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Experimental research on calibration of seismic traces

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Introduction

It is known that a key to efficiency of functioning of the International Seismic Monitoring System (ISMS) is the definition of the location and identification of a source of seismic waves. The priority issues are those of increasing the accuracy of solving these problems. Here errors in the determination of the location are reflected in local and regional variations of wave hodographs [1, 2]. Empirical approach to solving these problems is to use events for which the locations and times are known, in order to determine a set of corrections to the regional model of wave propagation.

Numerous experiments associated with the recording of the high-power 100-ton chemical explosion "Omega-3" at the 630-km profile, quarry explosions of the Kuznetsk basin with power from 50 to 700 tons, with simultaneous recording in a distance range from 0.6 km to 355 km, and azimuthal directions within 250–300° were performed within the framework of such approach.

Experiments on the recording of signals from the CV-100 and CV-40 vibrators at different azimuthal directions and distances of up to 280 km were carried out in accordance with the reciprocity principle.

Many experiments were performed with the help of the method of vibrational sounding for detailed investigation of the velocity characteristics of the medium at the *Bystrovka–Zalesovo–Novokuznetsk* trace, the length of which is 350 km. Additional investigations were performed to study the deep structure in the region of the Zalesovo station, which is one of the basic stations of the International Seismic Monitoring System (ISMS).

The basic tasks of experimental works consist in:

- Analysis of equivalence of wave fields from explosions and vibrators on specified traces of seismic wave propagation;
- Research of possibility of taking into consideration of azimuth medium heterogeneity using the high-power vibration sources on basis of measuring of travel time attributes.

Taking into account the goals of works under consideration, the processing of the data obtained was aimed at:

- determination of kinematic and dynamic characteristics of the main types of waves at different azimuthal directions;
- analysis of the velocity characteristics of the medium at the Bystrovka–Zalesovo–Novokuznetsk profile;
- study of the deep structure in the region of the Zalesovo station;
- determination of the characteristics of the source location.

In the present work, the basic results of the executed works are briefly resulted.

1. Work procedure

The quarries were placed on various azimuth directions within 58–270° and range of distances of 130–334 km in relation to recording points. In the correspondence with the developed work procedure, the explosion recording was carried out in immediate proximity to explosion epicenters in quarries (within safety zone) and on the Bystrovka vibroseismic proving ground. Except of these recording points the intermediate ones were introduced, located on a trace "quarries – Bystrovka polygon".

All source and recording points and azimuth directions "explosion–receiver" with binding to a rectangular coordinate system are schematically shown in Figure 1. The explosion points (quarries), vibrator location, recording points of explosions and vibrator are displayed in the figure.

Recording in Bystrovka polygon was carried out with the help of two recording systems: VIRS-M [3], including 5 sensors such as SS1-P, located on a linear profile with general base 800 m and with a step between two next sensors 200 m; the Baikal system incorporating three-component borehole seismometer with parameters, similar to the characteristics of the SS1-P sensors. Seismometer settles down on depth of 100 m.

In explosion areas the ROSA-N, ROSA-D complexes [3] were used for records. In the intermediate recording points, the VIRS-K and the ROSA-D complexes were used.

At conducting of explosion records on quarries, the recording complexes were placed within safe zone on 600–800 m distances from epicenter. In this case, the line of sensors position was directed to epicenter. Except of seismic sensors for recording of acoustic signal, spreading from explosion in an air along the Earth' surface, a hydrophone with a conversion coefficient 200 μV/Pa as an acoustic transmitter was used. Using a system of profile sensors the distribution velocity V_s of seismic wave of the first arrival along

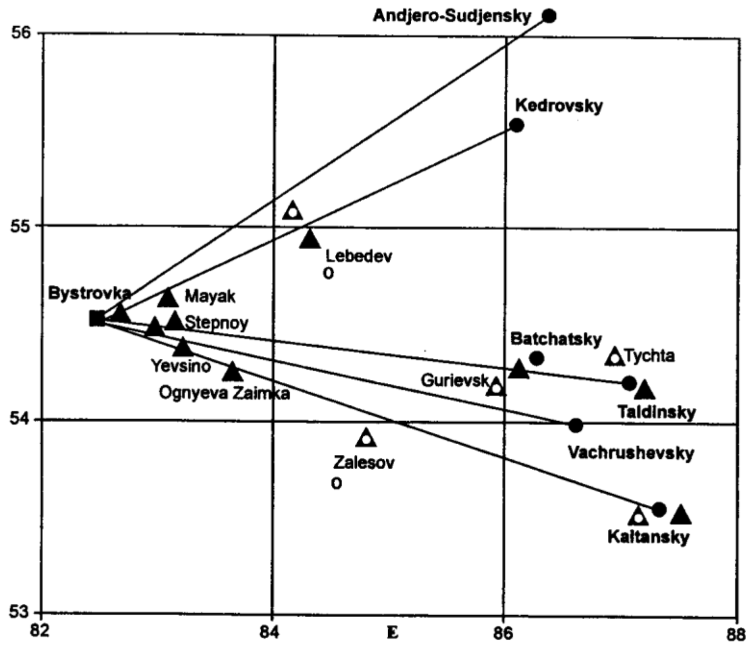


Figure 1. ▲ recording points of explosion; ■ vibrator CV-100, CV-40; ● quarries; and △ recording points of vibrators

