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AN OVERVIEW OF THE TECHNIQUE FOR SEISMICITY MICROZONATION MAPPING OF THE ULAN-UDE CITY TERRITORY

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Abstract: For purposes of seismicity microzonation of the Ulan-Ude city territory, engineering geophysical studies are conducted to reveal which types of rocks and soils are dominant in the study area and to classify them by site-specific velocities of P- and S-waves and amplitude-frequency characteristics. The article describes a technique for establishing the baseline seismic signal corresponding to parameters of relatively strong earthquakes in potential earthquake foci (PEF) zones. It is shown that the established baseline signal is applicable. Presented are results of theoretical calculations based on seismicity-soil models providing reference parameters of bedrock, medium and water-saturated soils (soil categories 1, 2 and 3, respectively).

Seismic impacts are assessed for the zone with the baseline seismic intensity of 8 points, as per MSK-64 seismic intensity scale. The reference model is used to identify zones with seismic intensity from 7 to 9 points in the city territory, and it is established that such zones differ in thickness of water-saturated and non-water-saturated soil layers. As a result, a schematic map showing the main parameters of seismic impacts is constructed in the first approximation. The obtained data are useful for the development of recommendations concerning further engineering seismological studies and activities for the appropriate revision and upgrading of the seismic microzonation technique in order to complete seismic microzonation of the Ulan-Ude city territory.

Key words: Ulan-Ude, seismicity, seismic microzonation map, engineering seismological surveys, seismic waves velocity, accelerogram, spectra, frequency characteristics, maximum acceleration.

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К ТЕХНОЛОГИИ ПОСТРОЕНИЯ КАРТЫ СЕЙСМИЧЕСКОГО МИКРОРАЙОНИРОВАНИЯ ТЕРРИТОРИИ Г. УЛАН-УДЭ

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Аннотация: Город Улан-Удэ расположен в сейсмически активном районе и характеризуется сейсмической интенсивностью 8, 8 и 9 баллов для средних грунтовых условий [*The Map..., 1999*] и трех уровней сейсмической опасности – 10 % (A), 5 % (B) и 1 % (C). По результатам анализа макросейсмических данных отмечается, что максимальный сейсмический эффект от сильных землетрясений за исторический период для г. Улан-Удэ не превышает 7 баллов. Он вызван двумя событиями, произошедшими в Южном и Центральном Байкале: Цаганским (12.01.1862 г; M=7.5) и Среднебайкальским (29.08.1959 г; M=6.8) землетрясениями.

Для уточнения исходной сейсмичности территории г. Улан-Удэ за счет грунтовых условий проведены инженерно-геофизические работы, необходимые для характеристики преобладающих типов грунтов по скоростям распространения в них продольных и поперечных волн и по амплитудно-частотным характеристикам. При расчетах за эталон выбран скальный грунт с Vp=2200 м/с, Vs=1200 м/с и ρ=2.5 г/см^3 (средние значения скоростей в 10-метровом слое на участках выхода коренных пород на поверхность). Сейсмическая опасность участков с такими значениями скоростей оценивается на один балл меньше исходной. В этом случае средние грунты (неводонасыщенная толща песчаных и гравийно-галечных грунтов) будут иметь значения Vp=600 м/с, Vs=300 м/с и ρ=1.8 г/см^3. Сейсмическая опасность участков с такими значениями соответствует исходной сейсмичности.

Таким образом, проведенные измерения скоростей сейсмических волн на территории города и расчет приращений балльности (табл. 2) показывают, что относительно выбранного эталона (скальный грунт – 7 баллов) грунты, служащие основаниями сооружений города Улан-Удэ, будут иметь приращение балльности от +0.17 до +2.3 балла, а их сейсмическая опасность изменится от 7.17 до 9.3 балла.

Представлена методика формирования исходного сейсмического сигнала, отвечающего параметрам относительно сильных землетрясений из зон ВОЗ (вероятных очагов землетрясений). Отмечается, что выбранные акселерограммы относились к землетрясениям с различными магнитудами, поэтому была использована зависимость $\beta_M(f)$. Она показывает изменения уровня спектра ускорения с изменением магнитуды и зависит от частоты.

Используя эту зависимость, мы приводили амплитудные спектры к магнитуде рассматриваемой зоны ВОЗ. Завершающим шагом стало получение записей акселерограмм землетрясений из конкретных зон ВОЗ заданных магнитуд, являющихся характерными для каждой конкретной зоны (рис. 5). Это реализовано путем обратного преобразования Фурье среднего спектра ускорения данной зоны и фазового спектра наиболее сильного землетрясения, зарегистрированного из данной зоны ВОЗ.

В результате показана возможность использования полученного сигнала и проведены теоретические расчеты для сейсмогрунтовых моделей, характеризующих вероятностные параметры эталона для коренных пород (грунтов 1-й категории), средних грунтов (2-й категории) и водонасыщенных грунтов (3-й категории).

По результатам теоретических расчетов (раздел 2), данным экспериментальных измерений (раздел 1), имеющимся инженерно-геологическим и гидрогеологическим сведениям составлена в первом приближении схематическая карта (рис. 10) основных параметров сейсмических воздействий. На территории города выделены 7–9-балльные участки, характеризующиеся различной по мощности грунтовой толщей водонасыщенных и неводонасыщенных отложений. В каждой из зон по сейсмической опасности (рис. 10) при СМР могут быть выделены участки от 7 до 9 баллов. В этом случае они будут отвечать той или иной грунтовой модели (табл. 5) и требуют дальнейшего уточнения в соответствии с масштабом СМР территории города путем детализации расчетных моделей по предлагаемой нами методике.

Результаты исследований предполагается использовать для разработки рекомендаций по направлению, видам и очередности проведения дальнейших инженерно-сейсмологических исследований и для обновления технологии построения карты сейсмического микрорайонирования территории г. Улан-Удэ.

Таким образом, показано, что для конечного варианта карты СМР следует выявить и охарактеризовать на новом вероятностном уровне потенциальные сейсмические источники (локализацию деформаций и активных разломов, период повторяемости землетрясений, уровень сейсмичности, а также вероятность возникновения землетрясений), которые связаны с прогнозированием сильных сейсмических воздействий для г. Улан-Удэ. Необходимо определить параметры распространения сейсмических волн и их эффекты, обусловленные проявлением сейсмичности, на конкретных строительных площадках города. Затем необходим расчет спектров реакции и связанной с ними вероятности возникновения сильных землетрясений для составления карты сейсмического риска с указанием параметров, которые могут оказаться полезными в строительной политике региона.

Ключевые слова: Улан-Удэ, сейсмичность, карта сейсмического микрорайонирования, инженерно-сейсмологические исследования, скорости сейсмических волн, акселерограммы, спектры, частотные характеристики, максимальные ускорения.

1. Introduction

The city of Ulan-Ude is located in the seismically active region of Russia. According to [*The Map*..., *1999*], the city's territory with medium soil conditions is characterized by seismic intensity of 8, 8 and 9 points (as per MSK-64 seismic intensity scale) and three levels of seismic hazard with 10 % (A), 5 % (B), and 1 % (C) probabilities of exceedance in 50 years. Analyses of historical macroseismic data [*Solonenko, Treskov*, *1960*] show that the maximum seismic impact of the strongest earthquakes in Ulan-Ude did not exceed 7 points even with account of two major events which took place in the Southern and Central Baikal regions – the Tsagan (12 January 1862; M=7.5) and Middle Baikal earthquakes (29 August 1959; M=6.8).

Under the code of practice in the construction industry in the Russian Federation, the baseline seismic intensity was assessed according to the RF construction standards and rules specified in SNiP II-A.12-69* dated 01 July 1970, and for the Ulan-Ude territory with medium geological conditions, it was estimated at 7 points. Later on, SNiP II-A.12-69* was replaced by SNiP II-7-81 (in force since 01 January 1982), and the baseline seismic intensity for Ulan-Ude is now estimated at 8 points [*The USSR Seismic Zonation Map*, *1984*] which assumes the recurrence of a major seismic event every 1000 years, according to Map (B) under SNiP II-7-81* (updated revision) [*SNiP..., 2011*].

It is envisaged by the current construction regulations and standards that optimal locations must be selected for construction projects with account of seismic resistance calculations, which necessitates quantification of the main parameters of seismic impacts that may be imposed to foundations of building and facilities. In this regard, a seismicity microzonation (SMZ) map needs to be constructed for the Ulan-Ude city territory in scales 1:25000 and 1:5000 with account of new assumptions. The required mapping should be preceded by stages when a general seismic zonation map and a detailed seismic zonation map of the territory are constructed in larger scales.

Therefore, to achieve the objective of seismic microzonation mapping of the Ulan-Ude city, it is required to update the general seismicity zonation data and assess levels of seismic hazard for new construction project areas in the city. These tasks can be fulfilled by combining geotechnical, instrumentation and computational methods. For the purpose of seismicity microzonation, seismic intensity is estimated in points as per SNIP II-7-81* or determined as seismic loads shown by estimated or real accelerograms, i.e. curves showing how vibrations of soil layers are accelerated during strong earthquakes. To assess potential seismic hazard, it is needed to take into account the intensity and other parameters of elastic vibrations under the base structures of buildings and facilities and consider the manifestations of inelastic strain and residual deformation of soil layers. Ranges of elastic vibrations of the soil layers are recordable by direct instrumental observations conducted in the study area.

Comprehensive studies can provide source data for dividing the study area into zones which seismic intensity may differ by ±1–2 points, and forecasts for each zone can be adjusted with regard to site-specific tectonic, geological and geomorphological conditions. Calculations of incremental points against the baseline seismic intensity are significantly influenced by data on groundwater levels and lithological compositions of rocks and soils. Such calculations are also impacted by significant variations in the intensity of the seismic field due to heterogeneities in the bedrock to a depth comparable to the wavelength (up to 1 km). Should any sudden change take place in geological conditions while new construction activities are performed, the relevant seismic microzonation data should be revised and updated accordingly.

In this article, we present results of the initial stage of engineering seismological studies in the Ulan-Ude city territory and consider possibilities of zonation by the main parameters of seismic impacts of potential strong earthquakes in order to identify potential seismic hazard areas in compliance with the current regulatory requirements concerning urban construction. A technique for construction of a new seismicity microzonation map of the Ulan-Ude city territory is justified.

2. Results of engineering seismological studies with application of indirect seismicity microzonation methods

Generally, seismic hazard assessment is based on results of the acoustic (seismic) impedance method, data from catalogues of recorded earthquakes and microseisms, and data obtained by computational methods. Herein we briefly describe our technique of measurements, present estimations of seismic parameters and describe the rocks and soils that dominate in the study area.

The seismic impedance method [*Guidelines..., 1985, 1986; Medvedev, 1962; RSN 60-86, 1986; Pavlov, 1984*]. Incremental points are calculated from the equation published in [*Medvedev, 1962*]:

$$\Delta I=1.67\mathrm{Lg}(\rho_э V_э/\rho_i V_i)+Re^{-0.04h*h}, \quad (1)$$

where ΔI is estimated value of incremental points; $\rho_э V_э$ and $\rho_i V_i$ is seismic impedance of the reference soil and the studied soil for P-/S-waves, Vp/Vs; h is groundwater level; coefficient R=1 is accepted for areas with dominant sandy and clayey soils, and R=0.5 for areas with dominant gravel-pebble and coarsely clastic rocks. If the groundwater level is at a depth below 10m from the ground surface, the correction coefficient is close to zero.

In order to calculate the seismic hazard in points and then to estimate it in terms of maximum acceleration, the following data are needed: rock and soil composition, velocity of seismic wave propagation in rocks and soils, thickness and composition of unconsolidated soil layers, and bulk weight of the reference rocks and soils and the studied rocks and soils [*Guidelines..., 2004; Pavlov..., 1988*].

