SEISMIC HAZARD FOR AN OIL AND GAS FIELD IN THE WATERS OF THE MIDDLE CASPIAN SEA

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Abstract

In order to ensure trouble-free operation of offshore oil production and transportation facilities, it is necessary to consider seismic hazard in their design. As part of this work, seismic hazard calculations were performed for the Zhenis oil and gas field facilities located in the Kazakhstan sector of the Middle Caspian. According to this project, the initial seismicity and seismic microzoning were clarified, i.e., accounting for real soil conditions made by different methods. Calculations showed that the intensity of seismic shocks in the Zhenis field can be 8.31 points on the MSK-64 scale, which corresponds of acceleration of a sea bottom ground of 0.253 g.

Keywords: Caspian Sea, seismic hazard, offshore oil and gas facilities, seismic microzoning

I. Introduction

The assessment of the seismic hazard of the water areas is carried out to ensure the seismic resistance of marine structures. However, research in this area makes it possible to solve other tasks that are not directly related to the problems of seismic safety of field development facilities. In particular, information about the maximum seismic impacts in a particular region makes it possible to solve not only the traditional tasks of engineering seismology and earthquake-resistant construction, but also to find application in the study of global climate change.

There are many hypotheses that differently explain the global climate change on our planet. Among them, as it seems to the authors of this article, a new theory of academician L. I. Lobkovsky about the influence of strong subduction earthquakes on the Earth's climate [24]. The author shows that strong earthquakes (M=8-9) result in tectonic waves in the lithosphere, which contribute to the emergence in the sedimentary cover of additional stresses commensurate with the stresses created by tidal deformation waves, and which are accompanied by the dissociation of metastable gas hydrates and the release of large volumes of methane into the atmosphere, which in turn leads to rapid global warming and global sea level rise. In this regard, it seems relevant to assess the level of seismic hazard in other areas, in particular, in the Caspian Sea, which contains gas hydrates in its sedimentary apron [3] and located at a relatively short distance from the Alpine-Himalayan collision zone.

Modern normative maps of general seismic zoning OSR-2015 A, B, C do not contain information on the intensity of seismic shaking (score) in the water areas of inland and marginal seas of Russia. Such information in integer MSK-64 score values is contained in the OSR-97 maps, which are not up to date.

Seismological monitoring using temporary and permanent networks of autonomous (ground and bottom) seismic stations is carried out to refine seismotectonic models of the studied region and detailed seismic zoning (DSZ) [10-13]. Description of operating systems of bottom seismological monitoring is given in works [14,18,21,26]. The results of using monitoring data for constructing seismotectonic models are given in [15,16,22,23,26]. If instrumental observations are not carried out, it is necessary to carry out work to clarify the initial seismicity (CIS) by computational methods, using both seismotectonic models already developed for the area under study and refined models. In our case (the Middle Caspian region), an example of such a model is given in [27], and a refined model in [19].

The purpose of seismic microzoning (SMR) is to quantify the influence of local conditions (soil composition, relief features, presence of active faults, etc.) on the seismicity of the site, indicating the change in the intensity of shaking in points according to GOST 6249-52 (Russian Standard) or in acceleration values in units of gravity (g).

II. Clarification of initial seismicity

The initial seismic impacts for the offshore oil and gas field Zhenis (Kazakhstan sector of the Middle Caspian Sea) were calculated by the method of probabilistic seismic hazard analysis (PSHA) [9] using the modified program SEISRISK III [6].

The input data for the PSHA are models of possible earthquake source zones (PES zones), earthquake recurrence models for these zones, and suitable attenuation models for the computed ground motion parameters (accelerations or response spectra). These models are prepared based on the analysis of available geological-geophysical and seismological data for the study area.

In this work we used the lineament-domain-focal (LDF) model of seismic hazard zones of the Middle Caspian Sea, which is the basis of seismic hazard calculations under the Global Seismic Hazard Assessment Program project [27], refined in accordance with [19] and shown in Fig. 1.