the profile as well as absolute time of the first arrival on seismic and acoustic sensors was determined. With regard to "explosion–receiver" distance the shot time is calculated by the following formula:

$$t_{\text{expl}} = \tau_1 - R/V_s,$$

where τ_1 is time of the first arrival on 1st nearest to explosion sensor; R is the distance "epicenter – sensor". Other evaluation of explosion time in a source is calculated as follows:

$$t'_{\text{expl}} = \tau_a - R_a/V_a,$$

where τ_a is the time of the first wave arrival on the acoustic sensor, R_a is the distance "epicenter – acoustic sensor", V_a is the sound velocity in an air.

On the above described technique, 10 industrial explosions with a power of 50–194 ton, carried out on 5 open coal sections of Kuzbass: "Vachrushevsky", "Kedrovsky", "Kaltansky", "Taldinsky", "Batchatsky" have been recorded in June–September 2001. Each explosion presents a sequence of explosion series by a common power to 4 ton, divided by intervals of 30–50 ms.

The principal characteristic of each explosion are the date and time of its making, the geographical coordinates, total mass of explosive material.

Industrial explosion characteristics

Explosion date	Explosion time, hh:mm:ss	Quarry name	Explosion coordinates	Power, tons	Recorder point coordinates	Dist-ance, km	Comment
05.06.01	03:51:30	Kedrovsky	55°32′59.6″N 86°05′14.5″E	194.2		244.5	
06.07.01	04:31:12	Kaltan	53°32′35.7″N 87°27′20.3″E	73 (58*)	53°32′35.8″N 87°27′51.1″E	333.3	27 blast trains at 3 t, 50 ms span
23.07.01	06:47:38	Kaltan	53°32′26.7″N 87°28′00.0″E	54	53°32′01.2″N 87°28′21.2″E	333.3	18 blast trains at 3 t, 50 ms span
31.07.01	08:09:09	Kaltan	53°32′40.1″N 87°24′33.8″E	105	53°33′57.1″N 87°20′05.9″E	333.3	30 blast trains at 3.5 t, 50 ms span
09.08.01	08:34:14	Taldinsky	54°10′39.2″N 87°11′59.9″E	51.6	54°10′44.9″N 87°11′27.1″E	296.6	14 blast trains at 3.7 t, 30 ms span
10.08.01	10:28:29	Bachatsky	54°17′26.9″N 86°08′15.2″E	68.2	54°17′50.3″N 86°07′22.2″E	227.3	253 apts. at 300 kg, $D = 60$ m
10.08.01	09:08:07	Bachatsky	54°17′26.9″N 86°08′15.2″E	39.9	54°17′50.3″N 86°07′22.2″E	227.3	222 apts. at 180 kg, $D = 150$ m

* – TNT equivalent.

These data are presented in the table "Industrial explosion characteristics". In this table and further, absolute time on Greenwich (GMT) is given. As an additional characteristics in the table data on a partition of a common charge on series number and quantity of explosive material in one series, time delay between series as well as distance "explosion–receiver" are included.

In Figure 2, as an example the sample of record of explosion from a quarries "Kaltansky", executed on components x_1, x_2, x_3, y_1, y_2, y_3, z_1, z_2, z_3, and also on the acoustic sensor is given. The distance made nearest sensor from epicenter 600 m, acoustic transmitter – 990 m. The beginning of all records corresponds to the settlement moment of explosion.

The records of signals from explosions in the removed items of registration were carried out lengthways 5 of the basic direction converging in final item Bystrovka (see Figure 1).

The signal records from explosions are synchronized with each other on GPS signals. The time synchronization is carried out with an accuracy of 0.1 ms. In addition, with the help of GPS the geographical binding of items

