INVESTIGATIONS AIMED AT ENHANCING THE EFFECTIVENESS OF SEISMIC MONITORING IN WEST KAZAKHSTAN

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History of seismic observations in the west of Kazakhstan.

Permanent seismic observations In Soviet time, seismic observations at the region of West Kazakhstan were not regular. The only Organization that deployed seismic stations equipped with short-period instruments with natural period 1.5 s, 1.25 s (Table 1) for the period of about one year was Complex Seismological Expedition (CSE) of the Institute of Physics of the Earth AS USSR. All these stations operated at relatively small territory near Myugodzhary mountain range that is a southern spur of the Ural mountains. Seismic observations at Mangyshlak peninsula, Caspian depression and other regions of Western Kazakhstan were not conducted in the Soviet era.

A temporary station Novotroyitskoye of the IPE AS had been operated in 1979 – 1980 (Table 1); it was equipped with narrowband seismic instruments RVZT and KSE [1]. In 1980-s and beginning of 1990-s the station had been operated as "Aktyubinsk" station under the service of special control of the USSR; its task was monitoring of nuclear tests. Starting from 1994 the seismic network of the RSE IGR consisting of sensitive seismic arrays and broadband three-component stations have begun its seismic monitoring of Kazakhstan territory and adjacent regions of Central Asia (Figure 1) [2]. "Aktyubinsk" seismic station was transferred to the Institute of Geophysical Researches of RK in 1994. In 1994 the station was equipped with a broadband seismometer CMG3ESP and a digitizer REFTEK72A; data were accumulated to a hard disk during a month and then processed. AKTK station was installed on the ground surface, thus the seismic noise level was relatively high [3, 4]. In July 2005, "Aktyubinsk" station was included into the International Monitoring System (IMS) CTBTO, and following the IMS requirements it was equipped with new instruments – seismic sensor CMG-3TB of Guralp Company that was installed in a borehole of 65 m depth. Recording instruments were: 24-bit analog-digital converter Europa-T of Nanometrics Company with sample rate 40 samples/sec/channel. Time scale reference was GPS. The station was certified by the Commission on November 10, 2005.

Table 1. Parameters of CSE stations in Western Kazakhstan.

station code	start time	end time	latitude	longitude	h, m	station name	instrument type
BUGS	1974194	1975085	50,12	59,1		Bugetsay	RVZT,KSE
LNSK	1974181	1975090	50,73	57,9		Leninskoye	RVZT,KSE
NTR	1979121	1980151	50,4348	58,0164	380	Novo-Troitskoye	RVZT,KSE
NVG	1974228	1975107	48,95	59,1167		Novogodnyaya	RVZT,KSE

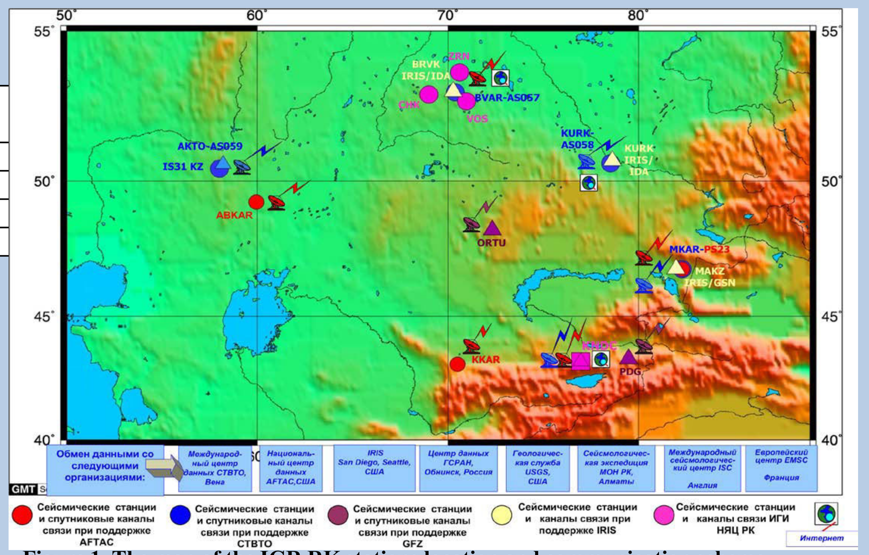

Figure 1. The map of the IGR RK stations location and communication scheme between KazNDC and International Data Centers

One of the effective methods to estimate the sensitivity of seismic stations is investigation of seismic noise by the station records. Each station has specific parameters of seismic noise considering the station location – geologic conditions, location regarding noise sources, instrument specifications.

Figure 2 shows a graph of seismic noise spectral density for AKTO station, Z-component as well as the global noise models of Peterson.

The Figure shows that the noise at Aktyubinsk AKTO station is closer to the global low noise model ensuring its high efficiency for seismic monitoring works. It should be noted that in 1994 – 2005 when Aktyubinsk station was installed on the surface, the values of seismic noise spectral density for this station at periods <0.8 were 20 dB higher than for the borehole station [4].

To estimate the recording range by AKTO station the graphs of mpv dependence on distance were constructed (where mpv is body-wave magnitude calculated using regional calibration curve) [5]. For analysis, data from the interactive bulleting of Data Centre (IGR) for 2010-2013 were selected. From [6] it follows that dependence mpv_{min} and mpv_{repr} depends on distance: up to 1000 km $mpv_{repr} = mpv_{min} + 0.5$, and more than 1000 km $mpv_{repr} = mpv_{min} + 0.9$ (Figure 3). Table 2 shows the values of mpv_{min} and mpv_{repr} for AKTO station.