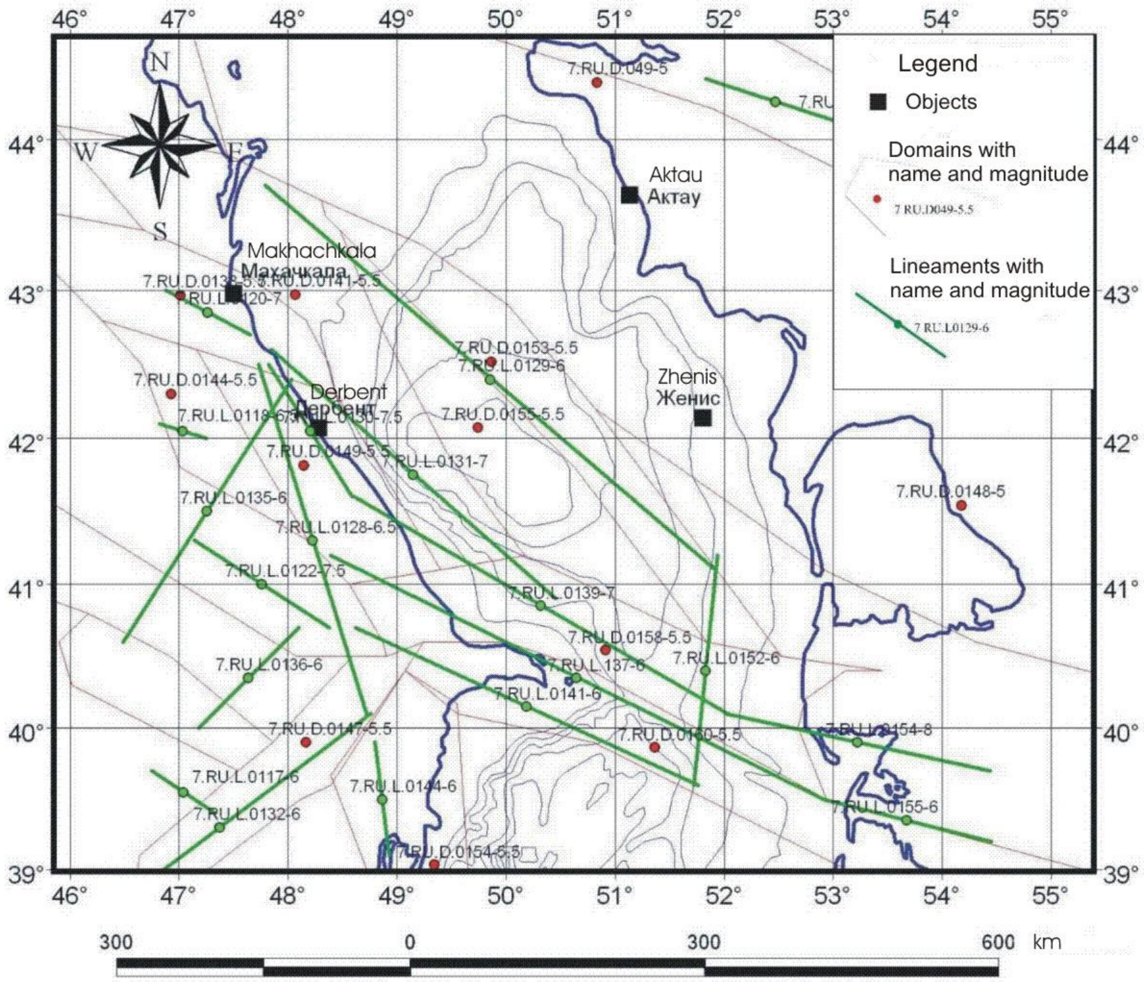

Figure 1: *Lineament-domain-focal model of seismic hazardous zones of the Middle Caspian Sea, which is the basis for seismic hazard calculations under the Global Seismic Hazard Assessment Program Project [27], refined in accordance with [19]*

The recurrence curves for this model are shown in Fig. 2 (lineaments). They are nonlinear relationships between the decimal logarithms of the number of earthquakes occurring over a period of one year within the specified PES zone (lineament or domain) and the magnitude of the earthquake. The plots are constructed using the database of the Global Seismic Hazard Assessment Program Project [27] with refinements in accordance with [11,12].