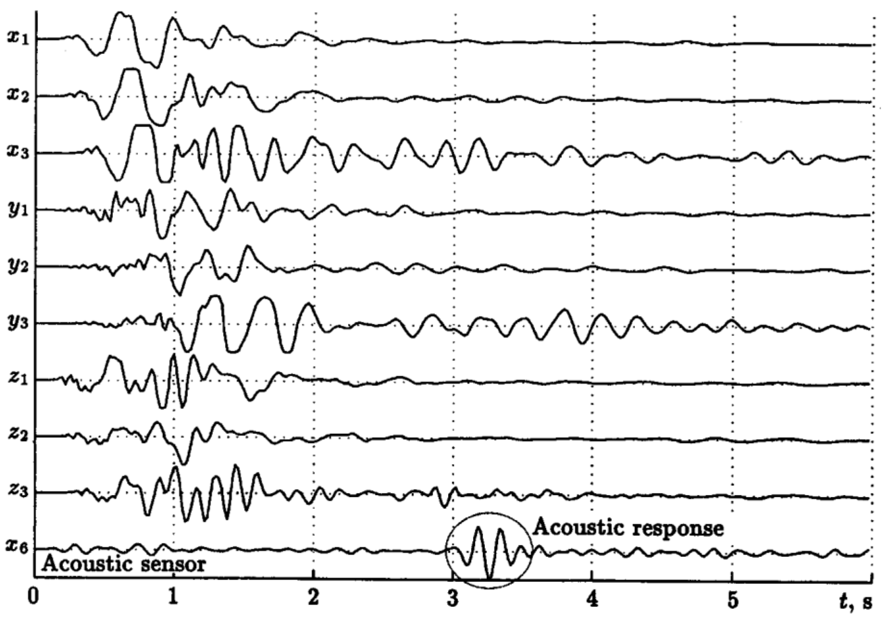


Figure 2. Record of explosion, Katlan quarry, 23.07.2001, Rosa-D

of radiation and registration is carried out. Such technique of realization of works allows with a high degree of accuracy to interpret the wave travel times from explosion and to determine distances and azimuths in a direction "source–receiver".

In interests of improvement of a technique and reception of the data the detailed deep seismic research was fulfilled on 200 km sites of a detailed profile Bystrovka–Zalesovo–Novokuznetsk, which were made by method of the refracted and reflected waves (detail CMRW-MRW). In addition, regional 350 km profile of depth seismic sounding (DSS) with vibrators and industrial explosion from territory of Kuzbass was made.

Thus as sources of seismic waves were used mobile seismic vibrator CV-40 and stationary vibrator CV-100, and also industrial explosions submitted in the table. The technique of works provided records from powerful vibrators on distances more than 200 km, where in the first introductions begins confidently to be registered a longitudinal wave P_n from the Mohorovichich surface.

At such approach to problem solving the perspective of application of powerful movable vibrators for the purposes of calibration of stations of the International Seismic Monitoring System (ISMS) and study of territories with a nonuniform structure is unclosed. That is also rather important for precise restoring of epicenter parameters of seismic events on data of the international net of station.