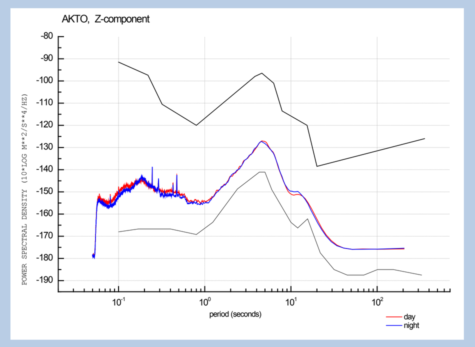

Figure 2 – Spectral density of seismic noise for AKTO station

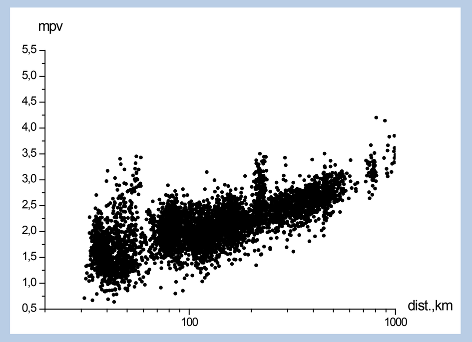

Figure 3 – a graph of mpv dependence on distance by data of Aktyubinsk seismic station

Table 2 – Recording range by AKTO and ABKAR station

Distance, km	AKTO		ABKAR	
	mpv_{min}	$mpv_{пред}$	mpv_{min}	$mpv_{пред}$
100	1.3	1.8	1.13	1.63
200	1.8	2.3	1.31	1.81
500	2.31	2.8	1.97	2.47
1000	3.48	4.38	3.09	3.59

Another permanent seismic station at the region was constructed in 2003 together with AFTAC (USA) for verification of the Comprehensive Test-Ban Treaty compliance (CTBT). The station is located in the west of Kazakhstan at the east part of Aktyubinsk region, and was named following the area name – "Akbulak" [7]. "Akbulak" seismic array configuration is similar to the one of "Makanchi" and "Karatayu" seismic arrays, and consists of 10 observation points located along two circles with a common central site (Figure 4). The radius of large circle is 2 km, small – 500 m. Along the large circle there are five instrumental wells (AB05 – AB09), along the small one – 3 instrumental wells (AB02 – AB04). The wells depth is 40 m. There are 2 instrumental wells (AB01, AB31) of 80 m depth in central site. 9 one-component vertical seismometers GS21 are installed at nine sites in the wells. In addition, there is one broadband three-component station with KS54000 seismometer (ABKAR(AB31)) installed in the center of the array. From January 2004, data of "Akbulak" seismic station are included into the processing together with data of other IGR network stations.

Figure 5 shows the graphs of spectral density of seismic noise for ABKAR station, Z-component for day and night time, and global models of Peterson. The figure shows that ABKAR station noise is closer to the low-level noise model that ensures its effectiveness in works on seismic monitoring. Figure 6 shows mpv dependence on distance for ABKAR the analysis, data from the interactive bulletin of the Data Centre IGR for 2010-2013 were selected. Table 2 shows the mpv_{min} and mpv_{repres} values for ABKAR station. station. For

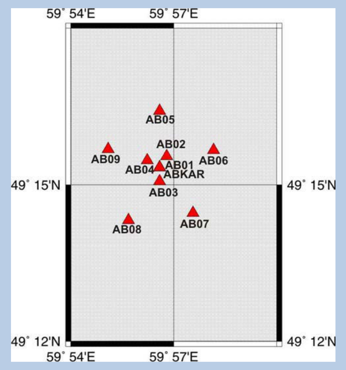

Figure 4 – A scheme of Akbulak seismic array elements location (ABKAR)

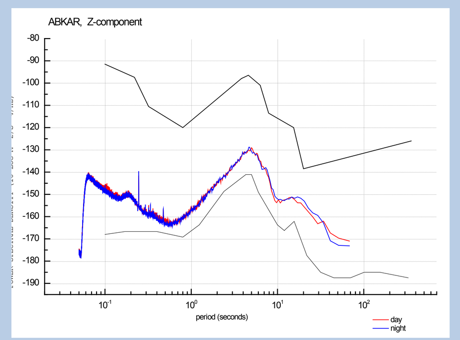

Figure 5 – Spectral density of seismic noise for ABKAR station

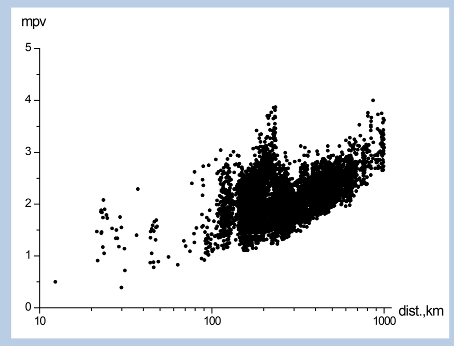

Figure 6– Graph of mpv dependence on distance for ABKAR

By data of seismic events with epicenters near Akbulak station (distance up to 130 km), for investigation of the attenuation field at the station region, S-coda envelops were constructed (narrow band filters with central frequencies 1.25 and 5 Hz were used) (Figure 7). Using this data the section of attenuation field at Akbulak station region was constructed (it is assumed that coda was formed by reflected shear waves, see Figure 8).