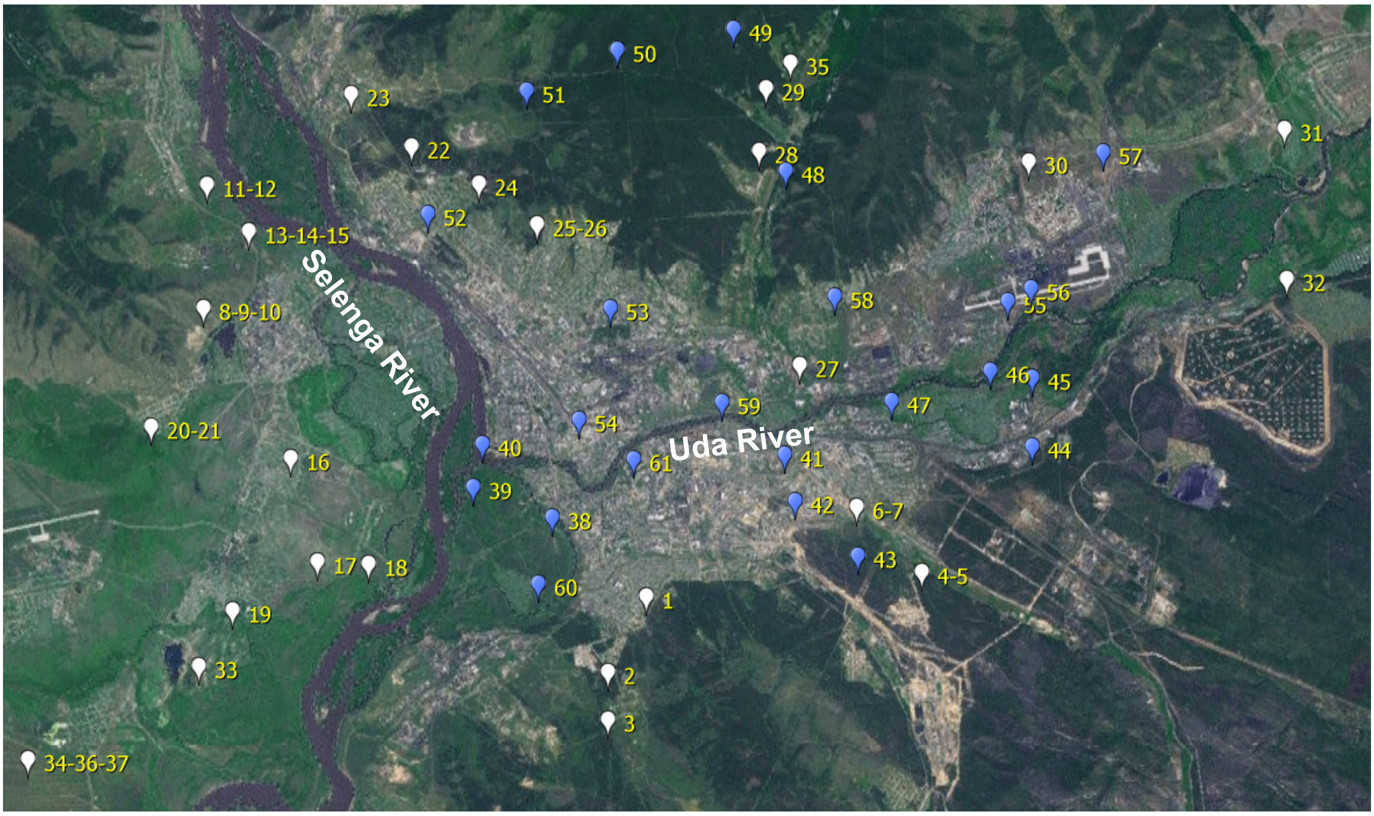

Fig. 1. The schematic map showing areas covered by seismic sounding studies in the Ulan-Ude city territory. 1–37 – locations where observations are conducted for seismic hazard assessment (UoM – point); 38–60 – locations where seismic wave velocities are measured for construction of seismicity-soil models.

Рис. 1. Схема сейсморазведочных зондирований на территории г. Улан-Удэ. 1–37 – пункты наблюдений для оценки сейсмической опасности в баллах; 38–60 – пункты измерения скоростей сейсмических волн для построения сейсмо-грунтовых моделей.

Therefore, the top section of the profile of rocks and soils to the bedrock needs to be characterised to correctly select locations of measurements and then to properly analyse the measurement results. A general description of the top section is presented herein at a level sufficient to support the first stage of our studies aimed at seismic microzonation mapping of the Ulan-Ude city territory.

In the regional Quaternary deposits, facies are diverse, and compositions of rocks and soils are variable. On the left-bank floodplain terrace of the Selenga River (Fig. 1), powdery fine-grained alluvial sands are alternating with small lenses of sandy loam and clay. The sand beds are 1.0 to 5.0 m thick and underlain by gravel. Groundwater occurs at depths ranging from 1 to 3 m. The left bank of the Uda River is composed of eolian fine-grained sand, and the sand beds vary in thickness from 10 to 15 m along the river and 50 to 80 m closer to the slope. Groundwater occurs at depths of 5–10 m and 50–60 m. Bedrocks are represented by the Jurassic-Cretaceous sandstone, argillite and granitic rocks.

The right bank of the Selenga River comprises a thick bed of conglomerates with sandstone interlayers that are overlain by either gravelly soil or fine-grained sands (1.5–3.0 m and 10–15 m thick beds, respectively). The groundwater table is deep-seated.

In terms of geomorphology, the terrain of the Ulan-Ude area is significantly rough. In the north, spurs of the Ulan Burgasy ridge are low, and hills are cut by ravines and gullies and located almost perpendicular to the valleys of the Uda and Selenga Rivers. In the south, spurs of the Tsagan-Daban ridge come to the Uda River valley.

Several terraces are recognized in the valleys of the Uda and Selenga Rivers: Terrace 1 is 2 to 4 m high (Ulan-Ude downtown), Terrace 2 is 10 to 20 m high (the Soviet and Oktyabrsky districts of the city), and Terrace 3 is 40 to 50 m high (the Zheleznodorozhny district and a part of the Oktyabrsky district).

Therefore, seismic sounding locations (Fig. 1) were selected with regard to data on the geological structure of the territory, composition of the unconsolidated Quaternary sediments, physical properties of rocks and

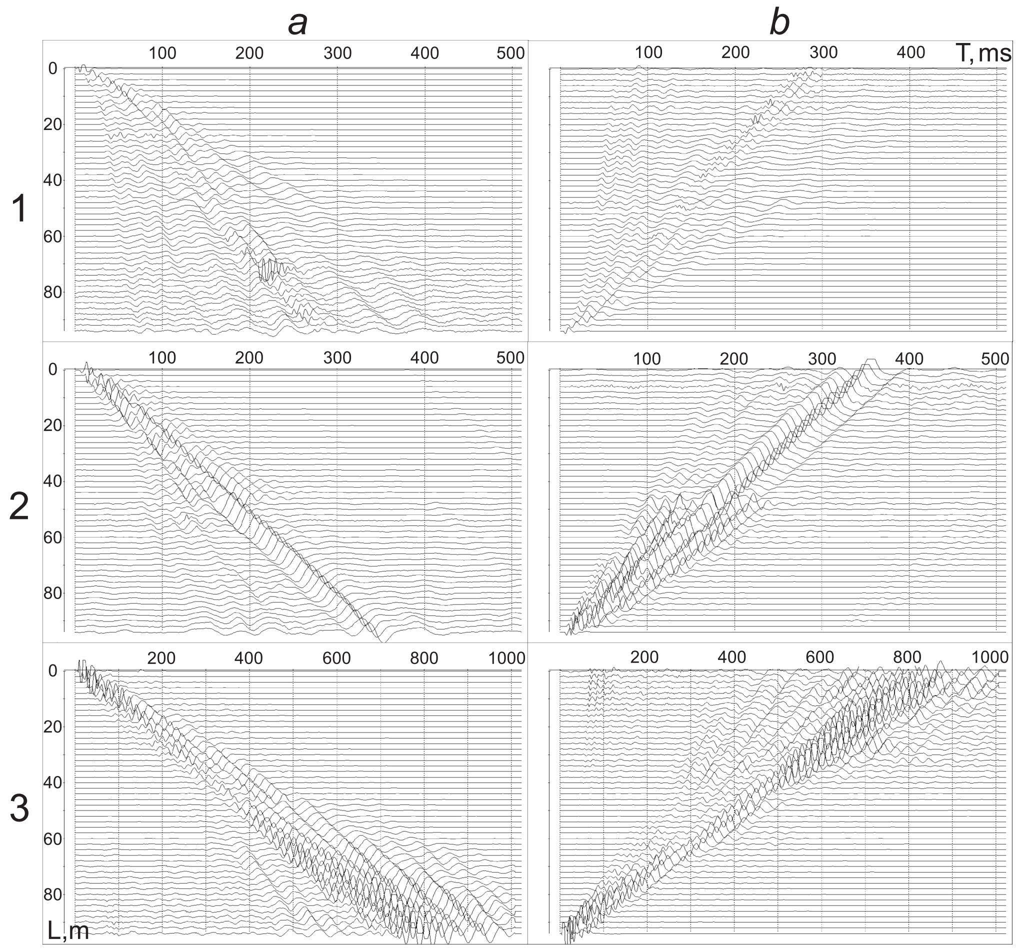

Fig. 2. An example of the direct (*a*) and impact (*b*) seismograms for rocky (1), medium (2) and water-saturated (3) soils, according to records in observation scheme YY.

Рис. 2. Пример прямой (*a*) и встречной (*b*) сейсмограмм для скальных (1), средних (2) и водонасыщенных (3) грунтов, зарегистрированных по системе наблюдений YY.

soils and dominating types of rocks and soils that are present on new construction sites. The GPS survey data were used to snap the locations to the grid.

Seismic wave velocities were measured by a LAKKOLIT digital 24-channel engineering seismic station made in Russia. The refraction method was applied as described in [*Seismic Surveying*, *1981*]. Measurements were carried out in separate sounding sessions, and reverse and catch-up time-distance plots (46, 92 and 150 m) were provided. Geophones were spaced by 2, 4 and 6 m (in the downtown, the distance was 12 m). Seismic waves were generated by shocks. Recording was done under observation schemes ZZ and YY corresponding to vertically oriented geophones and horizontal shocks perpendicular to the profile, with receivers oriented in the same direction. The selected measurement technique made it possible to obtain average values of seismic wave velocities for the top zone of the profile to depths from 10 to 30 m. It should be noted that the detection of 'useful' waves was challenging due to considerable background noise, and notwithstanding the accumulation of shocks, the detection of transverse waves was supported by data on surface waves.

In the city territory, velocities of P- and S-waves were measured at 37 locations assumed to cover all of the areas distinguished by the available geotechnical data. In the 'reference' bedrocks, Vp and Vs were measured in the city territory and in the vicinity of the city (measurements were taken in quarries and on sites where the bedrocks occur at shallow depths). At 23 locations (Nos. 38 to 60), special measurements were taken in order to design seismicity-soil models corresponding to zones in the city which may be subject to the highest and lowest seismic hazard. Such models also provided information complementing to the measurement statistics. Reflection seismic data processing was performed by the RadExPro software.