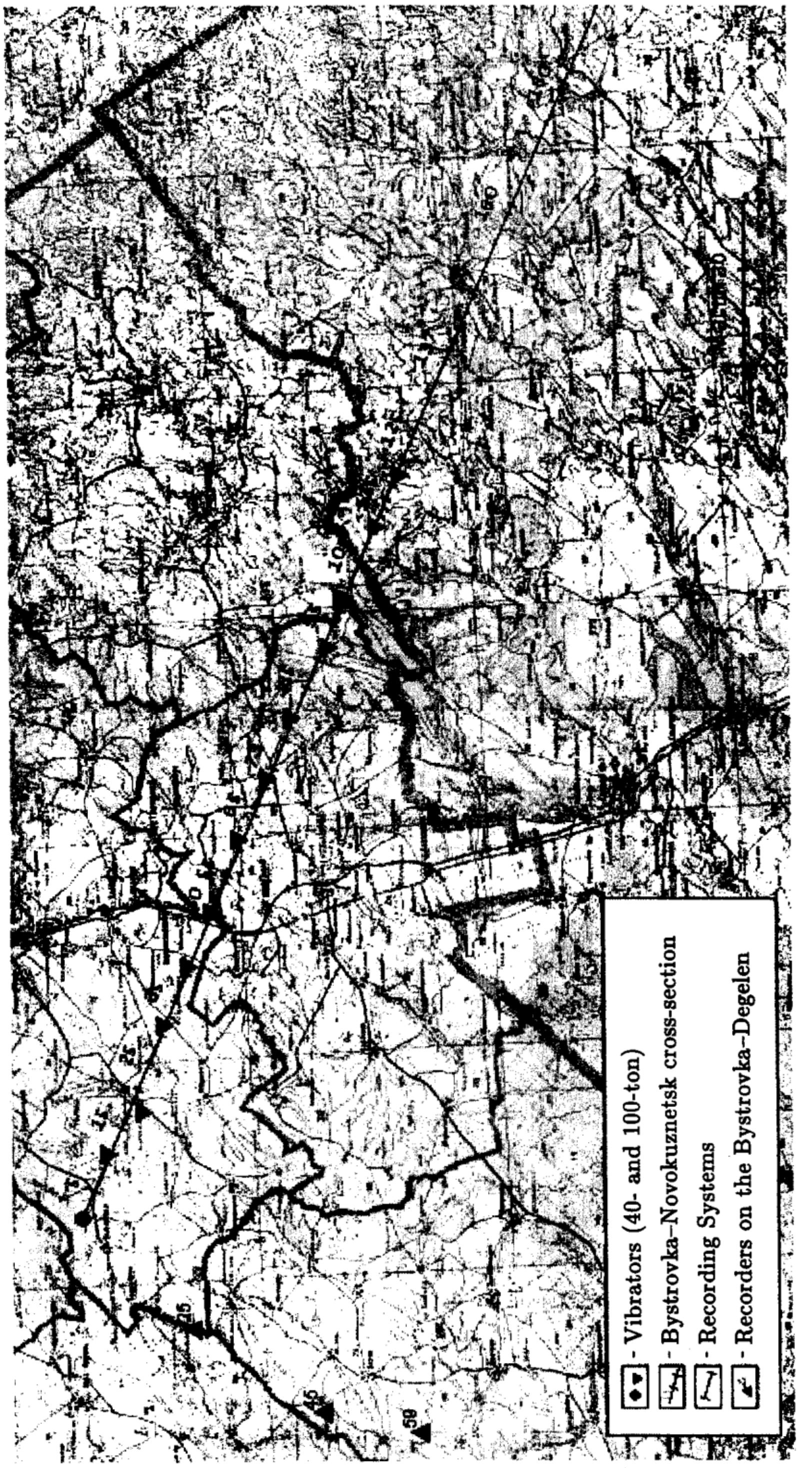


Figure 3. The scheme of observations on vibroseismic the profile of Bystrovka–Novokuznetsk

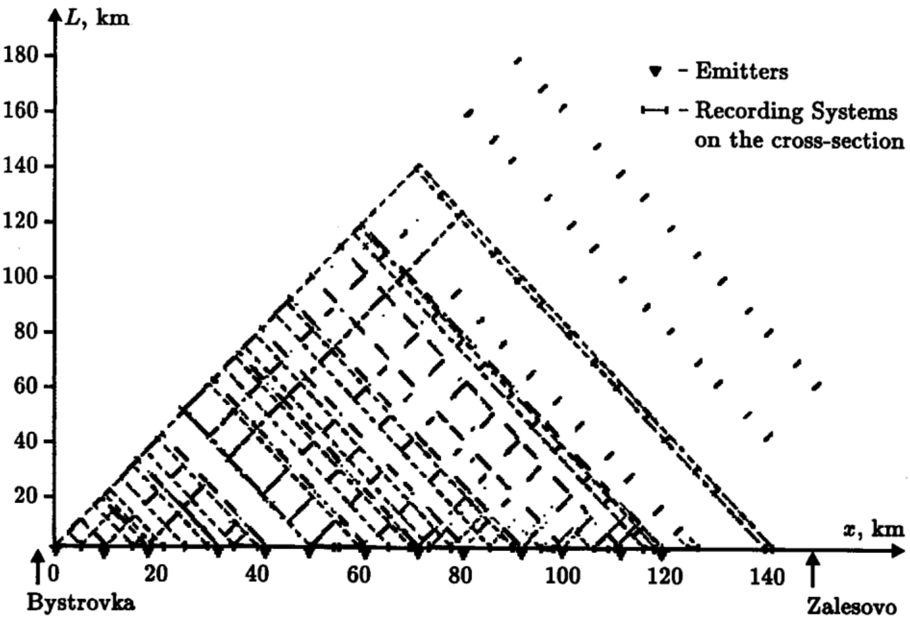


Figure 4. The system vibroseismic of observations on the profile Bystrovka–Zalesovo–Novokuznetsk

Implemented on today the scheme and system vibroseismic of observations are represented in Figures 3 and 4. The registration was carried out on 17 continuous, extended registering installations with distances between seismic sensors of 300 meters and overall length up to 4200 m. On a site of the profile x = 0–140 km the average distances between continuous installations made 5–10 km, on a site x = 140–200 km three arrangements of stations through 20 km were disposed. As registering instrumentation on the profile 150 packages of the American one-channel digital registering instrumentation "Reftek" with vertical sensors were used. On separate arrangements, along of with instrumentation "Reftek", there were packages the Russian 24 bit digital stations of "Baikal" with three-component sensors SS1-P and 24 bit multichannel digital telemetering station STS-24. The coordinates of installation sensors and the distances from vibrational sources were determined with the use of the GPS-receivers.

The vibrational sources completed in 13 points of the profile: (CV-100 and CV-40 on a site of the profile x = 0 km, polygon "Bystrovka") and CV-40 on a site of the profile x = 0–120 km with an interval in 10 km, on a site of the profile x = 155 km (the vibrator CV-40 was installed in region of the station "Zalesovo") and in points of the profile 180, 200, and 230 km.

As a result of a realization of this technique of wide-angle and detail observations on CMRW-MRW method (the recording of the reflected and refracted waves) more than ten types of various waves (refracted P- and

S-wave from the interfaces of the upper and middle parts of the Earth' crust and M discontinuity, reflected P- and S-waves from the interfaces in the Earth' crust and from M discontinuity) will be recorded and simultaneously interpreted, that will allow to construct a combined section on P- and S-waves – subcritical, supercritical reflected, refracted, head.