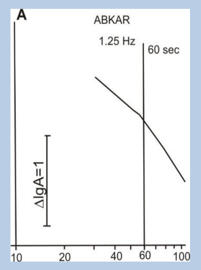

Figure 7. General envelop of coda for local events by Akbulak station. Channel 1.25 Hz.

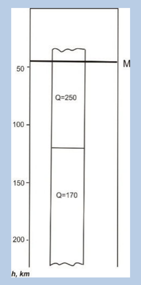

Figure 8. The section of attenuation field for Akbulak station. The effective Q-factor for two depth intervals is shown.

Monitoring of oil and gas fields. There are many oil and gas fields on the territory of Western Kazakhstan; the largest of them conduct geodynamic monitoring of the fields territory. For instance, Kashagan field located in the north part of the Caspian Sea has a seismic monitoring system consisting of 11 borehole instruments CMG-3T Guralp. At Tengiz field in Atyrayu region of Kazakhstan, 350 km south-eas of Atyrayu town, the contemporary observation network has been operating since 2001, and currently consists of 23 borehole seismic stations Nanometrics: seismometer Trillium-Compact750-20 and digitizer Trident305 [8]. Data of local networks for geodynamic monitoring are for official use only.

Temporary seismic networks. In the west of Kazakhstan, starting from 90-s of the past century, various field experiments were conducted, some of them are described below.

At Mangystayu region, CSE IPE RAS conducted field seismological observations at Mangyshlak peninsula in September – November, 1992 [9]. The field works were aimed at estimating of seismic hazard of local earthquakes. The observations were conducted on the territory of Mangyshlak peninsula constrained by 43-44 N, 51-53 E; at the site there were 9 permanent and 4 mobile observation points equipped with recorders ASS-3/12 and narrow-band seismometers SM-2 and SM-3 [1].

In 1997-1998, CSE IPE RAS conducted field seismic observations at Tengiz field region to investigate local seismicity [10]. During the investigations 9 seismic stations equipped with radio and telemetry seismic set RTSS-AN, and with seismic stations ASS-6/12 with magnetic record were installed.

In June 2010, in the west of Kazakhstan, under financial support of AFTAC USA, and IGR NNC RK, there was an experiment on recording of several chemical explosions on the territory of quarries. The explosions were recorded by permanent and temporary stations network. To investigate wave properties of geological environment at the region of Akbulak seismic station by recording of seismic vibrations from mining explosions by field seismic stations, two active reference mines located in different directions from Akbulak station were selected. These were Myugolzhar mine (130 km, azimuth SW 230°), and "50 let Oktyabrya" mine (150 km, azimuth NW 330°). From the selected mines, along the lines of two profiles of 230 and 250 km length laid via Akbulak seismic station, 7 field seismic stations were installed at 25 – 50 km interval; the stations were equipped with seismometers CMG40T, SK-1P, and digitizers PMD DAS6102 and 6501 [11].

In 2016, from August 19 to September 12 at Mangystau region there were field works conducted by joint expedition of Michigan State University (USA) and IGR RK aimed at investigating of seismic noise parameters to select a site for installation of a new seismic station in the west of Kazakhstan. 10 seismic stations equipped with digitizer Reftek RT130 and broadband sensitive seismometer Guralp CMG-3T were installed [12].

Ground truth events in the west of Kazakhstan.

Figure 9 shows a map of minimal magnitudes of seismic events included into the interactive catalogue of seismic events of KNDC for 2010 – 2017. The whole territory was divided into squares of $0.5^0 \times 0.5^0$, after that the minimal mpv magnitude of the events entered a cell was selected. The Figure shows that magnitude sensitivity of Akbulak seismic array regions is very high. Within 555 km radius earthquakes with magnitude 2 and higher are recorded, and within 1300 km radius - the events with mpv=3.5 and higher, that coincides completely with results of Table 2. The region of the west Kazakhstan and the Caspian Sea is characterized by high threshold magnitude of events detection.

Contemporary assessments of seismic hazard of different sites of the west Kazakhstan, as rule, calculate seismic impacts from origins related to tectonic structures located outside Kazakhstan, for instance, Kopetdag-Kavkaz-Crimean zone of faults traversing the Caspian Sea from Turkmenistan to Azerbaijan [13]. This zone is known for its constant high seismic activity. Annually, within the zone there are several hundreds of small and moderate earthquakes. In its eastern part there was one of the largest of known in Asia earthquakes – Krasnovodskoye, 08.07.1885, M=8.2. On the territory of Kazakhstan it was felt with intensity up to 6. Mangyshlak peninsula possesses paleo-seismic dislocations testifying a destructive earthquake occurred in the Middle Ages with magnitude 6.5 at least [14]. On April 26, 2008 there was the earthquake near Shalkar Lake with intensity 7 [13]. In addition, at the region there are many oil and gas fields, and activation of induced earthquakes is possible [15].

However, the accuracy of events epicenters location by KNDC data for the regions westward 55 degree E, regions of near-Caspian depression, Mangystayu region, Caspian Sea is far from perfect. From the ISC seismic bulletins [16] we have selected events occurred at the Caspian Sea and possessing high accuracy of coordinates determination, Smajax<5 km, detected by at least 100 stations, and availability of stations close to an epicenter. The comparative analysis of selected events parameters with the same events from KNDC catalogue showed significant differences; median difference for latitude was $\delta\varphi=\varphi_{kndc}-\varphi_{isc}=0.53°$, for longitude $\delta\lambda=\lambda_{kndc}-\lambda i_{sc}=0.87°$, median of distance between the epicenters Δ=95 km, $\delta t_0=t_{0kndc}-t_{0isc}$=5.5 s (Figure 10). Low accuracy of the epicenters coordinates determination was caused by unilateral location of the IGR stations, large distances from epicenters, and lack of appropriate velocity model.