Examples of the recorded seismograms are given in Fig. 2. Time-distance plots of P- and S-waves and

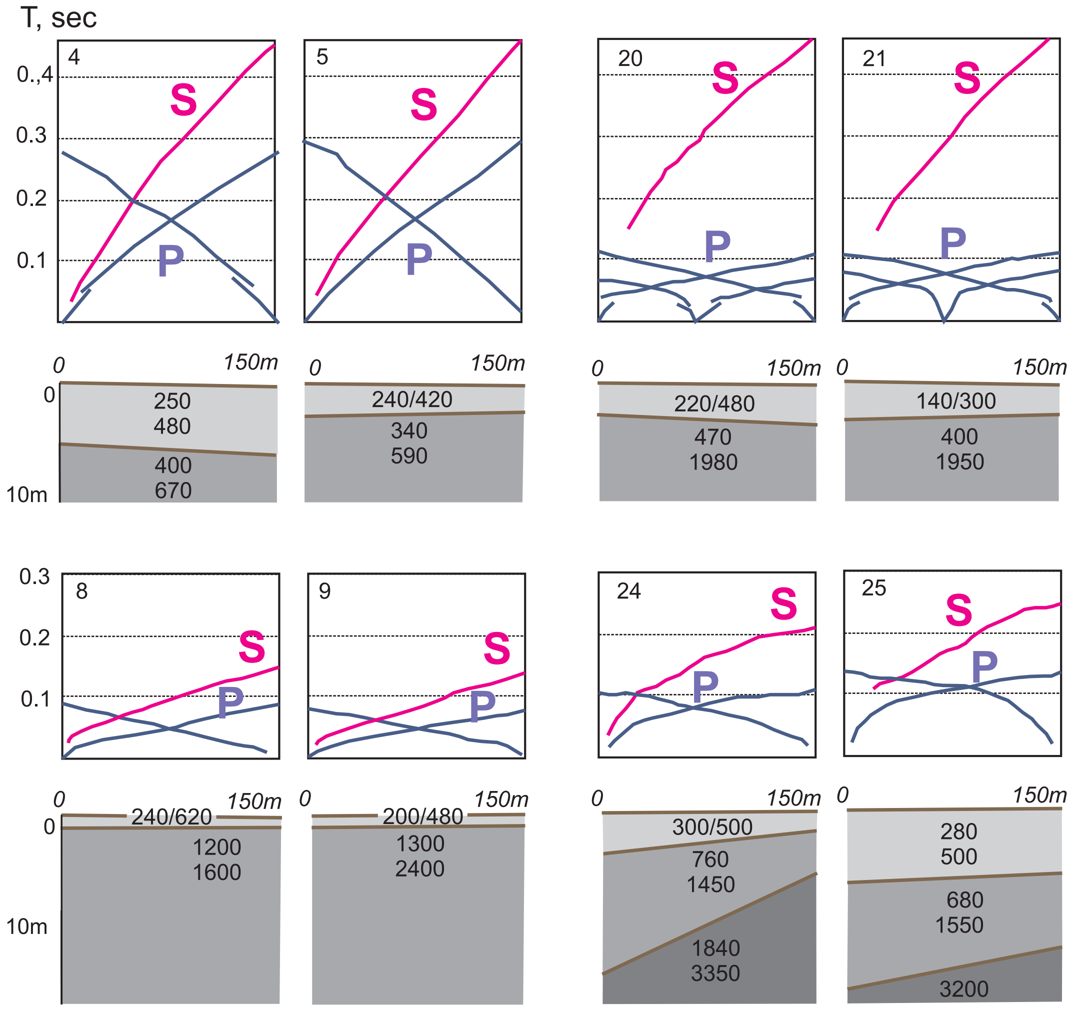

Fig. 3. Examples of travel-distance plots of P- and S-waves, and velocity profiles.

4–5 – unconsolidated none-water-saturated soil; 20–21 – water-saturated gravel-pebble sediments; 8–9 – strongly and weakly fractured rocky soils; 24–25 – unconsolidated, broken rocks and relatively intact bedrocks. Top and bottom numbers show velocities of P- and S-waves, respectively.

Рис. 3. Примеры годографов продольных и поперечных волн и скоростные разрезы.

4–5 – рыхлые неводонасыщенные грунты; 20–21 – водонасыщенные гравийно-галечные отложения; 8–9 – сильно- и слаботрещиноватые скальные грунты; 24–25 – рыхлые, разрушенные скальные и относительно сохранные коренные породы. Цифры сверху – скорости P-волн, снизу – скорости S-волн.

seismic wave velocity profiles for sites that meet the specified seismicity-soil conditions are given in Fig. 3. The seismograms, plots and profiles give evidence that it is challenging to select 'useful' waves when seismic measurements are taken in urban areas, even if special attention is given to registration timelines, the amount of accumulated excitations and their intensity. Data from all the seismic measurement locations (see Fig. 1) were consolidated, and histograms were constructed to show the distribution of wave velocities and reveal most probable values (Fig. 4). However, the available histograms are limited in number, and additional measurements are required for each type of soil.

In general, it is evidenced by the seismic velocities recorded in the top zone of the profile near the city of Ulan-Ude that the seismic velocity values differ dramatically in ground conditions of three types – rocky, water-saturated soil and unconsolidated non-water-saturated soil.

The bedrocks are represented mainly by conglomerate, sandstone, argillite and granitic rocks. Velocities of P- and S-waves in these rocks are low in the top zone of the profile (to depth from 3 to 5m). In the uppermost zone, the P-wave velocity range from 1400 to 2000 m/sec. In less fractured rocks, Vp values range from 1500 to 3500 m/sec (Fig. 4, *a*) and Vs values range from 1000 to 2100 m/sec with increasing depth (Table 1). According to measurement in 50 bedrock samples

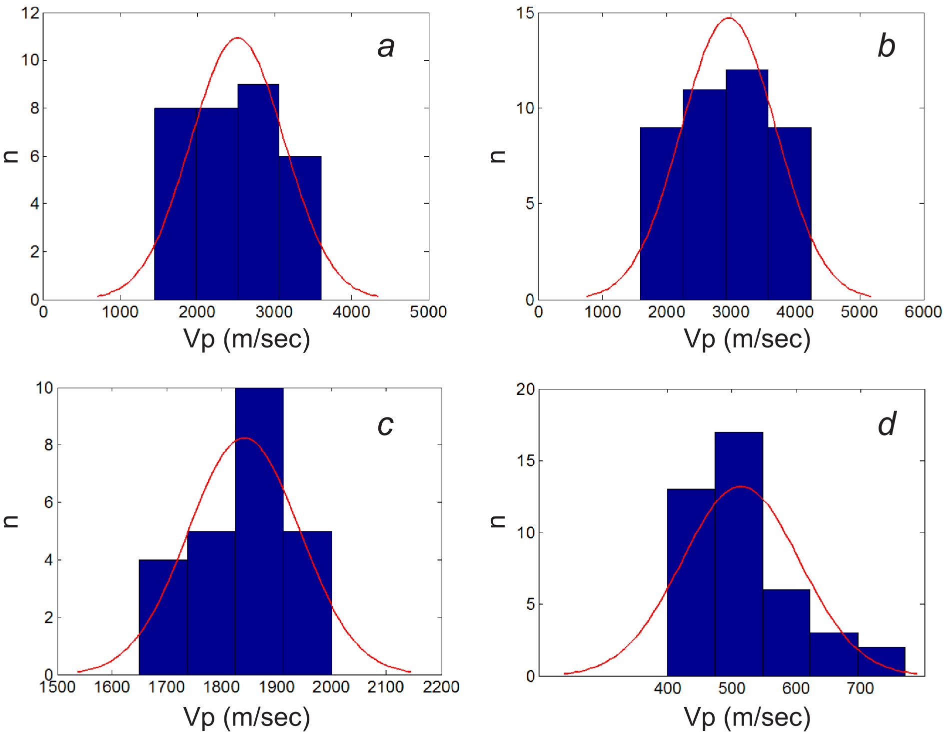

Fig. 4. Histograms of the distribution of P-wave velocities in the rocks and soils typical of the Ulan-Ude city territory: *a* – rocky soil; *b* –in the rock samples; *c* – flooded soil; *d* – air-dry soil.

Рис. 4. Гистограммы распределения скоростей продольных волн в грунтах района г. Улан-Удэ: *a* – для скальных грунтов; *b* –в образцах скальных пород; *c* – для обводненных грунтов; *d* – для воздушно-сухих грунтов.

taken from the outcrops, the range of ultrasound velocities shows an increase towards higher values of Vp (Fig. 4, *b*). The most probable P-wave velocities amount to almost 3000 m/sec, and the maximum velocity exceeds 4000 m/sec.

For water-saturated gravel-pebble and sandy soils, the typical velocities of P-waves range from 1650 to 2000 m/sec (Fig. 4, *c*), and the P/S-wave velocity ratio varies from 3.0 to 4.5 (Table 1). Measurements in soils of the same type but not water-saturated show P-wave velocities from 400–500 to 800 m/sec and S-wave velocities from 180 to 420 m/sec (note: the layer of seasonal freezing was excluded from the calculations) (Fig. 4, *d*). The available data on physical properties of soils which are required for further calculations are summarized in Table 1.

Data on soil composition, velocities of seismic wave propagation in soils of the specified types, thickness of unconsolidated sediments in the upper segment of the profile, and bulk weight of the reference and studied soils were collected as required for seismic hazard assessment, construction of the set of seismic models and application of the selected computational methods (see Section 2). Equation (1) was used to estimate values of incremental seismic intensity for each observation location. The average velocity value estimated for the top 10-meter thick zone was taken into account. Calculation results are given in Table 2.

T a b l e 1. **Physical properties of rocks and soils**

Т а б л и ц а 1. **Физические свойства грунтов**

Rocks and soils	Specific gravity, g/cm³	Bulk weight, g/cm³	Porosity, %	Water absorption, %
Granitic rock	2.73–2.86	2.53–2.57	2.1–3.3	0.10–0.79
Medium- and coarse-grained sandstone	2.62–2.81	2.15–2.74	2.8–9.1	0.09–7.30
Argillite	2.64	2.21	19.5	2.8
Conglomerate	2.71	2.40	12.0	0.6–3.4
Gravel	2.70–2.79	1.60–1.90	38–40	–
Sand	2.63–2.77	1.68–1.90	38–40	–

T a b l e 2. **Seismic properties of rocks and soils in the Ulan-Ude city territory**

Т а б л и ц а 2. **Результаты исследования сейсмических свойств грунтов на территории г. Улан-Удэ**

Item #	Rock and soil conditions	h, m	Vp, m/sec	Vs, m/sec	ρ, g/cm³	Vp/Vs	Average Vp, m/sec	Average Vs, m/sec	ΔIp, point	ΔIs, point
1	Powdery fine-grained sand	6	400 690	210 420	1.8 1.8	1.9 1.65	480	262	+1.34	+1.37
2	Powdery fine-grained sand Sandstone	20	440 2900	230 –	1.8 2.6	1.9 –	440	230	+1.40	+1.44
3	Powdery fine-grained sand Granitic rock	6	450 3000	210 1800	1.8 2.6	2.15 1.67	685	326	+0.93	+1.1
4	Powdery fine-grained sand Fine-grained sand	11	480 670	250 400	1.8 1.9	1.93 1.67	480	250	+1.40	+1.39
5	Powdery fine-grained sand Fine-grained sand	5	480 580	240 340	1.8 1.9	2.0 1.7	530	290	+1.29	+1.30
6	Fine-grained sand Water-saturated sand	10	350 1650	180 400	1.9 2.0	1.94 4.2	350	180	+1.50	+1.59
7	Sand, gravel Water-saturated sand	11	510 1890	210 520	1.9 2.0	2.4 3.6	510	510	+1.26	+1.45
8	Coarse-grained rocks Conglomerate	2	620 1900	240 1200	2.0 2.6	2.5 1.58	1350	670	+0.36	+0.46
9	Coarse-grained rocks Conglomerate	2.5	480 2400	200 1300	2.0 2.6	2.4 1.84	1200	550	+0.39	+0.42
10	Coarse-grained rocks Conglomerate	2.5	380 2400	160 1400	2.0 2.6	2.4 1.7	1030	480	+0.46	+0.69
11	Sand, gravel Water-saturated gravel	3	350 1900	170 420	1.8 2.0	2.1 4.5	350	170	+1.64	+1.83
12	Sand, gravel Water-saturated gravel	6	430 1880	140 430	2.0 2.0	3.0 4.4	430	140	+1.74	+2.14
13	Gruss, debris, sand Conglomerate	6	520 2400	280 1400	2.0 2.6	1.85 1.7	765	413	+0.86	+0.88
14	Debris, sand Conglomerate	2	440 2800	– 1680	2.0 2.6	– 1.68	1345	–	+0.36	–
15	Coarse-grained rocks Conglomerate	2	600 2700	320 1650	2.0 2.6	1.88 1.64	1590	900	+0.23	+0.23
16	Sand, gravel Water-saturated gravel	2	330 1800	160 500	2.0 2.6	2.05 3.6	330	160	+1.62	+1.65
17	Sand, gravel Water-saturated gravel	2,5	450 1960	180 480	2.0 2.0	2.6 4.1	450	180	+1.52	+1.67
18	Sand, gravel Water-saturated gravel	6	390 1840	180 460	2.0 2.0	2.2 4.0	390	180	+1.81	+1.95
19	Sand, gravel Water-saturated gravel	5	340 2000	150 400	2.0 2.0	2.26 5.0	480	220	+1.60	+1.79
20	Sand, gravel Water-saturated gravel	5	480 1980	220 470	2.0 2.0	2.18 4.2	480	220	+1.60	+1.79
21	Sand, gravel Conglomerate	5	300 1950	140 400	2.0 2.0	2.1 4.9	1125	270	+0.65	+1.28
22	Sand, coarse detrital rocks Conglomerate	4	550 2250	230 1300	2.0 2.6	2.4 1.74	1000	455	+0.60	+0.76
23	Debris, sand Conglomerate	6	500 2200	220 1300	2.6 2.6	2.25 1.68	725	330	+0.79	+0.94
24	Sand Coarse-grained rocks Conglomerate	5 12	500 1450 3350	300 760 1840	2.0 2.0 2.6	1.67 1.90 1.83	975	580	+0.75	+0.78
25	Sand Fractured rocks Conglomerate	12 15	500 1550 3200	280 680 –	2.0 2.6 2.0	1.80 2.30 –	500	280	+1.26	+1.23
26	Coarse-grained rocks Conglomerate	6	400 2050	180 1100	2.0 2.6	2.2 1.85	590	270	+1.06	+1.27
27	Sand, gravel Water-saturated gravel	2	400 1670	– –	2.0 2.0	– –	400	-	+1.7	1.8