In this work, we used the models of attenuation of SA (T, 5%) acceleration response spectra for the simplest oscillatory systems modeling the response of individual elements of complex structures to seismic effects - linear oscillators with 5% attenuation. For each spectral period T of ground oscillations, a separate dependence of the response spectrum on the magnitude M and the distance R to the observation point is required. Values of M: from 4.0 to 8.0 in steps of 0.5; values of R: from 1 km to 1024 km to the observation point. These models were developed from databases of strong ground motions recorded from earthquakes with foci in the Earth's crust (H<=35 km) occurring in tectonically and, therefore, seismically active regions of the globe. Among the initial data were records of earthquakes in Turkey, Iran, Caucasus (Spitak), Central Asia. The Caspian Sea region also belongs to tectonically active regions of the globe, and the main hazardous events here are earthquakes with foci in the Earth's crust. Therefore, the applicability of these attenuation models in this case can be considered justified. The used models [1,2,4, 7] are shown in Fig. 3.

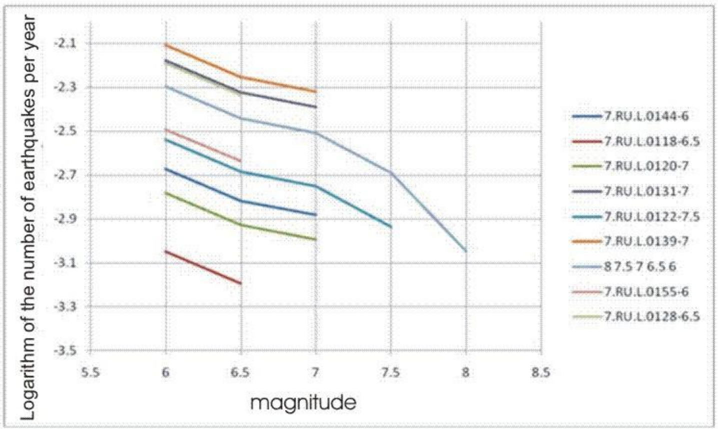

Figure 2: *Earthquake recurrence curves for earthquake dangerouse lineaments of the Middle Caspian Sea and adjacent land areas*

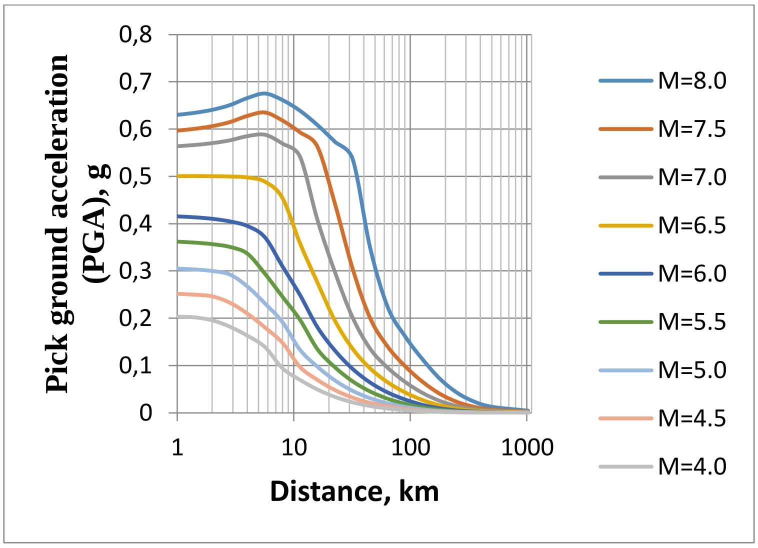

Figure 3: *Models of peak ground acceleration attenuation (PGA, g) as a function of distance*

The performed calculations have shown that for average soils of the Zhenis site for the design-basis earthquake (DBE, recurrence period 5000 years) seismic shaking intensity is 0.2 g in terms of PGA (peak horizontal ground acceleration) or 8 points in terms of seismic shaking intensity in MSK-64 scale points, which practically coincides with the data of OSR-97C map.

For the operating-basis earthquake (OBE, 500-year recurrence period), the seismic shaking intensity is 0.075 g in terms of PGA (peak horizontal ground accelerations) or 6.55 in terms of seismic shaking intensity in MSK-64 scale points, which is 0.45 points below the value shown on the OSR-97A map.