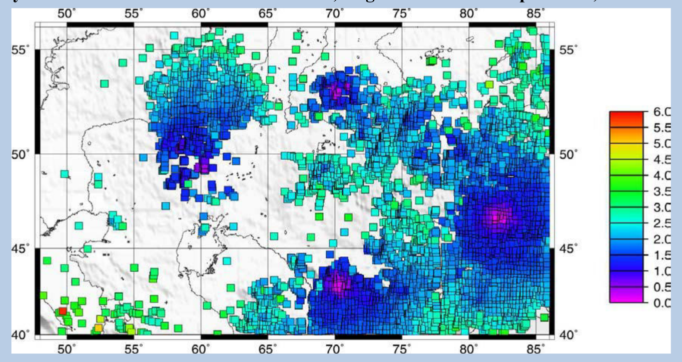

Figure 9 – The map of minimal mpv magnitudes for 2010-2013.

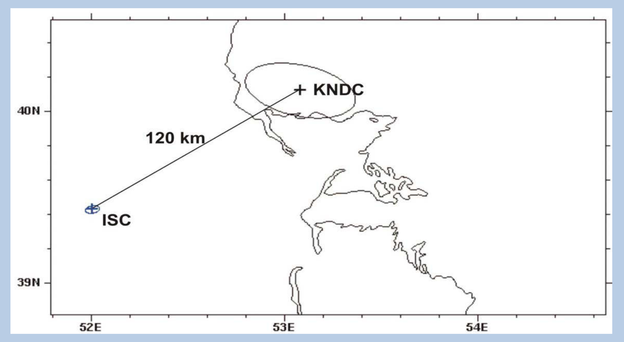

Figure 10. The map of earthquake epicenter location, 2005-09-24, t0=19:28:09.5, by data of the ISC and KNDC, and error ellipses.

For seismic events hypocenter location, currently, KNDC applies IASPEI91 velocity model (International Association of Seismology and Physics of the Earth's Interior). However, the routine processing of events from the west Kazakhstan and Caspian regions showed significant difference of the observed arrival times of the main regional phases and calculated arrival times obtained by the IASPEI91 model. For construction of the précised travel-time curve it is necessary to have large amount of seismic events with accurately determined coordinates and origin time, but the west of Kazakhstan is the region of low seismicity.

Note that for the considered region there are seismic models developed by the Institute of Seismology of Kazakhstan basing on the interpretation and generalization of retrospective archive and published materials on deep seismic sounding by profile systems [16, 17]; however, these models were not tested with actual events, and were not compared with other travel-time curves. Shatsilov V.I. made the zoning of Kazakhstan territory basing on generalization of materials on regional seismic soundings of the earth crust (DSS, DSS-ECWM, RCM, profile tomography) conducted for solving of different tasks. Approximate borders of regions which velocity models were used for forming of generalized models are shown in Figure 11. The main features of the marked regions of the west Kazakhstan are the following.

Region V – territory of South Ural and Myugodzhar, in the north the region continues to Russian territory due to availability of decent data on crust velocities; in the west it borders with the Caspian depression, in the east – with Torgay trough. The crust thickness ranges from 42 km to 50 km, average value is 46 km.

Region VI – Karabogaz-Mangyshlak-Ustyurt part of Turan plate in the east Caspian region. Despite that the territory is mainly Kazakh, the region crust, the same as III, is not modeled due insufficient data on V_s.

Region VII – Caspian depression in the south-east of the Russian platform, in the east borders with Ural structures, in the south-east – with Ustyurt. The inner structure of the region crust is unique, and characterized by thick (up to 22 km) sedimentary cover, low velocity in the upper part and high velocity in the lower part of the crust. Average thickness is 39 km, but ranges from 36 to 43 km.

Shatsilov V.I. has constructed the travel-time curves for regions V and VII, for region VI there were insufficient data. Considering all mentioned above the construction of a regional travel-time curve for the west part of Kazakhstan is of high scientific and practical interest. The reference events were used as sources (Figure 11a):

1. Underground peaceful nuclear explosions (PNE) conducted in the Soviet times (1968-1984) on the territory of the West Kazakhstan and adjacent territory of Russia and which coordinates and origin time are known with high accuracy (Table 3, Figure 11b). The PNE coordinates were recently précised by K. Mackey during his field works [18, 19, 20]. The explosion yield was Y=2.6÷80 Kt, magnitudes range mb=4.7÷6.0.
2. Mining explosions at Myugolzhar and "50 let Oktyabrya" mines (2010) with known parameters [11] and recorded by permanent and field stations (Table 3, Figure 11c). Explosions yield was Y=10÷25 t, magnitudes range mb=2-2.3.
3. Earthquakes at Atyrau region recorded by local seismic network (Figure 11c) in 2014 – 12016, the accuracy of coordinates determination is 50 – 100 m, magnitudes range mb=2.7÷4.2. Shalkar earthquake of 26.04.2008 .