E n d o f T a b l e 2

О к о н ч а н и е т а б л и ц ы 2

Item #	Rock and soil conditions	h, m	Vp, m/sec	Vs, m/sec	ρ, g/cm3	Vp/Vs	Average Vp, m/sec	Average Vs, m/sec	ΔIp, point	ΔIs, point
28	Sand, gravel	13	500	260	2.0	1.94	500	260	+1.26	+1.37
	Conglomerate		2400	1650	2.6	1.45				
29	Coarse-grained rocks	2	520	280	1.8	1.85				
	Fractured rocks	14	1450	800	2.0	1.82	1070	574	+0.72	+0.74
	Conglomerate	–	3000	1600	2.6	1.88				
30	Fractured rocks	8	1560	920	2.2	1.70	1720	1000	+0.24	+0.24
	Conglomerate		2800	1500	2.6	1.87				
31	Sand, gravel	5	500	220	1.8	2.28	500	220	+1.79	+1.86
	Water-saturated gravel		1760	470	2.0	3.70				
32	Sand, gravel	7	310	180	1.8	1.74	310	180	+2.30	+2.34
	Water-saturated gravel		1700	550	2.0	3.10				
33	Fine-grained sand	25	420	200	2.0	2.10	420	200	+1.48	+1.47
	Granitic rock		3600	2100	2.6	1.70				
34	Fine-grained sand	17	510	220	1.8	2.30	510	220	+1.26	+1.45
	Water-saturated gravel	40	1900	480	2.0	3.90				
	Conglomerate		3400	–	2.6	–				
35	Fractured rocks	5	570	300	1.8	2.6	1975	1090	+0.17	+0.19
	Conglomerate		3380	1880	2.6	1.8				
36	Fine-grained sand	11	460	220	1.8	2.10	460	220	+1.40	+1.45
	Conglomerate		3200	1900	2.6	1.68				
37	Fractured rocks	3.0	480	–	1.8	–				
	Conglomerate		3050	–	2.6	–	1800	–	+0.2	–

In our calculations, the reference is the rocky soil with Vp=2200 m/sec, Vs=1200 m/sec and ρ=2.5 g/cm^3 (average velocities in the 10-metre thick layer on sites with bedrock outcrops). For sites with the above-mentioned values, the seismic hazard is assumed one point lower than the baseline level. In this case, the average soil type (i.e. non-water-saturated sand and gravel-pebble) is characterised by Vp=600 m/sec, Vs=300 m/sec and ρ=1.8 g/cm^3. In zones with the above-described soil, the seismic hazard corresponds to the baseline seismic intensity.

Our measurements of seismic wave velocities in the city of Ulan-Ude and calculations of incremental seismic intensity (Table 2) show that relative to the selected reference soil (rocky soil – 7 points), the rocky/soil foundations of buildings and facilities may be subject to an incremental seismic impact (+0.17 to +2.3 points), and the seismic hazard for the rocks and soils ranges from 7.17 to 9.3 points.

3. Results of the initial study stage to forecast how strong earthquakes may impact the rocky/soil foundations in the Ulan-Ude city territory

To solve the problem related to seismicity microzonation mapping in compliance with the current regulations concerning urban construction, the seismic hazard of rocky/soil foundations should be mapped with account of the maximum seismic wave acceleration, dominant periods of strong earthquakes, resonance frequencies of unconsolidated beds and other characteristics of the seismic impacts.

To provide a basis for seismicity microzonation mapping of the Ulan-Ude city territory, quantitative data on soil movements of ground are needed. In the current stage of our studies, we analyze dynamic characteristics of perceptible earthquakes that occurred in the study region, establish seismic signals corresponding to the baseline seismic intensity, develop the seismicity-soil models, try to forecast seismic impacts with regard to different construction conditions and classify zones in the Ulan-Ude city territory by the seismic impact parameters. To achieve the objectives, modeling and computer simulation methods are applied.

The priority task is to establish the baseline seismic signal for the Ulan-Ude city territory [*Dzhurik, 2014*]. Determining a ‘baseline’ seismic impact is challenging as a reference accelerogram cannot be unambiguously selected. The unambiguity is due to the fact that an earthquake can be manifested in different ways in particular local zones, depending on characteristics of the earthquake source, seismic signal propagation track, structures and compositions of rocky/soil foundations of buildings and facilities. Besides, it is needed to take into account a number of complicating factors, such as

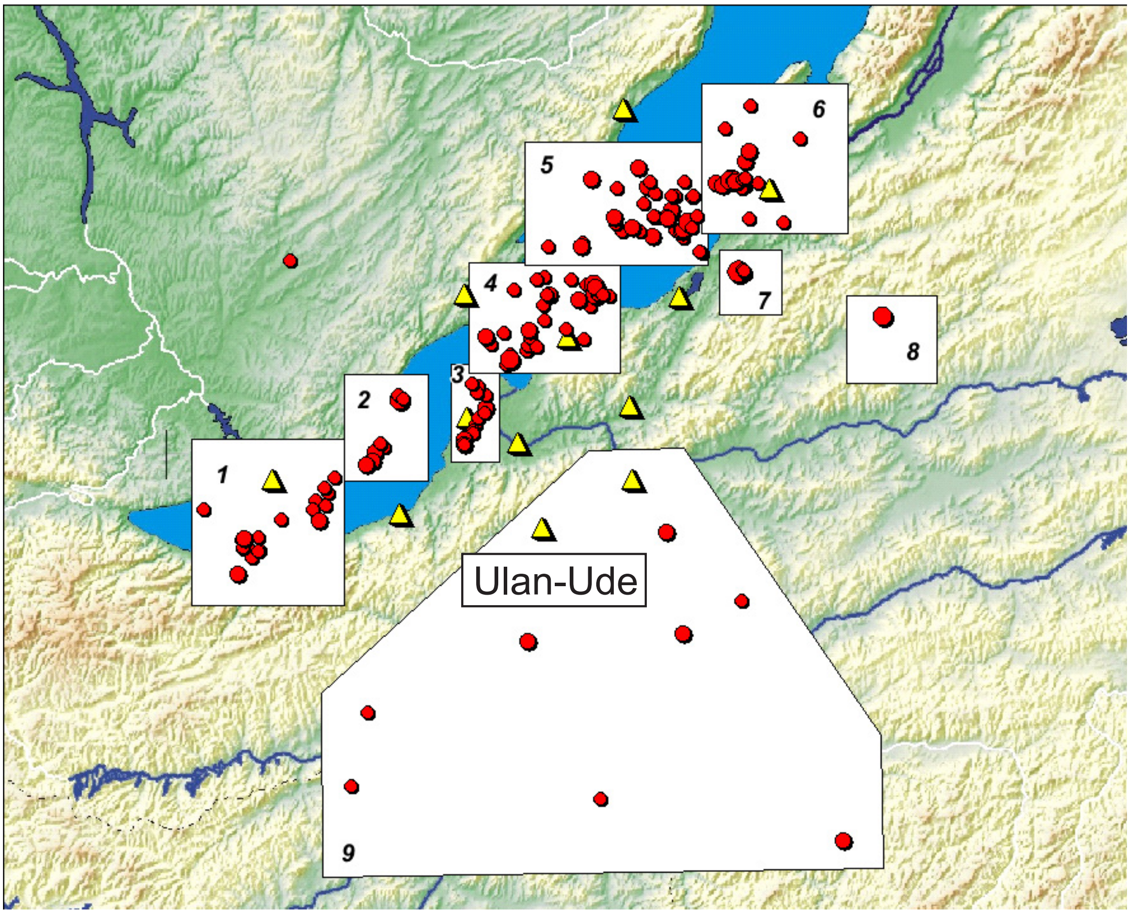

Fig. 5. Earthquake foci zones (Nos. 1 to 9, see Table 3) of potential danger for the Ulan-Ude city territory. Circles show earthquake epicentres selected for establishing the reference signals; triangles show locations of permanent seismic stations.

Рис. 5. Зоны очагов землетрясений (1–9, см. табл. 3), потенциально опасные для территории г. Улан-Удэ. Кружками обозначены эпицентры землетрясений, отобранные для задания исходных сигналов; треугольниками – постоянные сейсмические станции.

several potential earthquake foci zones (Fig. 5), physical and mechanical properties of rocks and soils, and types of displacement/movement in earthquake foci areas. Such factors predetermine whether an impulse-type seismic event may occur or an earthquake with a relatively slow increase and decrease of seismic intensity on the surface may take place.

Methods for selecting the baseline accelerograms are mainly oriented at the acquisition or calculation of peak accelerations and scaling [*Pavlov*, *1988*] in accordance with relevant seismic scales [*Nazarov, Shebalin*, *1975*]. Due to the fact that registered strong seismic events are not numerous in potential earthquake foci zones (and also in the vast regions under review), it becomes necessary to refer to data from catalogues of strong earthquakes registered by the global seismic network or use data on small earthquakes and establish phase characteristics [*RB-006-98*, *1998*].

In this study, we use only the earthquakes records by the regional network of seismic stations [*Drennov et al*., *2011*]. Since the medium is considered as a form-generating factor of a focal pulse, the phase spectrum of local earthquakes, one way or another, takes into account the earthquake excitation and scattering properties of the inhomogeneous medium.

In engineering surveys for construction purposes, the earthquake resistance of buildings and facilities is typically calculated from accelerograms [*Ratnikova*, *1984*]. It is advisable to obtain accelerograms for each PEF zone that can be described by sets of average seismic characteristics.

In view of the above, our study has two main objectives: (1) Obtain potential earthquake accelerograms for each PEF zone with the reference to the available accelerograms of earthquakes that actually took place in the studied zones (for three components, NS, EW and Z); (2) Using the properly grounded models showing seismicity of the ‘reference’ rocks, correlate the obtained maximum acceleration rates with the seismic hazard scale specified in points.

In our study, to justify the seismic hazard of the Ulan-Ude city territory, we analyze accelerograms of actual earthquakes (M from 3.0 to 6.3) recorded by the Ulan-Ude seismic station. For each PEF zone, an average spectrum is calculated and taken as a characteristic of the entire zone. In total, the processed database includes records of 55 earthquakes from 2001 to 2011. Data on components NS, EW, and Z are processed separately. Some of the recorded accelerograms are rejected due to various reasons, such as an insignificant signal/noise ratio. For each earthquake, amplitude and phase spectra are calculated.

It should be noted that we select accelerograms of earthquakes differing in magnitudes and thus refer to relation $\beta_M(f)$ showing how the acceleration spectrum changes with magnitude variations and depends on frequency. In our study, we use the equation for the Baikal rift zone which was published in [*Drennov et al., 2013*]:

$\beta_M(f) = -0.31 log(f)+0.93$ (0.78–20 Hz);
$\beta_M(f) = 0.96$ (<0.78 Hz) R^2=0.98,

where $\beta_M(f)=lg\Delta S/\Delta M$. It determines a spectrum logarithm incremental value at the *i*-th frequency with an earthquake magnitude increase by ΔM.

Based on the above relationship, the amplitude spectra are scaled to magnitudes of the PEF zones. Finally, earthquake accelerograms are obtained for the PEF zones characterized by their specific magnitudes (Fig. 5). This objective is met by using the inverse Fourier transform of the average acceleration spectrum for a specified PEF zone and the phase spectrum of the strongest earthquake recorded in the given PEF zone.