Various methods exist for modeling the nature of expected ground motions at the site under investigation. One of the most useful methods for design purposes is the method of calculating synthetic (artificial) accelerograms, velocigrams and seismograms whose response spectrum coincides with the design one.

In this work, we used the method proposed in [25] to calculate the ensemble of the most probable expected accelerograms for the area of the Zhenis well site. The method is based on the summation of a Fourier series consisting of sinusoidal oscillations with amplitudes varying according to the lognormal law, both in time and frequency, and with random phases uniformly distributed in the interval [0, 2π].

Fig. 4 shows the response spectrum with 5% attenuation calculated with the SEISRISK III program for a recurrence period of 5000 years assuming that the Zhenis site is composed of soils of II category according to SNiP II-7-81* (Russian Standard), as well as the average statistical response spectrum constructed from an ensemble of 10 synthetic accelerograms. This ensemble of accelerograms (Fig. 5) corresponds to the design-basis earthquake (DBE) - close seismic events with magnitudes MLH=5.5 occurring at a distance of 5 km from the site. Both spectra are close to each other. The difference does not exceed 10%.

The performed calculations have shown that for average soils of Zhenis site for the design-basis earthquake (DBE, recurrence period 5000 years) seismic shaking intensity is 0.2 g in terms of PGA (peak horizontal ground acceleration) or 8 points in terms of seismic shaking intensity in MSK-64 scale points, which practically coincides with the data of OSR-97C map. For the operating-basis earthquake (OBE, recurrence period 500 years) intensity of seismic shaking makes 0.075 g in terms of PGA (peak horizontal ground acceleration) or 6.55 points in terms of intensity of seismic shaking in MSK-64 scale points, which is 0.45 points lower than the value specified in OSR-97A map. The SEISRISK III-calculated spectra of initial seismic shaking for medium soils with 5% attenuation (red curve in Figure 4) and synthetic accelerograms modeling the initial seismic shaking were further used for SMZ purposes.

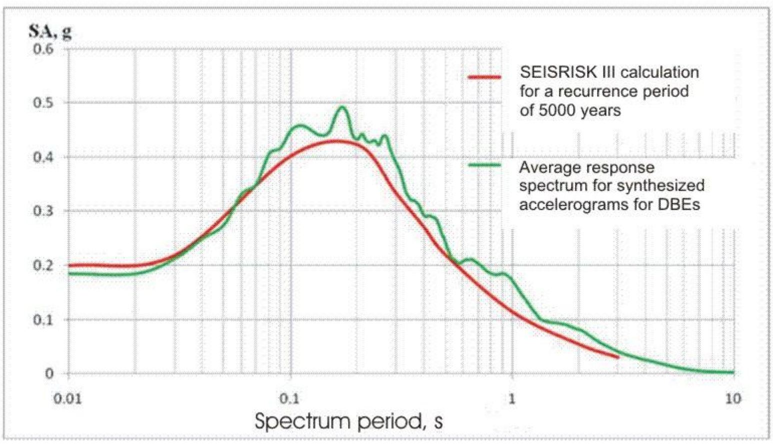

Figure 4: *Reaction spectrum with 5% attenuation calculated using the SEISRISK III program for the recurrence period of 5000 years and the average statistical reaction spectrum constructed from an ensemble of 10 synthetic accelerograms of the corresponding DBEs*

III. Seismic microzonation

For the purposes of seismic microzonation of the Zhenis site seafloor ground models were developed using high-resolution seismic data from the HR MRW CDP seismic survey and drilling data (Fig. 6).

The HR MRW CDP seismic record obtained in the study area is divided into two parts corresponding to the Cenozoic and Mesozoic stages of sedimentation.

The upper part of the section (interval - 50÷1000 ms, the most interesting for SMZ purposes), corresponding to the Cenozoic sediments (Quaternary, Pliocene-Quaternary, Miocene and Maikop), is characterized by parallel-layered, rather high-frequency record with numerous extended reflecting horizons (Fig. 6).