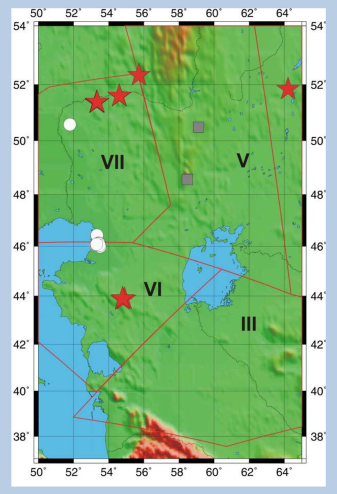

Figure 11a. The map of reference events location on the territory of Western Kazakhstan and adjacent territories. Star – UNE, square – mining explosions, circle – earthquakes, red]. lines – borders of the regions by Shatsilov [16].

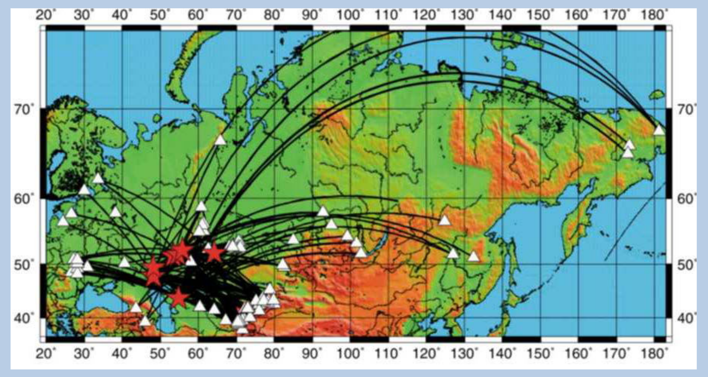

Figure 11b. The map of reference UNE location on the territory of the West Kazakhstan and adjacent territories, and monitoring system. Star – UNE, triangles – seismic stations participated in the processing.

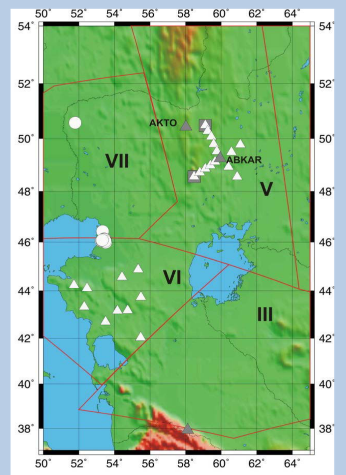

Figure 11c. The map of reference events location on the territory of Western Kazakhstan and adjacent territories. Square – mining explosions, circle – earthquakes, red lines – region borders by Shatsilov [16], grey triangles – permanent stations, white triangles – stations of temporary networks.

Travel-time curves by reference events for the west part of Kazakhstan.

Travel-time curve by UNE. Seismograms with industrial nuclear explosions records collected in the archives of Complex Seismological Expedition of the Institute of Physics of Earth of Russian Academy of Science (IPE AS USSR), and historical digital records of BRVK-Borovoye station of the IGR RK were used as source materials. To investigate kinematic parameters of different wave seismic groups at regional distances, industrial UNEs conducted in the west of Kazakhstan and adjacent Russia territory in 1968 – 1984 and which coordinates are well known were selected [5-7] (Figure 12). In total, 24 events with magnitudes 4.7 – 6.0 were selected. The events traces to the stations traversed the North Eurasia; epicentral distance for all events ranged Δ=350÷6810 (Figure 11b). In total, 494 seismograms were processed. For construction of regional travel-time curve, the stations at distances less than 2500 km were selected (Figure 12a, b).

By archived data we have collected information on the stations coordinates, period of its operation, instruments type and its parameters. The accuracy of coordinates determination for the stations was different as these were determined by GPS instruments, topographic maps of different scale, in some cases, by geographic maps.

Seismic instruments at the stations were of different type – RVZT and KSE instruments (seismic recorders SM-2), SKM, SKD [1]. The recording in RVZT and KSE channels was made on paper by ink, and in SKM and SKD – on photo paper. RVZT, SKM and SKD instruments recorded three components of seismic vibrations, and KSE recorded one vertical component. Borovoye station used digital instruments KOD, STsR-SS, STsR-TSG [21 – 23] with SKM-3 seismometers.

The records of analog stations show lower accuracy of arrival time determination in trains of longitudinal and shear waves than digital stations. The reason is that accuracy of arrival time determination for analog records depends significantly on seismogram sweeping, type of recording instrument, and station sensitivity. In addition, inability of frequency filtration also deteriorates the processing quality.

For correct interpretation of the wave pattern in analog seismograms, the epicentral distance was preliminary calculated basing on explosions coordinates and recording stations data. After that, to get oriented in seismic waves types at this epicentral distance KSE travel-time curve was used. This travel-time curve was created basing on materials received from a profile of seismic stations installed along Pamir – Lena river profile [24].

It should be noted that the narrow-band channels of KSE, RVZT and SKM type which records were used do not allow analyzing the wave pattern to its full extent. These filter arriving seismic signal according to its characteristics. In large distances the records are more deformed as oscillations spectrum shifts with distance to more long-period area outside the bandwidth of the instrument. S(Lg) waves are characterized by more long-period oscillations than P-waves, therefore these are hardly detected in large distances, and often it is almost impossible to make it correctly. That is why, the errors in arrival times for Sn and Lg waves are much higher than for P-waves, data scattering for shear waves is also larger than for longitudinal.

Determination of arrival times was conducted by definite arrivals marked in the records. The tables of arrival time were created for all marked phases for each type of instruments for a given station. Archive records of Borovoye seismic station stored in magnetic tapes were preliminary converted into contemporary format CSS3.0 [21]. Application of digital seismic records of Borovoye station for the travel-time curve construction allowed for more accurate determination of time during measurements. Figure 13 shows an example of nuclear explosion record from BRVK station – Borovoye of 8.20.1972 (Region-3). Figure 14a shows the results of measurements for all stations, 14и shows the measurement results for regional distances.