Based on the phase spectra of accelerations from various earthquakes, it is possible to obtain accelerograms of different durations, from accelerograms of the impulse type (when the released energy is concentrated in a small time window) to accelerograms of large time spans. In our study, phase spectra of accelerograms of the medium time span are mainly used.

The accelerograms and their spectra for all the studied PEF zones are shown in Fig. 6 and 7, and the corresponding spectral parameters are given in (Table 3).

According to Table 3, maximum and minimum acceleration rates for the rocks and soils under the Ulan-Ude seismic station can amount to 166 cm/sec^2 and 1.7 cm/sec^2, respectively (the three components are taken into account). The maximum acceleration rates are associated with frequencies from 1.2 to 8.3 Hz, the widths of the acceleration spectra for all the PEF zones range from 0.6 to 14.4 Hz at the level of 0.7S_m. Typically, for the PEF zones located closer and having larger potential magnitudes, the acceleration spectra are somewhat wider than those of the more remote PEF zone, and this expansion is due to higher frequencies. Besides, the maximum values of the spectra are widely variable (from 0.2 to 46 cm/sec) and correlate with the frequency range from 1 to 12.3 Hz.

It is revealed that ranges of maximum values of the studied parameters are widely variable for each component. Therefore, it is needed to conduct additional studies to eliminate the uncertainties. This problem can be solved by long-term recording of earthquakes on various sites in the city which have contrasting soil conditions, such as water-saturated or air-dry soils of specific compositions. In view of the above, at the current stage of our studies, we refer to relatively reliable analyses of seismic impacts by the frequency of their occurrence. Considering amplitudes, it is needed to scale the established baseline signals with regard to forecasted seismic impacts. Such objectives comply with requirement of the current construction regulations. However, a probability of establishing the maximum amplitudes can be properly justified by conducting the required comprehensive studies and consolidating the modeling and experimental data.

At the Ulan-Ude seismic station, geophones are located on soils of category 1. Such conditions may prove sufficient for seismological reconstructions; however, in order to solve problems of engineering seismology, we need quantitative data, including, in the first place, determinations of frequency response which (as a transfer function) are required to justify the baseline signals of the ‘reference’ rocks/medium soils represented in the seismicity-soil models. This objective can be achieved, as noted above, by direct and computational methods of seismicity microzonation [*Dzhurik et al., 2012*].

Thus, for further use of the accelerograms (see Fig. 6 and 7), they are assigned to the soils of category 1. For the Ulan-Ude city territory, a single baseline signal needs to be established. A mandatory condition is that it should take into account specific features of the spectral compositions of vibrations for each selected PEF zone (see Fig. 5). The vibration spectra are normalized and then averaged. A phase response of one of the earthquakes recorded is estimated, and normalized accelerograms are calculated by the inverse Fourier transform for the three components (Fig. 8, *a*). In its turn (Fig. 8, *b*), the amplitude spectrum of this signal reflects all the specific frequency characteristics of the accelerograms predicted for the PEF zones of the highest hazard (Nos. 3, 4 and 5). Its level exceeding 0.7 Smax is in the frequency range from 1.2 to 5.0 Hz. The main peaks of the spectra occur at frequencies from 1.6 to 2.2 Hz (Table 4).

For further theoretical calculations considering different soil conditions presented by the seismic models, it is required to correlate the background seismic

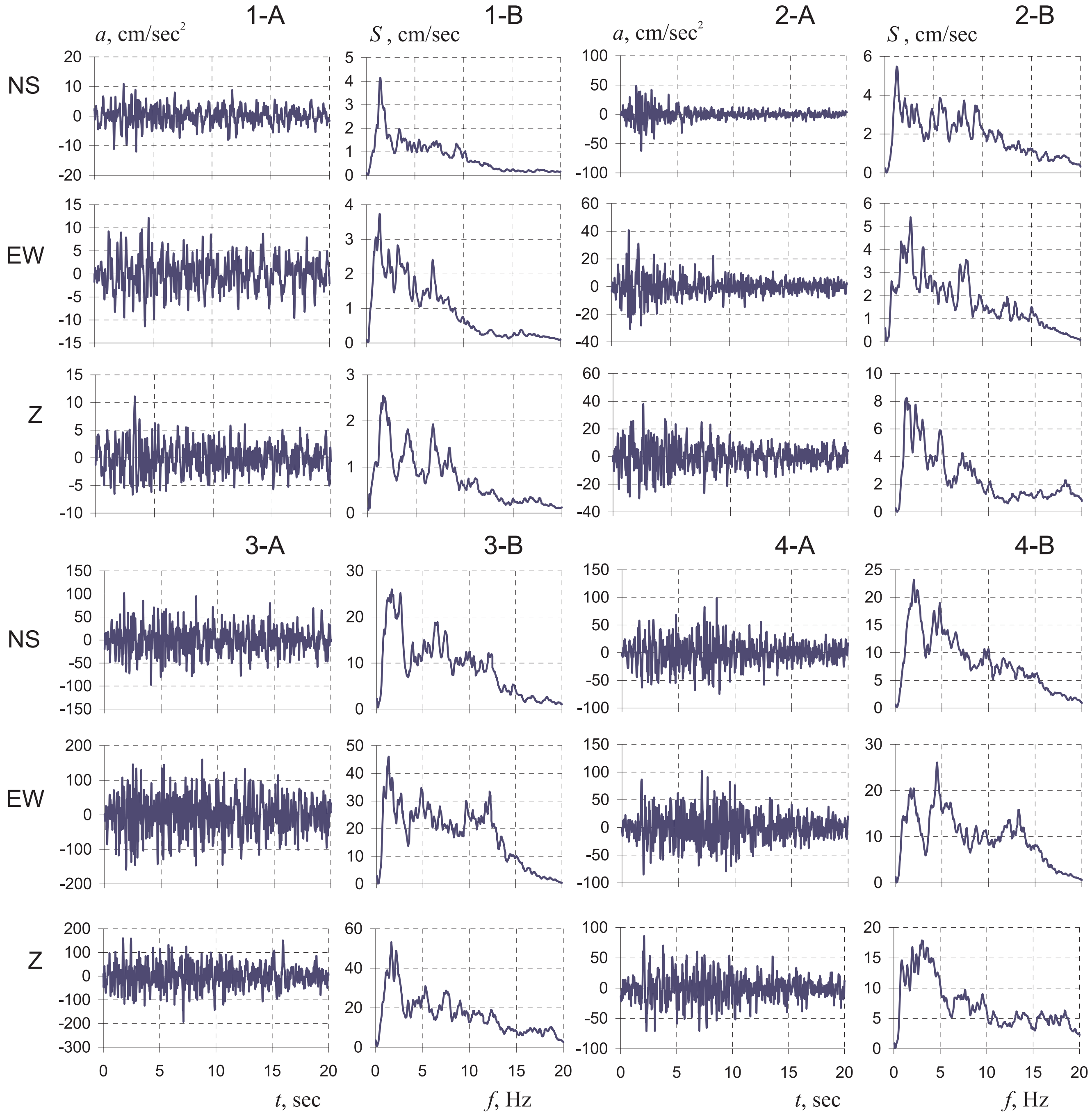

Fig. 6. Accelerograms (*A*) and their amplitude spectra (*B*) of components NS, EW and Z for potential earthquake foci zones (Nos. 1 to 4) (M=7.5, Δ=230 km; M=7, Δ=130 km; M=7.5, Δ=90 km; M=7.5, Δ=100 km).

Рис. 6. Акселерограммы (*A*) и их амплитудные спектры (*B*) для трех компонент (NS, EW, Z) для зон ВОЗ 1-4 (M=7.5, Δ=230 км; M=7, Δ=130 км; M=7.5, Δ=90 км; M=7.5, Δ=100 км).

signal with a reference soil/half-space, from which we can estimate changes in the signal by near-surface inhomogeneities. In further estimations, it is also reasonable to consider inhomogeneities located at depth.

To develop models that can characterize subsurface inhomogeneities, we use data on seismic wave velocities that are generalized with regard to soil compositions and conditions (see Table 2; Fig. 3 and 4) and also refer to the available file materials. Parameters of seismicity-soil reference models Nos. 1 and 2 (Table 5) are based on the above-mentioned data and correlated with predicted seismic impacts.

A set of the well-known methods and software packages [*Ratnikova, 1984; RB-006-98, 1998*] is used to carry out theoretical calculations.

Reference model No. 1 (see Fig. 9, *a–e*, and Table 5)

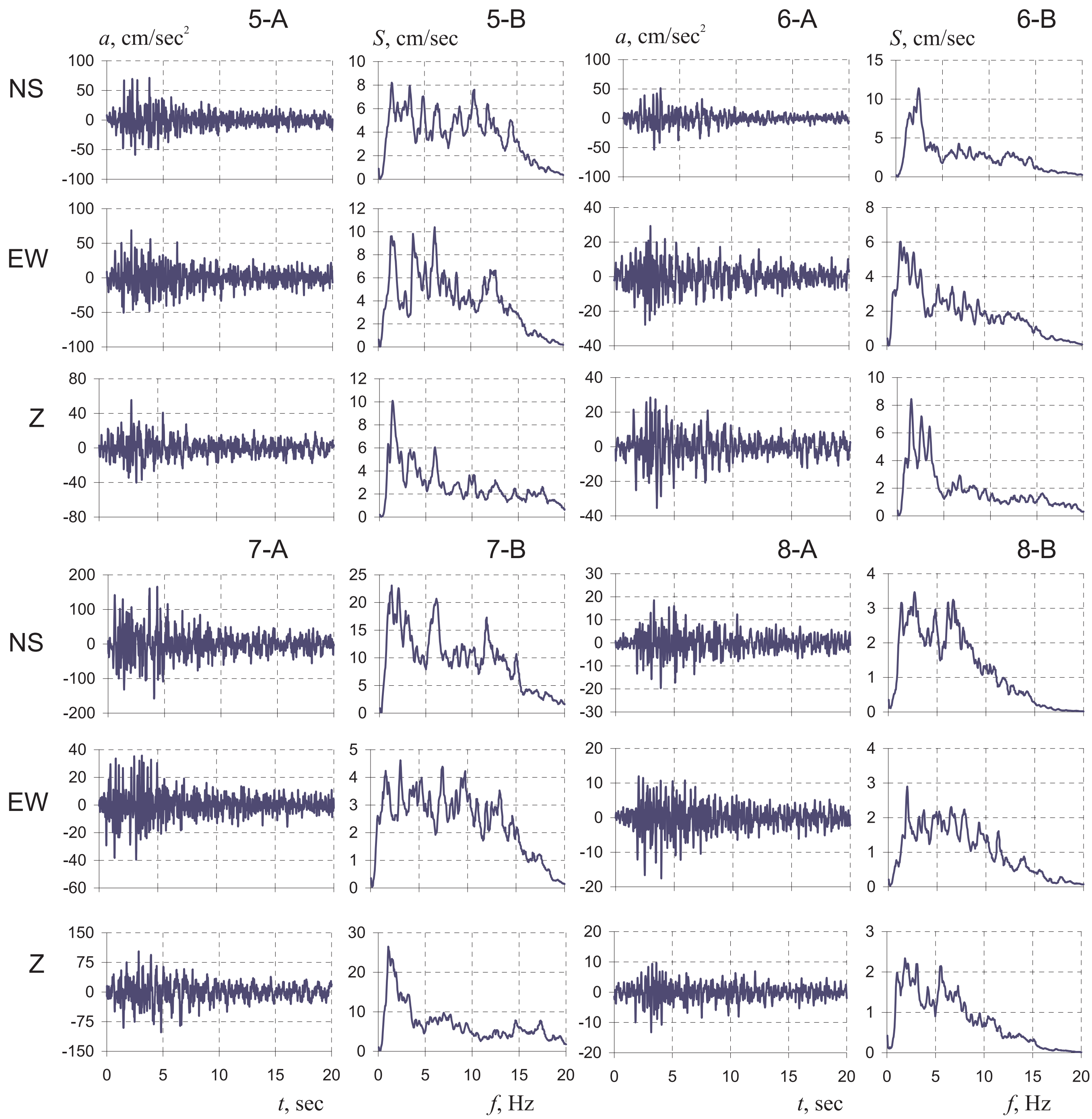

Fig. 7. Accelerograms (*A*) and their amplitude spectra (*B*) of components NS, EW, Z for potential earthquake foci zones (Nos. 5 to 8) (M=7.5, Δ=150 km; M=7, Δ=170 km; M=7, Δ=120 km; M=6.5, Δ=170 km).