Within the Quaternary seismic complex, there is an intense reflecting horizon A, corresponding to the roof of the Apsheron sediments (the crimson-colored line in the section shown in Fig. 6.1). This seismic horizon can be traced throughout the Caspian megabasin. In the central part of the megabasin it lies conformally with the overlying and underlying boundaries, in the lateral parts it is distinguished as a shear surface with elements of roof adjoining the lower boundaries. The horizon is traced over the whole area in the record interval of 163-172 msec.

The bottom of Quaternary sediments is marked at the level of 186÷197 msec. The B horizon corresponding to this boundary is traced on the temporary sections (light green color line in Fig. 6).

Several types of seismic geologic sections were developed.

● Cross-sections to a depth of 35 m from the seafloor, constructed from longitudinal seismic wave velocity data and recurrence relations linking longitudinal and transverse seismic wave velocities in the upper layer of bottom sediments. These are the Mudrock Line equation [7], and the Boore relations [8], which relate seismic wave velocities in sediments and rock densities.

● Cross-sections to a depth of 35 meters from the seabed, based on seismic and drilling data. The latter were used for reconstruction of the upper (15 m) part of the section.

● Cross-sections constructed to a depth of 140 m for a deep well using drilling data for the upper part (74 m) and seismic data to a depth of 140 m (Fig. 7).

SMZ calculations to take into account the influence of bottom soils on seismic parameters were performed using two different methods: the seismic rigidity method and the calculation method using the NERA program [5].

The NERA calculation for the section developed to a depth of 140 m at the location of the deep borehole gave A_{max}=0.215 g or 8.08 points of MSK-64 scale. This calculation for this section using the NERA program was performed in accordance with the recommendations of STO 95 12022-2017 (Departmental Standards of Rosatom State Corporation). For the section to a depth of 35 m, these values were higher: A_{max} = 0.253 g and 8.31 points in seismic shaking intensity values on the MSK-64 scale.

The calculations of grade increment by the method of seismic rigidity were performed using two relations.

1. S.V. Medvedev's formula:

$$\Delta I = 1.67\log(R_{ref}/R_i), \quad (1)$$

where R_{ref} is the seismic rigidity of the reference soil, R_i is the seismic rigidity of the investigated soil. ($R=V_s\times\varrho$, V_s – shear wave velocity, ϱ – density of the rock or ground). It was used to process the section constructed to a depth of 35 m.

2. Formula from the current SMZ norms SP 283.1325800.2016 (Russian Standard):

$$\Delta I = 2.5\log(bR_{ref}/(R_i+R_{ref})) \quad (2)$$

where R_{ref} is the seismic rigidity of the reference soil (V_s>800 m/s, ϱ>2.5 g/cm^3), R_i is the seismic rigidity of the investigated soil, b is the maximum dynamic coefficient.