Basing on the measurement results, the travel times of main regional phases were calculated, and travel-time curves were constructed. The linear regression equations were calculated for each regional phase (Figure 14b):

$$t(Pn)= 10.83+0.12 * \Delta,\ R=0.999 \quad (1)$$
$$t(Pg)= -1.40+0.15 * \Delta,\ R=0.999 \quad (2)$$
$$t(Sn)= 10.94+0.22* \Delta,\ R=0.998 \quad (3)$$
$$t(Lg)= -1.86+0.29* \Delta,\ R=0.999, \quad (4)$$

where R - correlation coefficient.

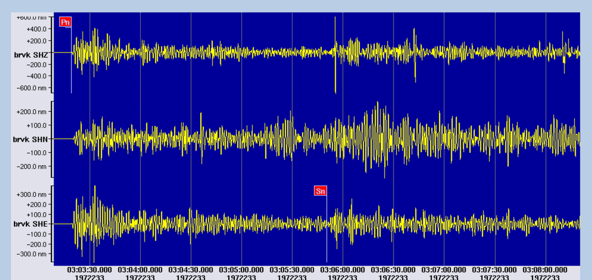

Figure - 13. Seismogram of underground nuclear explosion Region-3 of 8.20.1972, φ=49.4169°, λ=48.1616°. BRVK station – Borovoye.

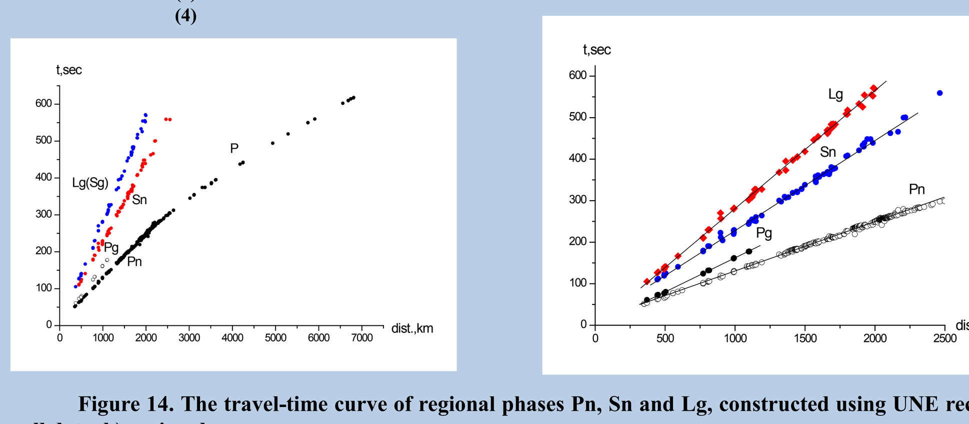

Figure 14. The travel-time curve of regional phases Pn, Sn and Lg, constructed using UNE records. a) all data, b) regional

The travel-time curve constructed using UNE records was compared with two travel-time curves of Shatsilov V.I. constructed by data of deep seismic sounding for two different regions of the West Kazakhstan. The travel-time curve "Shatsilov-1" was constructed for the territory of South Ural and Myugodzhar [16, 17]. In the north this region covers a part of Russia for better application of reliable data on crust velocities, in the west it borders with Pre-Caspian depression, in the east – with Torgay trough. Within the region the crust thickness ranges from 42 km to 50 km, average value is 46 km. Figure 15a compares "Shatsilov-1" travel-time curve and the new travel-time curve constructed using records of industrial UNE. The comparison shows that the values of velocities for Pn- and Sn-waves are almost similar, but velocity of Lg-wave of the travel-time curve constructed by records of industrial UNE is much lower than of the travel-time curve constructed by the data of DSS.

"Shatsilov-2" travel-time curve was obtained for the region of Pre-Caspian depression in the south-east of the Russian platform. In the east the region is constrained by Ural structures, in the south-east – by Ustyurt plateau. The earth crust thickness varies here from 36 km to 43 km, the average value is 39 km. The inner structure of the region crust is unique, and characterized by thick (up to 22 km) sedimentary cover with low velocity in the upper part and high velocity in the lower part. Figure 15b shows the comparison of "Shatsilov-2" travel-time curve with the one constructed by records of industrial UNE. The velocity values of Pn- Sn- and Lg-waves are almost similar.

The new travel-time curve was compared with IASPEI91 travel-time curve that is currently used for routine processing of seismic records in KNDC (Figure 15c). Figure 15c shows that for both travel-time curves the velocity of Lg-waves is almost the same, and velocity difference for Pn-wave is minor. Another pattern is for Sn-waves that shows large data scattering, the velocity values of Sn-wave by the new travel-time curve constructed using UNE records are higher than by IASPEI91 travel-time curve.

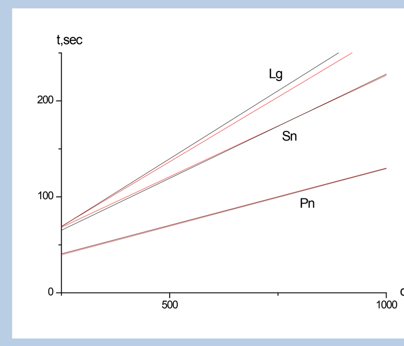

Figure 15a. Comparison of the travel-time curve constructed by UNE records and "Shatsilov-1" travel-time curve constructed for the territory of South Ural and Myugodzhar (for 0 km depth).