Рис. 7. Акселерограммы (*А*) и их амплитудные спектры (*В*) для трех компонент (NS, EW, Z) для зон ВОЗ 5-8 (M=7.5, Δ=150 км; M=7, Δ=170 км; M=7, Δ=120 км; M=6.5, Δ=170 км).

represents the bedrock in the 8-points zone. Calculated acceleration rates correspond to the seismic hazard by one point lower than that for the medium soil. The maximum acceleration rates amount to 98 cm/sec^2 and 53 cm/sec^2 for the horizontal and vertical components, respectively. The acceleration spectrum has the maximum of 0.7 in the frequency range from 1.12 to 4.93 Hz and 1.17 to 2.34 Hz for the horizontal and vertical components, respectively.

Models Nos. 3 to 7 characterize dominating seismic risk areas of the city (see Fig. 1, and Tables 5 and 6). They are also applicable to areas with different soil conditions and reference bedrock depths from 10 to 80m. It should be noted that our models are substan-

Т a b l e 3. **Main parameters of estimated spectra for potential earthquake foci (REF) zones**

Т а б л и ц а 3. **Основные параметры расчетных спектров для землетрясений разных зон ВОЗ**

PEF M Δ	Component	a_m, cm/sec²	$f\,a_m$, Hz	S_m, cm/sec	$f\,S_m$, Hz	$(f_1–f_2)_{0.7Sm}$	$\delta f_{0.7Sm}$	$(f_1–f_2)_{0.5Sm}$	$\delta f_{0.5Sm}$
1	NS	11	3.6	4.2	1.5	1.3–1.9	0.6	1.2–2.0	0.8
M=7.5	EW	12.2	2	3.7	1.4	0.8–3.4	2.6	0.7–4.9	4.2
230 km	Z	11.1	2.2	2.5	1.8	1.3–6.9	5.6	1.2–7.1	5.9
2	NS	62.4	5.3	5.4	1.2	1–3.7	2.7	0.9–9.7	8.8
M=7	EW	41	5.6	5.4	2.6	1.6–4	2.4	1.5–8.6	7.1
130 km	Z	38	1.2	8.2	1.3	1–3.1	2.1	0.9–5.2	4.3
3	NS	102	3.1	26	1.7	1–2.7	1.7	0.7–7.7	7
M=7.5	EW	160	2.8	46	1.3	0.6–13	12.4	0.7–12.7	12
90 km	Z	138	2	53	1.7	1.5–2.4	0.9	1–7.9	6,9
4	NS	99	2.6	23	2	1.4–4.9	3.5	1.1–6.8	5.7
M=7.5	EW	102	3.2	26	4.5	1.8–4.8	3	1.2–6.9	5.7
100 km	Z	86.2	1.7	17.8	3.1	1–4.7	3.7	0.7–5.1	4.4
5	NS	69.5	4	8.2	1.5	1.3–12	10.7	0.9–14.6	13.7
M=7.5	EW	68.8	3.8	10.4	6.1	1.3–6.4	5.1	1.1–12.8	11.7
150 km	Z	55.5	4.2	10	1.5	1.3–1.8	0.5	1.1–6.2	5.1
6	NS	53.7	4	11.3	2.5	1.6–2.7	1.1	1.1–3	1.9
M=7	EW	29.4	8.3	6	1.4	1.2–3.6	1.4	0.9–8	7.1
170 km	Z	33.6	2.9	8.4	1.5	1.7–3.6	1.9	1.3–3.7	2.4
7	NS	166	3.1	23	1.3	0.8–6.4	5.6	0.7–12.7	12
M=7	EW	40	4.2	4.6	3.1	1.3–10.3	9	1–14.7	13.7
120 km	Z	102	2.8	26.5	1.1	0.9–2	1.1	0.8–3.3	2.5
8	NS	20	3.7	3.4	2.7	1.6–7.7	6.1	1–8.7	7.7
M=6.5	EW	166	3.4	2.9	2.0	1.8–8.0	6.2	1.7–11.3	9.6
170 km	Z	133	6.7	2.3	1.9	0.9–7.4	6.5	0.9–8.1	7.2
9	NS	1.2	6.2	0.2	12.8	7.9–14.1	6.2	5–14.8	9.8
M=5.5	EW	2.7	4.2	0.4	12.3	6.4–14.4	8	4–15.9	11.9
90 km	Z	1.7	5.6	0.2	10.2	1.0–20	19	1.5–20	18.5
9	NS	4.8	3.3	0.6	1	1.2–4	2.8	0.6–4	3.4
M=6.5	EW	6.5	2.9	0.7	3.3	2.3–4.3	2	0.9–4.8	3.9
130 км	Z	4	2.4	0.8	1.9	1.1–2.2	1.1	0.8–3.1	2.3

N o t e. M is magnitude; Δ is distance to epicentre; a_m is maximum amplitude of calculated acceleration; fa_m is frequency corresponding to a_m; S_m is maximum amplitude level of the spectrum; f_{Sm} is spectrum peak frequency; f_1 and f_2 are frequencies that limit acceleration spectra at levels 0.7 and 0.5 S_m; $\delta f_{0.7Sm}$ and $\delta f_{0.5Sm}$ are spectrum widths.

П р и м е ч а н и е. М – магнитуда; Δ – эпицентральное расстояние; a_m – максимальная амплитуда расчетного ускорения; fa_m – частота, соответствующая a_m; S_m – максимальный амплитудный уровень спектра; f_{Sm} – частота максимума спектра; f_1, f_2 – частоты, ограничивающие спектры ускорения на уровнях 0.7 и 0.5 S_m; $\delta f_{0.7Sm}$, $\delta f_{0.5Sm}$ – ширина спектра.

tiated also by other geotechnical and geophysical data providing for the zonation of the study area in the first approximation.

At the current stage of studies, for reference model No. 2 (see Table 5, Fig. 9) representing the 10-metre thick water-saturated soil of the medium composition, the acceleration rates are scaled with regard to the acceleration rates to 397 cm/sec² and 173 cm/sec² for the maximum and vertical components, respectively. This corresponds to the seismic hazard of 9 points, i.e. one point higher than the reference level for the non-water-saturated soil. The resonant frequency amounts to 12.79 Hz; the main peak of the spectrum is at the frequency of 1.56 and 1.51 Hz; the maximum spectral density amounts to 85.3 and 51.9 cm/sec for components EW and Z, respectively (Table 6).

It is noteworthy that in further studies, special attention should be paid to the justification of the potential seismic hazard of water-saturated soils [*Dzhurik et al., 2011*] based on records of the behaviour of such soils during earthquakes. As noted earlier, frequency characteristics need to be determined for the water-saturated soil layers varying in thickness, and such data can facilitate achieving more reliable results by the calculation methods.

In general, models Nos. 3, 4 and 6 represent the unconsolidated non-water-saturated soils varying in thickness. According to estimations by the seismic

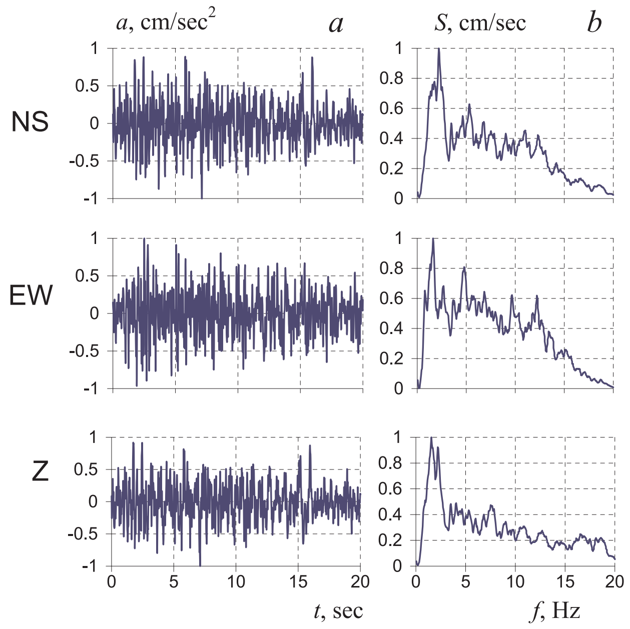

Fig. 8. Reference normalized accelerograms (*a*) and their amplitude spectra (*b*) (M=7.5, 90 km).

Рис. 8. Исходные нормированные акселерограммы (*a*) и их амплитудные спектры (*b*) (M=7.5, 90 км).

T a b l e 4. **Main parameters of normalized estimated spectra for earthquakes with M=7.5, Δ=90 km**

Т а б л и ц а 4. **Основные параметры нормированных расчетных спектров для землетрясения M=7.5, Δ=90 км**

Component	f_{am}, Hz	S_m, cm/sec	f_{Sm}, Hz	$(f_1–f_2)_{0.7Sm}$	$\delta f_{0.7Sm}$	$(f_1–f_2)_{0.5Sm}$	$\delta f_{0.5Sm}$
NS	3.3	1	2.2	1.5–2.6	1.1	1.1–6.8	5.7
EW	2.3	1	1.6	1.2–5.0	3.8	1.0–8.0	7.0
Z	2.3	1	1.6	1.2–2.4	1.2	1.0–2.7	1.7

T a b l e 5. **Parameters of standard seismicity-soil models**

Т а б л и ц а 5. **Параметры типовых сейсмогрунтовых моделей**

Model No., standard profile	h, m	Vp, m/sec	Vs, m/sec	ρ, t/m³	Average Vp, m/sec	Average Vs, m/sec	ΔI(Vp)	$Ä_{max}$, cm/sec² (point)
Reference model No. 1	10	2200	1240	2.5	2200	1240	0	98
	12	2600	1700	2.6				(7)
	∞	3500	1900	2.7				
Reference model No. 2	10	1600	480	1.9	600	300	2	396
(water-saturated soil)	10	2200	1240	2.5				(9)
h=10m	12	2600	1700	2.6				
	∞	3500	1900	2.7				
Model No. 3	2	500	290	1.6	820	441	0.76	171
Unconsolidated and degraded,	2	700	380	1.9				(7.76)
strongly fractured conglomerate	4	1000	510	2.0				
	9	1500	750	2.2				
	6	2000	990	2.4				
	10	2200	1240	2.5				
	12	2600	1700	2.6				
	∞	3500	1900	2.7				
Model No. 4	4	400	230	1.6	570	316	1.16	186
Gravel, sand (none-water-	2	600	330	1.8				(8.16)
saturated), h=36m	12	900	490	2.0				
	12	1500	750	2.2				
	6	2000	990	2.4				
	14	2200	1240	2.5				
	16	2600	1700	2.6				
	∞	3500	1900	2.7				

End of Table 5

Окончание таблицы 5

Model No., standard profile	h, m	Vp, m/sec	Vs, m/sec	ρ, t/m3	Average Vp, m/sec	Average Vs, m/sec	ΔI(Vp)	Ämax, cm/sec² (point)
Model No. 5	10	1500	420	1.9	600	247	2.1	410
Loam, sandy loam, sand	12	2000	560	2.4				(9.1)
(water-saturated),	12	2200	1240	2.5				
h=22 m	16	2600	1700	2.6				
	∞	3500	1900	2.7				
Model No. 6	8	600	340	1.8	583	332	1.02	154
Medium-type soil, sand, gravel	16	800	440	1.9				(8.02)
(none-water-saturated),	24	1000	510	2.1				
h=80m	20	1500	750	2.2				
	12	2000	990	2.3				
	12	2200	1240	2.5				
	16	2600	1700	2.6				
	∞	3500	1900	2.7				
Model No. 7	8	1500	430	1.9	600	300	2.1	398
Sand, gravel (water-saturated),	16	1600	550	2.0				(9.1)
h=80m	24	1800	600	2.1				
	32	2000	700	2.2				
	12	2200	1240	2.5				
	16	2600	1700	2.6				
	∞	3500	1900	2.7				

Note. The seismic impedance method is applied to calculate seismic hazard levels (UoM – point) with respect to the bedrocks (baseline seismicity of 7 points). Average seismic wave velocities are estimated for the 10-metre thick layer. The watercut correction is +1 point.