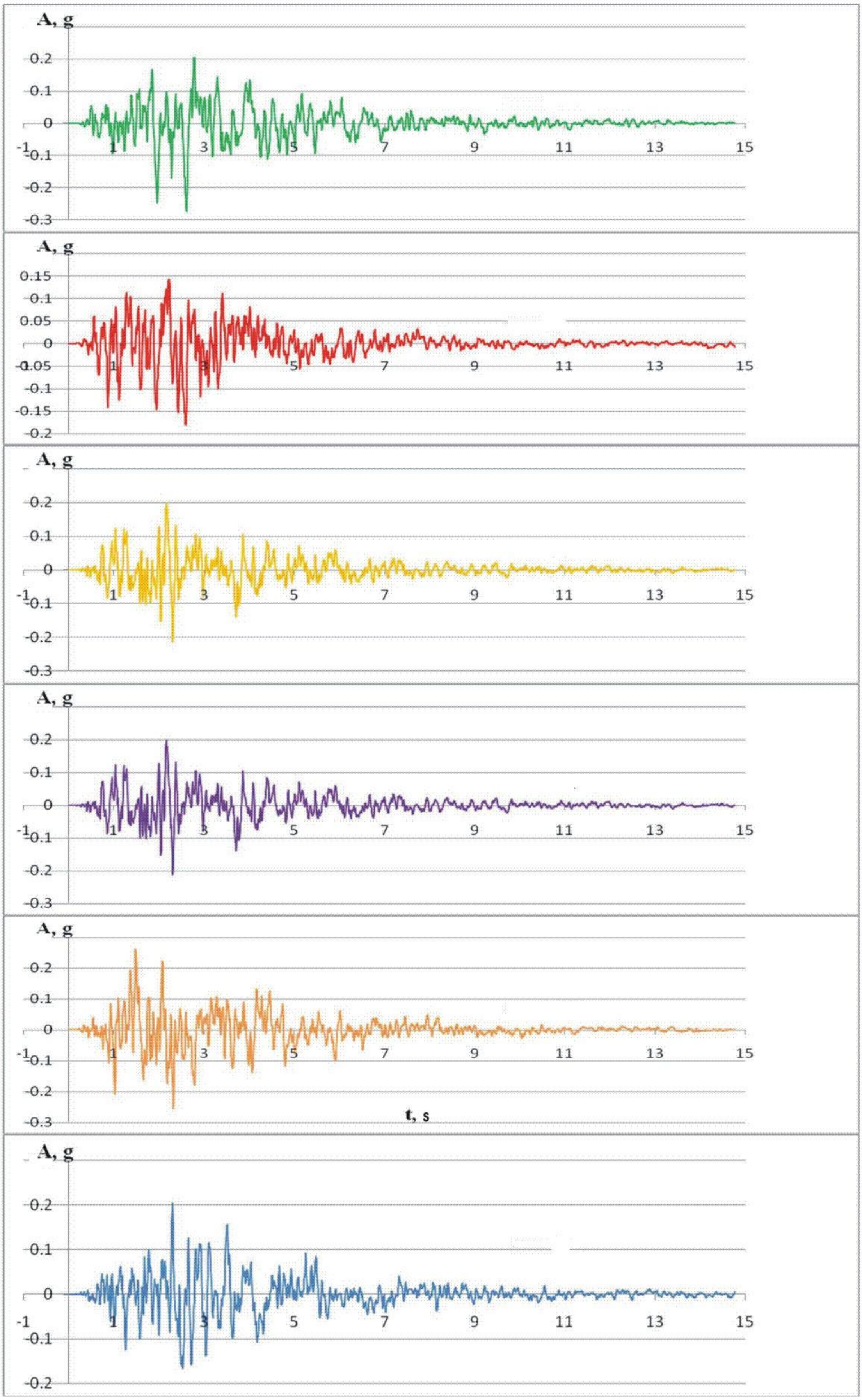
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Figure 5: *Examples of the ensemble of synthesized accelerograms for the design-basis earthquake (DBE) MLH=5.5, R=5 km*