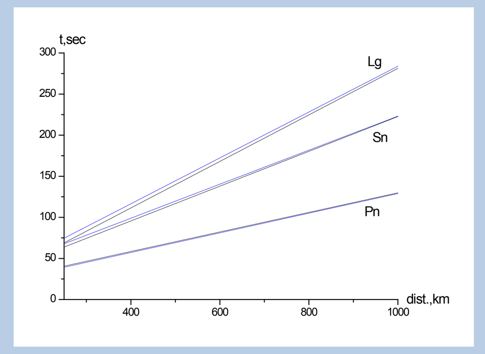

Figure 15b. Comparison of the travel-time curve constructed by UNE records and "Shatsilov-2" travel-time curve for the region of Pre-Caspian depression (for 0 km depth).

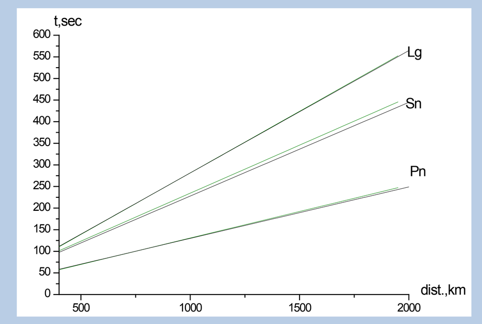

Figure 15c. Comparison of the travel-time curve constructed by records of peaceful nuclear explosions (black color) and IASPEI91 travel-time curve, the depth is 0 km (green color).

The travel-time curve constructed using records of mining explosions and earthquakes.

For the travel-time curve construction using records of mining explosions and reference earthquakes the records of the permanent seismic stations of the IGR RK and temporary field stations installed in the west of Kazakhstan in 2010 and 2016 were used [11, 12]. For the analysis the available data were divided into three groups differing by epicentral distance and wave pattern in seismograms, respectively. First group is the nearest zone, Δ = 0- 30 km. Second group is intermediate zone, Δ = 50- 300 km. Third group is remote zone, Δ up to 1000 km.

Figure 16a shows an example of calibration explosion record recorded by a station of the nearest zone. The arrival times of P(Pg), S(Sg) and Rg waves were determined by records of the nearest zone. Figure 16b shows the travel-time curves and average velocities for joint travel-time curves for the nearest zone stations. The intermediate zone shows another wave pattern (Figure 17a). The arrival times of Pn, Pg, Sn, Sg phases were determined by the records of the intermediate zone. Figure 17b,c shows the travel-time curves and average velocities for the travel-time curve in the intermediate zone of epicentral distances. Figure 18 shows an example of record, travel-time curves and average velocities for the travel-time curve in remote zone of the epicentral distances up to 1500 km.

Basing on the conducted measurements of arrival times and its analysis we managed to construct the travel-time curves of all regional phases. The joint travel-time curve WKTCC on all types of calibration sources (UNE, mining explosions and earthquakes) up to 1500 km is shown in Figure 19.

Travel times of the main regional seismic phases depending on epicentral distance can be represented by the equations shown in Table 3.

For the seismic stations of the IGR RK network the station azimuthal and time corrections of the observed and calculated azimuths and arrival times for the reference events at Tengiz field were calculated, Figure 20 shows the result of the earthquake epicenter relocation 2016-08-27, t0=06:25:10 with corrections, it is seen that the epicenter location headed towards to the true location of origin, the error ellipse scaled back.

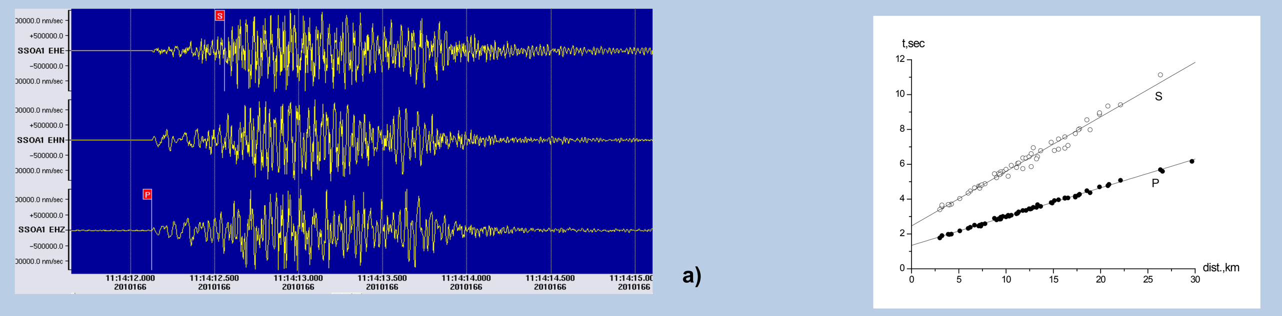

Figure 16. Examples of records (a) and travel-time curves (b) of seismic waves in the nearest zone (Pre-Caspian depression region).