Примечание. Расчет сейсмической опасности в баллах проведен по методу сейсмических жесткостей относительно коренных пород (исходная сейсмичность 7 баллов); средние скорости рассчитаны для 10-метрового слоя; поправка за обводненность +1 балл.

impedance method, the seismic hazard of the sites with such soils ranges from 7.76 to 8.16 points. For the specified soil conditions (see Table 6; Fig. 9), the peak acceleration rates range from 154 to 186 cm/sec² (Fig. 9, *a, b*) and from 64 to 86 cm/sec² (Fig. 9, *c, d*) for components EW and Z, respectively.

Models No. 5 and No. 7 represent water-saturated soil layers (22 and 80 m thick). The peak acceleration rates range from 397 to 410 cm/sec² and 199 to 223 cm/sec² for components EW and Z, respectively (see Tables 5 and 6, and Fig. 9). The calculated acceleration rates correspond to the seismic hazard of 9 points, i.e. one point higher than the baseline for the medium non-water-saturated soil. For model No. 5 and 7, the resonant frequency amounts to 6.75 and 2.2 Hz, respectively. The calculated spectral density reaches its maximum in the frequency range from 1.51 to 4.74 Hz and varies from 99 to 130 cm/sec and 53.8 to 84.6 cm/sec for components EW and Z, respectively. With increasing thickness of the water-saturated layer from 22 to 80 m, its resonant frequency decreases from 6.79 Hz to 2.2 Hz (see Fig. 9, *d*).

Based on the theoretical calculation results (see Section 2), experimental measurements (see Section 1) and the available geotechnical and hydrogeological data, a schematic map is compiled in the first approximation (Fig. 10) to show zones differing in the basic seismic impact parameters.

The zone with the potential maximum seismic hazard of 9 points includes floodplain areas and the first above-floodplain terrace composed by alluvium (sand, clay soil and gravel) where groundwater occurs at shallow depths, less than 5m. It is possible that the weakened near-fault northern site will be also included. This zone can be represented by seismicity-soil models No. 2 and No. 7 (see Fig. 9 and Table 6). In this zone, the maximum acceleration rates are 410 cm/sec² and 223 cm/sec² for components NS and Z, respectively.

The zone with the relatively high seismic hazard (8 and 9 points, a transition zone) includes the left-bank terrace of the Uda River which is composed of silty fine-grained sand (models No. 4 and No. 5). In this zone, the maximum acceleration rates range from 154 to 410 cm/sec² and 64 to 223 cm/sec² for components NS and Z, respectively.

The seismic hazard of 8 points (models No. 3 and No. 4) may be expected at slightly sloped terraces of the Uda and Selenga Rivers where groundwater occurs at depths from 8 to 20 m. In this zone, the maximum acceleration rates are 186 cm/sec² and 86 cm/sec² for components NS and Z, respectively.

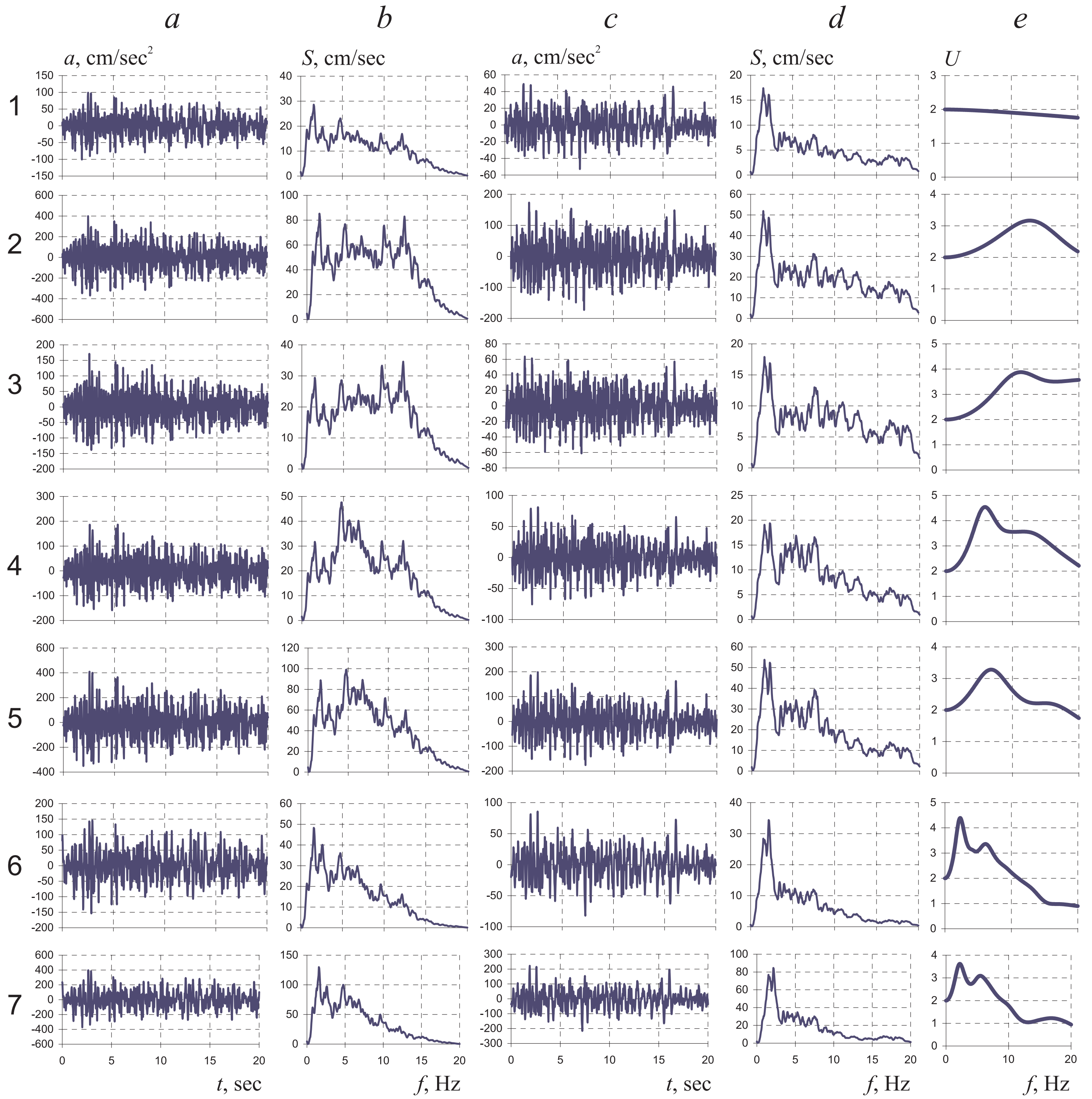

Fig. 9. Accelerograms (*a*) and their amplitude spectra (*b*) for the horizontal component; accelerograms (*c*) and their amplitude spectra (*d*) for the vertical component; frequency characteristics of unconsolidated soil layers (*e*).

Рис. 9. Акселерограммы (*a*) и их амплитудные спектры (*b*) для горизонтальной компоненты, акселерограммы (*c*) и их амплитудные спектры (*d*) для вертикальной компоненты, частотные характеристики рыхлых слоев (*e*).

The zone with the seismic hazard of 7 points includes sites composed of rocky and semi-rocky soils, except areas of tectonic fracturing (model no. 1). In this zone, the maximum acceleration rates are 98 cm/sec^2 and 53 cm/sec^2 for components NS and Z, respectively.

It should be noted that by applying the seismic microzonation method, it is possible to reveal sites with the seismic hazard from 7 to 9 points in each of the specified zones (Fig. 10). Such sites can be correlated with relevant soil models (see Table 5), and their locations can be further clarified and determined more precisely with regard to the scale of seismic microzona-

Table 6. **Main parameters of estimated accelerograms and corresponding spectra for models Nos. 1 to 7**

Таблица 6. **Основные параметры расчетных акселерограмм и соответствующих им спектров для моделей 1–7**

Model No., standard profile	Maximum acceleration $\ddot{A}_{max}$, cm/sec²	Peak spectrum value S_{max}, cm/sec	Frequency of main spectrum peak, Hz	Frequency range for $0.7{\cdot}S_{max}$ (f), Hz	Resonance frequency of unconsolidated layers, Hz
Horizontal component EW					
1	98	28.6	1.56	1.12–4.93	–
2	397	85.3	1.56	1.12–12.65	12.79
3	171	34.6	12.16	1.42–12.65	11.28
4	186	47.6	4.74	4.44–6.98	5.86
5	410	99	4.74	1.27–9.62	6.79
6	154	48.3	1.56	1.37–4.83	2.29
7	398	130	1.56	1.27–4.88	2.2
Vertical component Z					
1	53	17.4	1.51	1.17–2.34	–
2	173	51.9	1.51	1.22–2.34	12.79
3	64	17.9	1.51	1.22–7.67	11.28
4	81	19.4	2.15	1.27–7.86	5.86
5	199	53.8	1.51	1.22–7.62	6.79
6	86	34.4	2.15	1.42–2.39	2.29
7	223	84.6	2.15	1.32–2.34	2.2

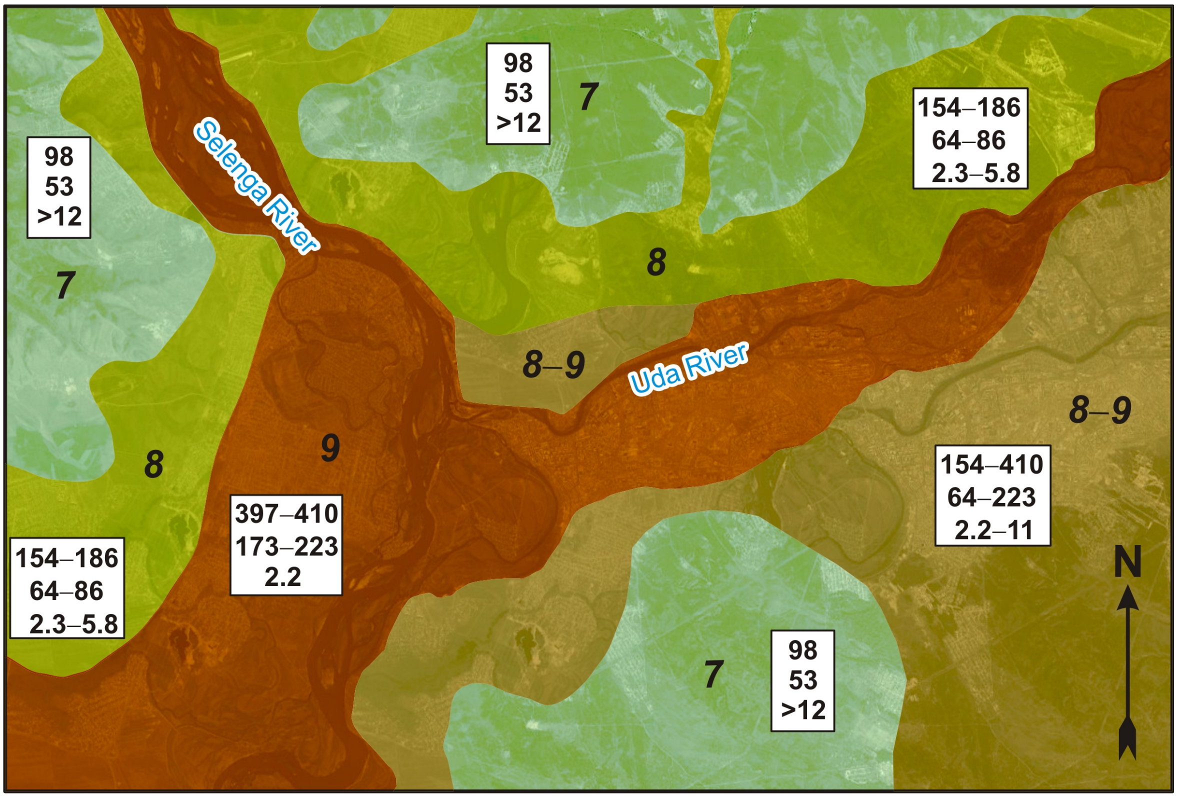

Fig. 10. The schematic map showing potential seismic hazard zones in the Ulan-Ude city territory. The map takes into account the soil and hydrogeological conditions of construction (reference seismic intensity – 8 points).

Numbers in boxes: top – maximum acceleration (cm/sec²) for the horizontal component (NS); middle – maximum acceleration (cm/sec²) for the vertical component (Z); bottom – resonant frequency (Hz) of the unconsolidated soil layer. 7–9 – potential maximum seismic intensity (UoM – point).