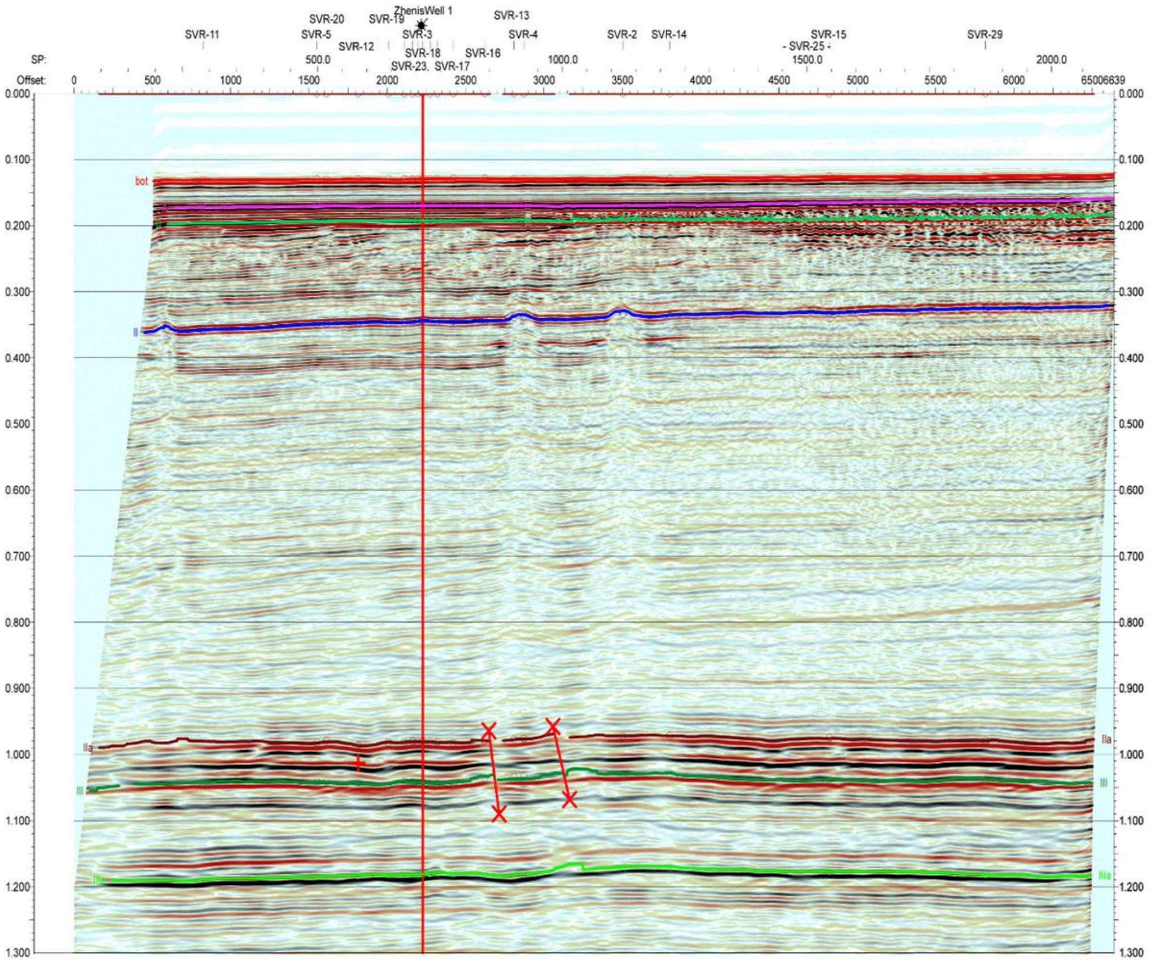

Figure 6: *Time section along the profile passing through the well at the Zhenis site*

Formula (2) was used to calculate the grade increment for the deep cross-section (140 m) in accordance with the guidelines of SP 283.1325800.2016 (Russian Standard). The use of these two formulas yielded the following values of the pointness at the bottom soil surface: for the 35 m cross-section A_{max} = 0.236g, I = 8.208; for the 140 m cross-section and the formula from SP 283.1325800.2016 A_{max} = 0.275 g, I = 8.430. The discrepancies in the results of using different calculation methods can be explained by the fact that all the above approaches to calculating seismic impact parameters to account for ground conditions have been developed for land. They need to be verified by in situ measurements on the seafloor using bottom seismographs and records of remote and local earthquakes. Such studies are very rare, but their necessity is evident for both SMZ and DSZ purposes. Examples of seismological monitoring and DSZ at sea are given in [10-15, 18, 21-23].

A total of 18 such cross-sections were constructed, which were further used for calculations using the NERA program to determine seismic parameters on the seafloor surface in the southwestern part of the Zhenis site.

The distribution of the calculated seismic parameters over the study area is shown in Fig. 8 and 9 for the design-basis earthquake (DBE).