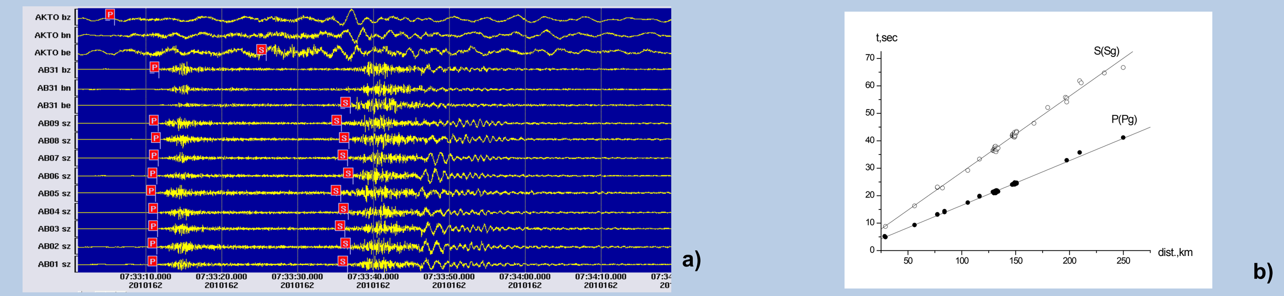

Figure 17. Examples of records (a) and travel-time curves (b) of seismic waves in the intermediate zone

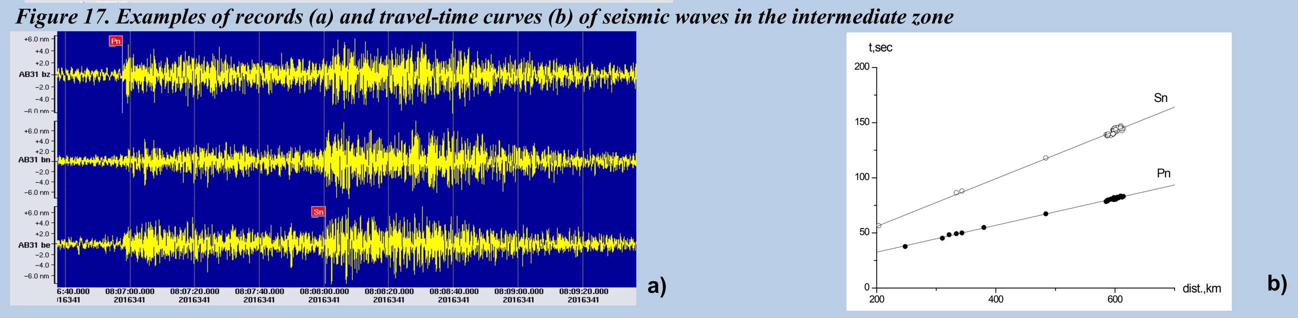

Figure 18. Examples of records (a) and travel-time curves (b) of seismic waves in the remote zone

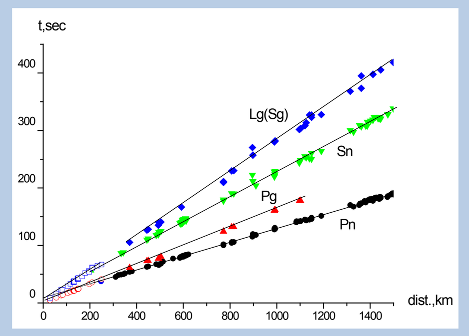

Figure 19. Joint travel-time curve by recording results of calibration sources in the west of Kazakhstan.

Table 3. Travel-time curves equations of the main types of seismic waves

Phase	Distance, km	Equation
P(Pg)	0-30 (Pre-Caspian depression)	1,34 + 0,17 · Δ
Pn	300 – 1500	9,23 + 0,12 · Δ
Pg	30-300 300-1100	0,20 + 0,16 · Δ -1,40 + 0,13 Δ
S(Sg)	0-30 (Pre-Caspian depression)	2,46 + 0,31 · Δ
Sn	300-1500	12,96 + 0,22 Δ
Lg(Sg)	30-300 300-1500	0,93 + 0,28·Δ 8,09 + 0,28 Δ

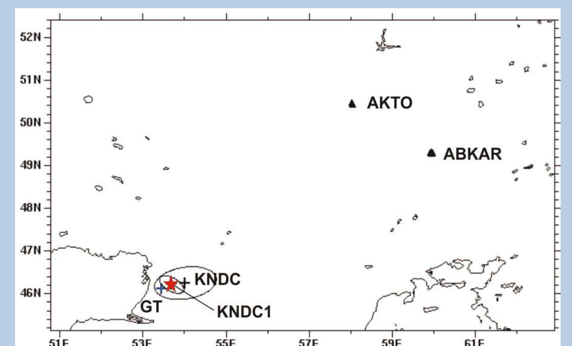

Figure 20. The map of earthquake epicenter location, 2016-08-27, t0=06:25:10, by data of the interactive seismic bulletin of KNDC, relocation result with azimuthal corrections and error ellipses.

CONCLUSION

Construction and investigation of a new WKTCC travel-time curve for regional distances by records of industrial nuclear explosions conducted in the Soviet time on the territory of the west Kazakhstan and Caspian depression, by calibration mining explosions, and by ground-truth earthquakes allow for some recommendations to improve the quality of seismic events hypocenters location occurred at the region:

- For the stations located in the west Kazakhstan (AS059-Aktyubinsk, Akbulak) it is reasonable to apply WKTCC travel-time curve, or "Shatsilov-2" travel-time curve (for Pre-Caspian depression region), or locate the events with azimuthal corrections.
- IASPEI91 travel-time curve should be applied for location of events occurring in the west of Kazakhstan, for Pn and Lg waves only, if those are surrounded well by the stations.
- To improve the location accuracy of events occurring in the west of Kazakhstan it is necessary to install additional three-component station at the Caspian region.

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