Рис. 10. Схематическая карта сейсмической опасности территории г. Улан-Удэ с учетом грунтовых и гидрогеологических условий строительства (исходная сейсмичность – 8 баллов).

В квадратах: верхнее значение – максимальные ускорения (см/с²) для горизонтальной компоненты (NS), среднее значение – максимальные ускорения (см/с²) для вертикальной компоненты (Z), нижнее значение – резонансные частоты (Гц) рыхлого слоя. 7–9 – вероятная максимальная интенсивность в баллах.

tion of the Ulan-Ude city territory by developing more detailed models with the application of the proposed technique.

4. Conclusion

The seismic hazard zonation of the Ulan-Ude city territory is a complex problem including studies by the seismic, seismotectonic, geotechnical and seismological methods. Each of the methods solves specific research problems, and their combination provides data for achieving the major objective to construct a seismic microzonation map of the territory.

At the current stage of studies, the indirect instrumental methods of seismic microzonation are used, and the types of rocks and soils prevailing in the studied territory are determined and classified by the propagation patterns of P- and S-waves. Using the acoustic impedance method, we estimate the incremental seismic intensity values for water-saturated and non-water-saturated sandy gravel-pebble sediments. The calculations are performed against parameters of the selected reference soil, i.e. the rocky soil with average seismic wave velocities in the upper 10-metre thick layer.

At the initial stage of forecasting how strong earthquakes can impact the rocks and soils under buildings and facilities in the Ulan-Ude city territory, we refer to the main parameters of significant ground movements that occurred in the Baikal rift zone in the past ten years. The established baseline seismic signal takes into account, in the first approximation, the main parameters of the potential earthquake occurrence zones and the previously established empirical relationships showing how the main dynamic characteristics of soil acceleration can vary depending on seismic event magnitudes and distances from earthquake foci. Based on such data, accelerograms can be forecasted for different epicentral distances and magnitudes and used for more reliable determinations of baseline seismic signals for the Ulan-Ude city territory with reference to the frequency characteristics.

It is shown that the established baseline signal is applicable, and the theoretical calculations are conducted on the basis of the seismicity-soil models characterizing bedrocks, medium soils and water-saturated soils (soil categories 1, 2 and 3, respectively). Based on the calculation results and the available geotechnical and hydrogeological data, and taking into account the soil and hydrogeological conditions for construction (the baseline seismic intensity of 8 points), a schematic map of seismic hazard is constructed for the Ulan-Ude territory in the scale sufficient for construction purposes. It shows that the seismic hazard is variable from 7 to 9 points through the studied territory. The map in the current format was used when we developed a detailed programme of studies aimed at seismic microzonation.

Obviously, the mapped data will be revised and updated in a more detail. Anyway, the obtained results can be useful today for planning possible construction sites in the Ulan-Ude city territory.

The technique of seismic microzonation mapping should be based on detailed measurements, and parameters for mapping the impact of seismic events should be determined at the precision level no less than that specified in requirements to engineering and design of earthquake-resistant buildings and facilities. It is recommended to apply GIS technologies and conduct more detailed engineering and seismic measurements in order to consolidate a database for construction of more detailed maps and schemes of the studied territory in smaller scales. In order to construct a digital map of seismic microzonation, the source materials should include topographical and special geotechnical and hydrogeological maps and schemes showing thickness of unconsolidated sediments, as well as various reference materials and data from other sources.

To complete seismic microzonation mapping, it is required to identify the potential seismic sources and characterize them at the new probabilistic level. It is thus needed to determine locations subject to deformation and active faulting, estimate the periods of earthquake recurrence, determine seismic intensity levels, and reveal probabilities of potential earthquake occurrence. Information on the potential seismic sources can facilitate forecasting of strong events for the Ulan-Ude city territory. Seismic wave propagation parameters and potential seismic impacts should be estimated for specific construction sites located in the city, and such estimations should be followed by calculations of response spectra and associated probabilities of the occurrence of strong earthquakes. Once the above-mentioned detailed data are consolidated, it will become possible to construct a map of seismic risks that can serve as a useful source of information for streamlining the regional construction policy.

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5. References

Drennov A.F., Dzhurik V.I., Serebrennikov S.P., Bryzhak E.V., Drennova N.N., 2013. Acceleration response spectra for the earthquakes of the southwestern flank of the Baikal Rift Zone. *Russian Geology and Geophysics* 54 (2), 223–230. http://dx.doi.org/10.1016/j.rgg.2013.01.008.

Drennov A.F., Dzhurik V.I., Serebrennikov S.P., Drennova N.N., 2011. Influence of the upper section on the amplitude-frequency content of a seismic signal by the example of seismic stations in the Baikal and the Transbaikal region. *Seismic Instruments* 47 (1), 57–65. http://dx.doi.org/10.3103/S0747923911010099.

Dzhurik V.I., 2014. Seismogeological, seismological and engineering seismological studies of the Laboratory of Engineering Seismology and Seismogeology of IEC RAS. *Geodynamics & Tectonophysics* 5 (1), 135–157 (in Russian) [*Джурик В.И.* Сейсмогеологические, сейсмологические и инженерно-сейсмологические исследования лаборатории инженерной сейсмологии и сейсмогеологии ИЗК СО РАН // *Геодинамика и тектонофизика*. 2014. Т. 5. № 1. С. 135–157]. http://dx.doi.org/10.5800/GT-2014-5-1-0121.

Dzhurik V.I., Serebrennikov S.P., Drennov A.F., Bryzhak E.V., Eskin A.Yu., 2012. Methodology of the establishment of a seismic signal for the seismic hazard zonation of urban agglomerations (a case of Irkutsk). *Izvestiya Irkutskogo gosudarstvennogo universiteta*, *Seriya* «*Nauki o Zemle*» (*The Bulletin of Irkutsk State University, Earth Sciences Series*) 5 (2), 96–110 (in Russian) [*Джурик В.И., Серебренников С.П., Дреннов А.Ф., Брыжак Е.В., Ескин А.Ю.* Методика формирования сейсмического сигнала с целью районирования сейсмической опасности городских агломераций (на примере г. Иркутска) // *Известия Иркутского государственного университета*. *Серия* «*Науки о Земле*». 2012. Т. 5. № 2. С. 96–110].

Dzhurik V.I., Serebrennikov S.P., Drennov A.F., Bryzhak E.V., Usynin L.A., Shagun A.N., Eskin A.Yu., 2011. On seismic hazard zonation of the city of Irkutsk. *Izvestiya Irkutskogo gosudarstvennogo universiteta*, *Seriya* «*Nauki o Zemle*» (*The Bulletin of Irkutsk State University, Earth Sciences Series*) 4 (2), 61–82 (in Russian) [*Джурик В.И., Серебренников С.П., Дреннов А.Ф., Брыжак Е.В., Усынин Л.А., Шагун А.Н., Ескин А.Ю.* К районированию сейсмической опасности территории г. Иркутска // *Известия Иркутского государственного университета*. *Серия* «*Науки о Земле*». 2011. Т. 4. № 2. С. 61–82].

Guidelines for Seismic Microzonation in Engineering Surveys for Construction, 1985. The USSR Gosstroy, Moscow, 73 p. (in Russian) [Рекомендации по сейсмическому микрорайонированию при инженерных изысканиях для строительства. М.: Госстрой СССР. 1985. 73 с.].

Guidelines for Seismic Microzonation in Engineering Surveys for Construction, 1986. The USSR Gosstroy, Moscow, 62 p. (in Russian) [Рекомендации по сейсмическому микрорайонированию при инженерных изысканиях для строительства. М.: Госстрой СССР, 1986. 62 с.].

Guidelines for Seismic Microzonation of Construction Sites for Transport Facilities, 2004. MDS 22-1. FGUP TsPP, Moscow, 48 p. (in Russian) [Методические рекомендации по сейсмическому микрорайонированию участков строительства транспортных сооружений. МДС 22-1. М.: ФГУП ЦПП, 2004. 48 с.].

Medvedev S.V., 1962. Engineering Seismology. Gosstroiizdat, Moscow, 260 p. (in Russian) [*Медведев С.В.* Инженерная сейсмология. М.: Госстройиздат, 1962. 260 с.].

Nazarov A.G., Shebalin N.V. (Eds.), 1975. The Seismic Scale and Seismic Intensity Measurement Methods. Nauka, Moscow, 279 p. (in Russian) [Сейсмическая шкала и методы измерения сейсмической интенсивности / Ред. А.Г. Назаров, Н.В. Шебалин. М.: Наука, 1975. 279 с.].

Pavlov O.V. (Ed.), 1984. Seismic Microzonation. Nauka, Moscow, 235 p. (in Russian) [Сейсмическое микрорайонирование / Ред. О.В. Павлов. М.: Наука, 1984. 235 с.].

Pavlov O.V. (Ed.), 1988. Assessment of Soil Conditions Impact on Seismic Hazard. Guidelines for Seismic Microzonation. Nauka, Moscow, 224 p. (in Russian) [Оценка влияния грунтовых условий на сейсмическую опасность. Методическое руководство по сейсмическому микрорайонированию / Ред. О.В. Павлов. М.: Наука, 1988. 224 с.].

Ratnikova L.I., 1984. Vibration calculations at the free surface at the points inside horizontally layered absorbent soil. In: O.V. Pavlov (Ed.), Seismic microzonation. Nauka, Moscow, p. 116–121 (in Russian) [*Ратникова Л.И.* Расчет колебаний на свободной поверхности во внутренних точках горизонтально-слоистого поглощающего грунта // Сейсмическое микрорайонирование / Ред. О.В. Павлов. М.: Наука, 1984. С. 116–121].

RB-006-98, 1998. Determination of Reference Seismic Vibrations of Soils for Design Basis. Gosatomnadzor of Russia, Moscow, 63 p. (in Russian) [*РБ-006-98*. Определение исходных сейсмических колебаний грунта для проектных основ. М.: Госатомнадзор России, 1998. 63 с.].

RSN 60-86, 1986. The RSFSR State Committee for Construction. The RSFSR Gosstroy, Moscow, 32 p. (in Russian) [РСН 60-86. Государственный комитет РСФСР по делам строительства: Госстрой РСФСР, 1986. 32 с.].

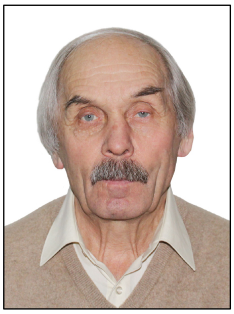
Seismic Surveying. Guidebook for Geophysicists. Nedra, Moscow, 462 p. (in Russian) [Сейсморазведка. Справочник геофизика. М.: Недра, 1981. 462 с.].

*SNiP II-7-81** (*Updated Revision*)*,* 2011. Construction in Seismic Regions. Ministry of Regional Development, Moscow, 71 p. (in Russian) [СНиП II-7-81*(Актуализированная редакция). Строительство в сейсмических районах. М.: Министерство регионального развития, 2011. 71 с.].

Solonenko V.P., Treskov A.A., 1960. The Middle Baikal Earthquake of 29 August 1959. Irkutsk Publishing House, Irkutsk, 36 p. (in Russian) [*Солоненко В.П., Тресков А.А.* Среднебайкальское землетрясение 29 августа 1959 года. Иркутск: Иркутское кн. изд-во, 1960. 36 с.].

The Map of General Seismic Zonation of the Russian Federation, 1999. Scale 1:8000000. The RF Ministry of Science and Technology, Schmidt UIPE, Moscow, 57 p. (in Russian) [Карта общего сейсмического районирования территории Российской Федерации. Масштаб 1:8000000. М.: Министерство науки и технологий РФ, ОИФЗ им. О.Ю. Шмидта, 1999. 57 с.].

The USSR Seismic Zonation Map, 1984. Scale 1:5000000. Explanatory Note. Nauka, Moscow, 32 p. (in Russian) [Карта сейсмического районирования СССР. М. 1:5000000. Объяснительная записка. М.: Наука, 1984. 32 с.].



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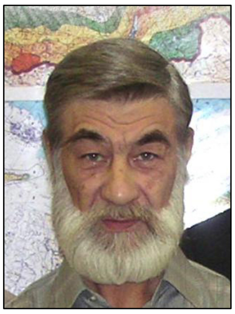

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