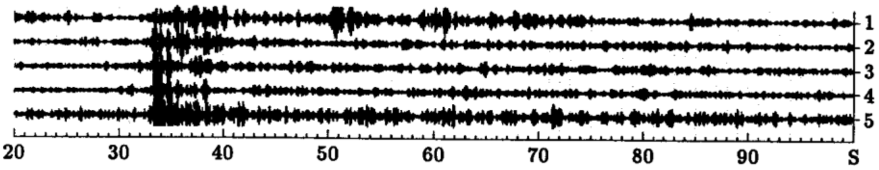
2. Results of operations

The analysis of undular fields on distances of 190–200 km. For the analysis of undular fields registered simultaneously from explosion and the vibrator on the same distance, in Figure 5 the records industrial of explosion from a quarries "Bachatsky" and vibrational seismograms from the vibrator CV-100 represented. In both cases, the distance "source–receiver" made 196.1–196.9 km.

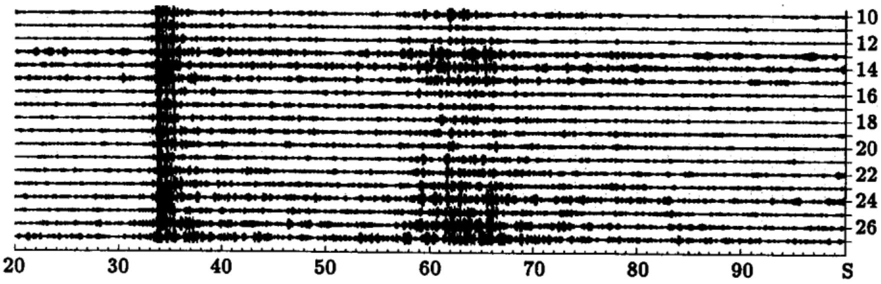
In frequency range of 6.25–9.57 Hz (on which the correlograms from a 100-ton vibrator have been obtained), S-waves are practically not enough expressive even on horizontal gears. This is related to records of explosions from quarries "Taldibsky" on basis of 190–192 km as well. However, in spite of a narrow spectrum of the presented records from explosions and correlograms from a vibrator in the field of longitudinal waves we note expressive records of waves in the first arrivals, moreover enough similar both under the form (wave packets) and on a relation of intensities. Really, as it is seen from correlograms, obtained on "Reftek" stations (see Figure 5 of seismograms of joint work of 100- and 40-ton vibrators and explosive records, made in Stepnoy on VIRS-K), the practically identical character of records is observed – weak 2–3-phase inexpressive wave ahead on times close to 33 seconds and very strong four-phase wave after 0.3–0.4 s from the first wave. The apparent velocities of the first waves on seismograms are close and make $\sim$ 8–9 km/s, that is close to values of velocities of $P^M_{\rm refr}$ waves from the M discontinuity. The similar character of records with a weak wave in the first arrivals and a strong wave in a consequent part is noticed also on experimental records from other sources. In next parts of records in Figure 5, after strong wave the weaker groups of waves are noticed and then behind them – lack of even weak groups of waves (record practically at a level of a noise background).

The example of good coincidence of wave packets of P- and S-waves, obtained practically in mutual points, illustrates Figures 6 and 7 (review records Bystrovka–Gur'yevsk and Bachatsky–Bystrovka). As it is seen from the presented figure from a 100-ton vibrator on vertical and horizontal components (at use of low-frequency detectors) the high-power field of S-waves is picked up, much stronger than a field of P-waves; moreover this relation of package amplitudes of S- and P-waves is much higher on correlograms, than on records from explosion.

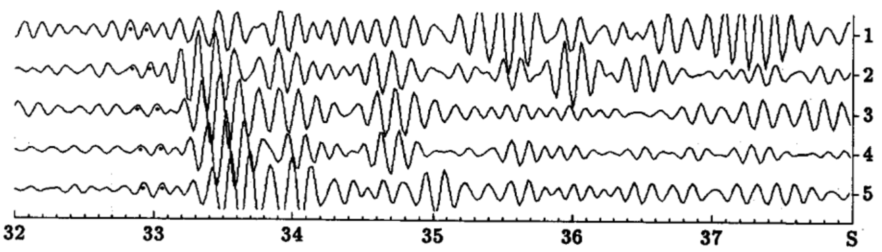
Explosion records in Bachatsky quarry, August 10, 2001, 16:08:7.2, Stepnoy vil., VIRS-K Recording System. Distance 196.1–196.9 km, pass filter 6.25–9.57 Hz



CVM-100 and CVP-40 (worked concurrently) corelograms, Reftek, 196.15–196.95 km, frequency range of emitters 6.25–9.57 Hz



Explosion records at the distance 196.1-196.9 km, pass filter 6.25–9.57 Hz



196.1-196.9 km distance corellograms

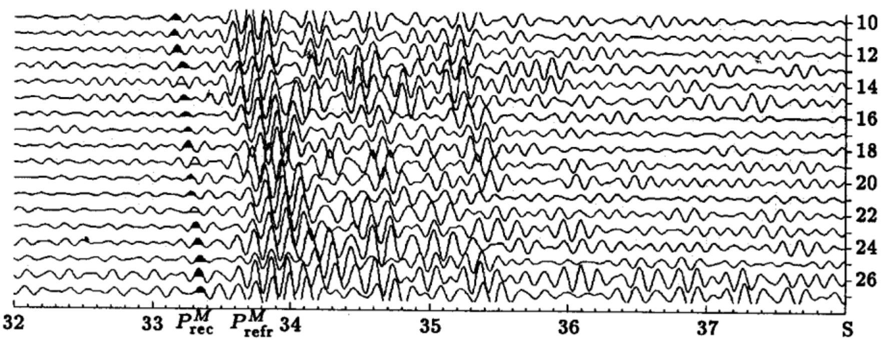


Figure 5. Powerful (40- and 100-ton) vibrators vs. explosions in quarries. Wave fie

