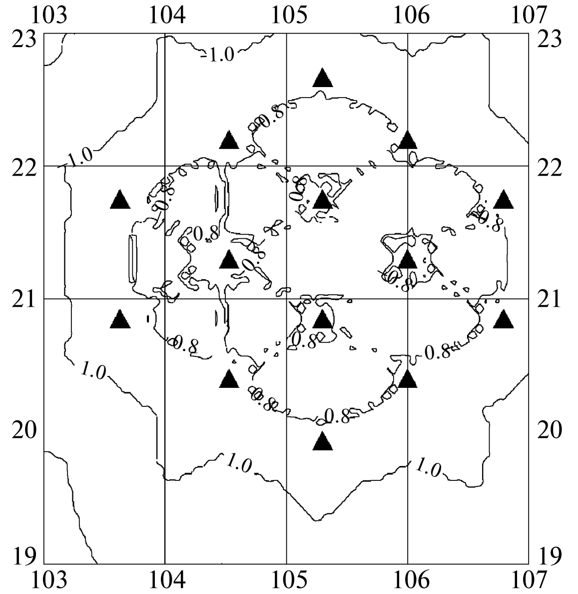

Fig. 8. Distribution of minimal magnitudes for optimal network in the north of Vietnam.

magnitude 1.3; in east-west direction, the network is more sensitive, than in north-south one. Errors in determination of (*X*, *Y*, *H*) coordinates of earthquake hypocenters at the Fig. 7 are also show at east-west direction as a preferable. Isolines of errors are greatly "pressed" in north-south direction, especially in determination of a source depth.

Let us construct an optimal network in accordance with principles, mentioned above and using the technique, considered in [9]. According to the results of this paper, an optimal network covers an area of stations location (planning area) with hexagons, in whose vertexes observation points are located. Distances between observation points are determined from conditions of uniform filling of a planning area at condition that recorded events have magnitude 1.0 or more. For this area, number of seismic stations is to be 14. In this case, network records without losses earthquakes with magnitude $M = 0.8$ within the system and $M = 1.0$ in periphery. At the Figs. 8 and 9 isolines of minimal magnitudes and errors in determination of earthquake hypocenter coordinates for the optimal observation network in the north of Vietnam are given.

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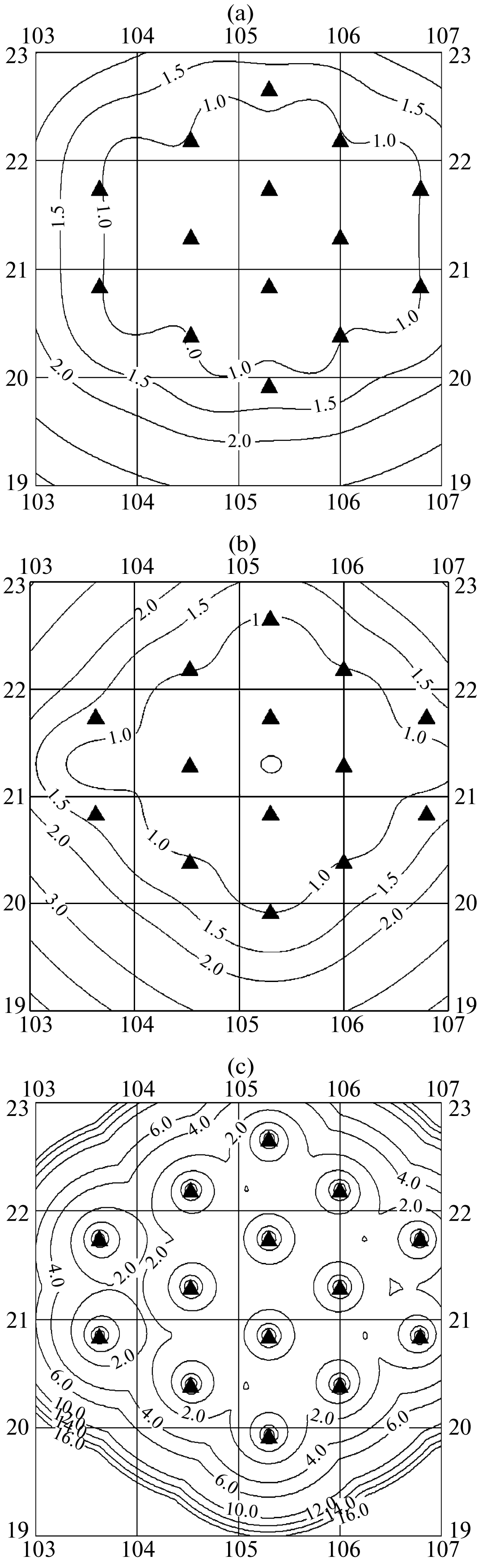

Fig. 9. Errors distribution in determination of *X* (a), *Y* (b), *Z* (c) coordinates in determination of hypocenter coordinates for an optimal network in the north of Vietnam.

CONCLUSION

Comparing errating bands for the modern and optimal networks of seismological observations in Vietnam, as well as distribution of minimal earthquake magnitudes, recorded by these networks, we can make the following conclusions:

1. Errating band for the optimal network has a more symmetric distribution, than one for the modern network.

2. Error values for the optimal network are less, than ones for the modern network.

3. Recording of earthquakes with minimal magnitudes is provided by both networks in a similar degree, but the number of stations in the optimal network is less than in the modern one.

In the paper, optimal observation network is constructed for the northern part of Vietnam, which is the most seismic one. Central and southern parts of Vietnam are prolonged from north to south (see Fig. 1) and almost aseismic [16]. In this relation, the left six stations are reasonably to be placed uniformly along the territory of Vietnam from northà to south. In this case, they would help to solve structural problems using records of seismic waves from distant earthquakes in the north of Vietnam and southwards of Vietnam, from seismoactive zones of Southeastern Asia. Moreover, whey would supplement the seismic network of Southeastern Asia.

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