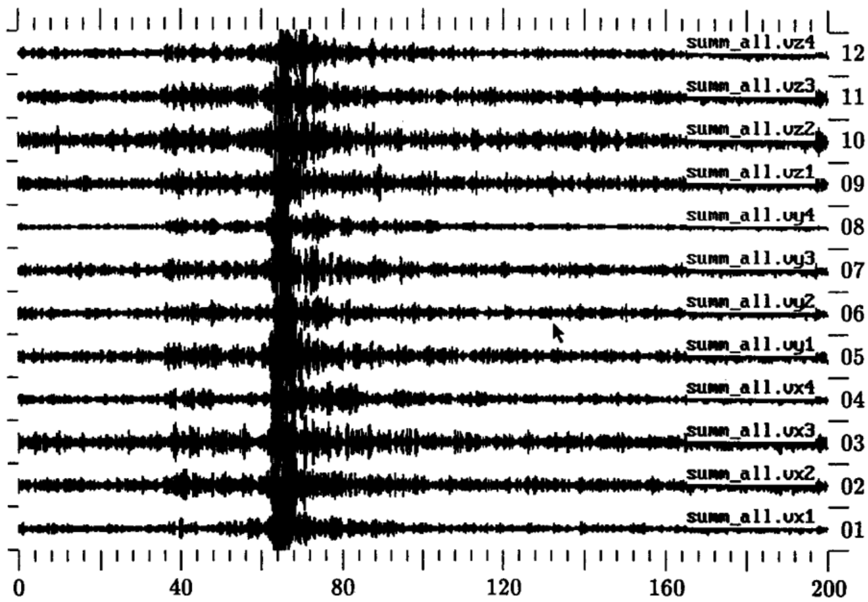


Figure 6. CV-100 seismograms, Bystrovka–Bachatsky, 215 km, VIRS-K, Gurievsk, Lesnoy. Distance 253–250 km, 6.25–9.57 Hz pass filter

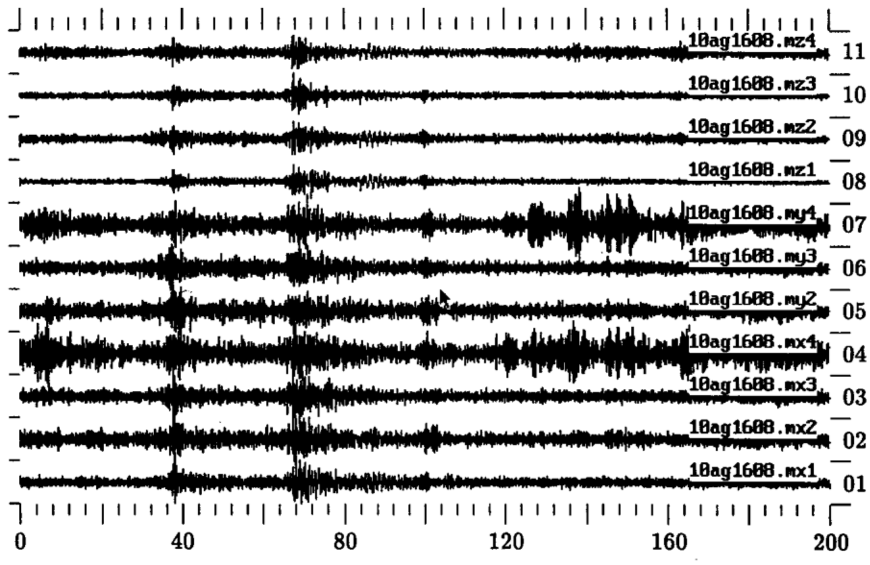
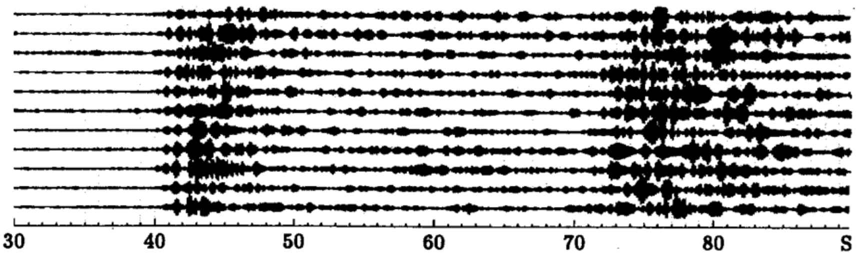
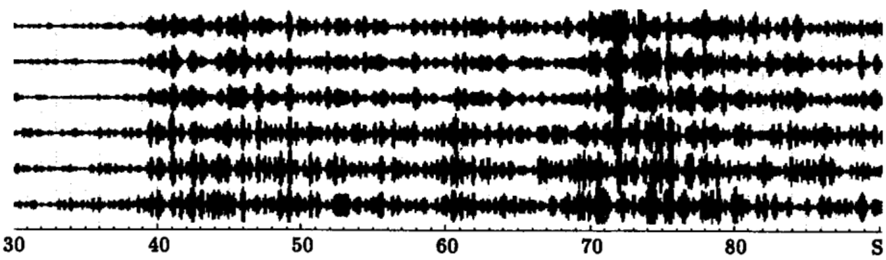


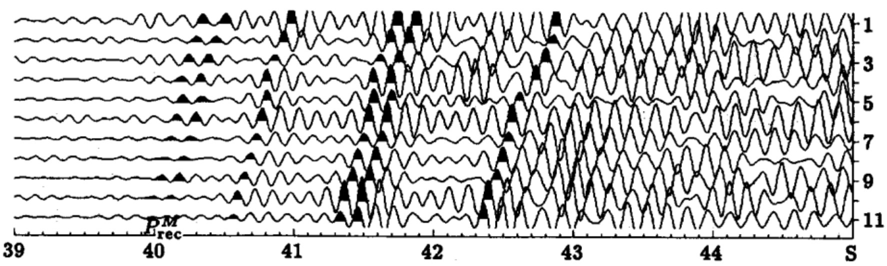
Figure 7. Explosion seismograms, Bachatsky–Bystrovka, 228 km, VIRS-M, Bystrovka. Distance 253–250 km, 6.25–9.57 Hz pass filter



CVM-100 and CVP-40 (concurrently) corelograms, 245.1-246.1 km distance, $\Delta f =$ 6.25–9.57 Hz



Explosion, 6.25–9.57 Hz pass filter, distance 253–250 km



CVM-100 and CVP-40 (concurrently) corelograms, 245.6-246.1 km distance, $\Delta f =$ 6.25–9.57 Hz

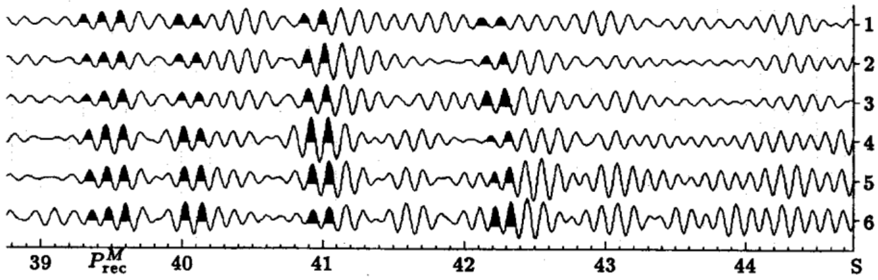


Figure 8. Explosion in Krasnogorsky quarry, July 28, 2001, 10:10:56.8 (N 53°63, E 87°98), total blast power 330 t

The analysis of undular fields on removals about 250 km. For the analysis the records, obtained from joint work of vibrators on distances of 245–246 km, and record from 330-ton explosions from Krasnogorsky quarry on distances of 253–250 km (Figure 8) are presented.

As may be seen from the presented figure on times 39.3–39.7 s (on correlograms) the strong wave with apparent velocities on seismograms 8–9 km/s, concerning to a refracted wave from the Moho discontinuity, is picked up. Two-phase wave on a record from Krasnogorsky quarry on times ~ 40 seconds corresponds to it (with regard to difference in distances). Behind this wave on a seismogram and correlogram after 0.5 s waves with low values of apparent velocities on seismograms, which can be referred to group of waves P_g or $P_{\text{refl}}(M)$ waves, are picked up. Further, within 0.8 s from this wave, one more group of P-waves and behind it on times more than 42 s one more P-wave are distinguished. Some unconformity of relations of intensities of first two waves on a seismogram and correlogram can be connected to different azimuths of recording from explosion and vibrator. The wave in the first arrivals, recorded from a vibrator, is related, in author's opinion, to a group of weak refracted waves that is why it is more expressive on correlogram, than wave in the first arrivals from explosion, referred by the researchers to a refracted wave from the Moho discontinuity.

3. Wave field on the profile Bystrovka–Zalesovo–Novokuznetsk

As a whole, with instrumentation "Reftek", "Baikal", and "STS-24", used on the profile, from stationary and movable vibrators CV-100 and CV-40 the qualitative experimental materials with records of target waves before removals 120–200 km are accordingly obtained. On the basis of the analysis of the obtained material the reduced hodographs of longitudinal waves (Figure 9) and waves of the first entrances (Figure 10) registered on the profile Bystrovka–Zalesovo–Novokuznetsk are constructed. The complete analysis of a pattern of a wave field on this site is represented in [3].

By results of the preliminary analysis, the kinematic and the dynamic characteristics of longitudinal waves on the investigated (studied) profile some approximate representation about a structure of earth crust and upper mantle of a site profile Bystrovka–Zalesovo–Novokuznetsk ($x = 0$–200 km). The velocities of longitudinal waves in the upper part of the Earth's crust are 5.45 ± 0.1 km/s at the profile section $x = 0$–50 km and 5.8 ± 0.1 km/s at the profile section $x = 50$–180 km. In the upper part of the Earth's crust at depths of 5–7 km, there is a refracting surface with velocities of 6.05 ± 0.1 km/s, and in the middle part of the crust at depths of 18–20 km there is a crustal reflecting boundary (with effective velocity to it constituting

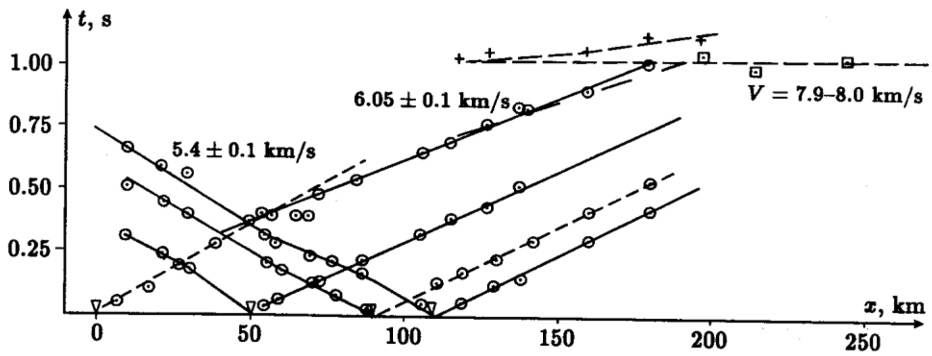


Figure 9. The reduced hodographs of longitudinal waves on the profile Bystrovka–Zalesovo–Novokuznetsk: ⊙ – data of refracted waves from boundaries in the Earth's crust, + – data of reflected waves from the Mohorovichich surface, ⊡ – data of refracted waves from the Mohorovichich surface

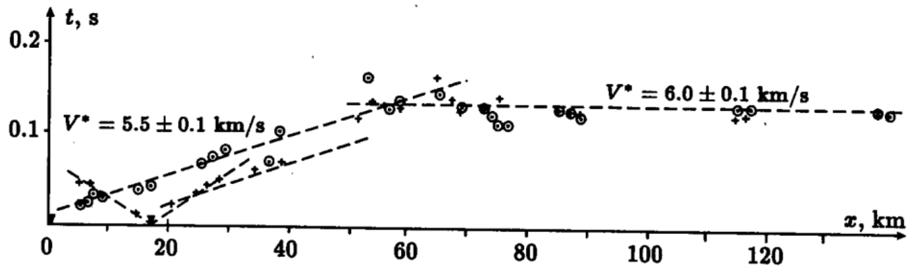


Figure 10. The reduced hodographs of waves in the first entrances on the profile Bystrovka–Novokuznetsk: ⊙, + – data from 100- and 40-ton vibrosurces accordingly

6.3 km/s): The Moho surface is at depths of 46–48 km under the Salair ridge and in a section of the Tom'–Kolyvan' folded zone. In the transition zone (contact of the Tom'–Kolyvan' zone, Biisk–Barnaul low, and Salair ridge), the depths of the Moho surface constitute 44–45 km. The boundary velocity of longitudinal waves along the Moho surface is 7.9–8.0 km/s.

Conclusion

In interests of a solution of a problem of calibration of seismic traces and seismic station, connected with the rise of efficiency of the International Seismic Monitoring System (ISMS) for control of nuclear trials the research is made on:

- To the comparative analysis of wave fields registered from powerful vibrators CV-100, CV-40 and of industrial explosions on mutual distances up to 300 km. The closeness of undular fields from both types of sources on cinematic characteristics, saving of the forms of record of reference waves at the analysis in the same frequency range is proved;

- At vibrational sounding from powerful vibrators the field longitudinal and transverse waves from main abutment boundaries of the Earth's crust and upper mantle (refracted and reflected P- and S-wave from a surface of the fundament and of crust boundaries, refracted and reflected P- and S-waves from the Mohorovichich surface) is generated;
- Constructed on vibroseismic data from powerful vibrators the seismic sections do not contradict available geologic representations about a deep structure of the Earth's crust and upper mantle of region, and also correlate with seismic sections on region obtained at depth seismic research with explosive sources;
- The results of processing of signal records from the movable 40-ton vibrator (and group vibrational sources) on distances up to 250 km prove perspective of its using for analysis of a depth structure and direct calibration of stations ISMS. This opens up new prospects for the use of powerful mobile vibrators to study the deep structure of the area under calibration and direct calibration of seismic stations of the International network (obtaining of hodographs at long distances of 1500–2000 km both from powerful mobile vibrators with the use of the property of parallelism of overlapping hodographs and at the grouping of powerful 100-ton (and more than 100-ton) vibrators.

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