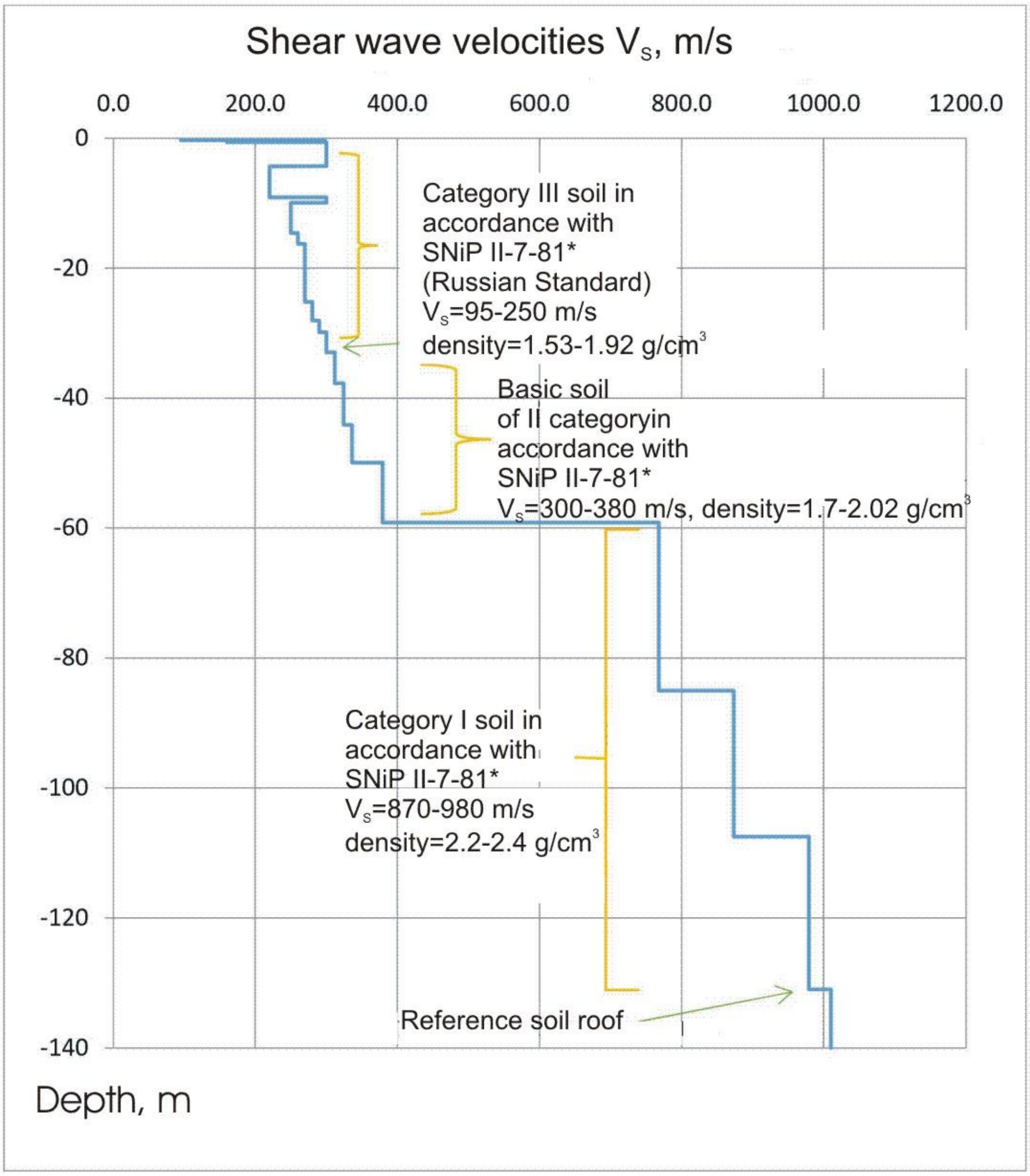

Figure 7: *Seismogeologic cross-section for the well obtained from drilling data to a depth of 74 m and seismic data from CDP reflection waves to a depth of 140 m*

Thus, the results of seismic zoning of the Zhenis site, obtained by two different methods and different input parameters: the method of seismic rigidity and the computational method according to the NERA program with cross-sections constructed solely on the basis of seismic data and cross-sections constructed with the involvement of geotechnical data, showed insignificant differences in the values of seismic effects on the ground surface.

In addition, it is necessary to point out the following circumstance: from Fig. 10 it can be seen that the spectrum on the surface of bottom sediments, calculated without taking into account real soil conditions, significantly differs in shape from the spectrum calculated taking into account geotechnical data. Although the amplitudes of maximum accelerations in both cases practically coincide. Perhaps the spectrum acquires a resonant shape due to the presence in the section of a layer of very soft clays up to 9 m thick, which is detected by drilling and not found by seismic methods. Or it is necessary to take into account the properties of bottom sediments according to the methods described in the works [17, 20].

VI. Conclusion

The performed calculations have shown that for average soils of the Zhenis site for the DBE seismic shaking intensity is 0.2 g in terms of PGA (peak horizontal ground acceleration) or 8 points in terms of seismic shaking intensity in MSK-64 scale points, which practically coincides with the data of OSR-97C map.

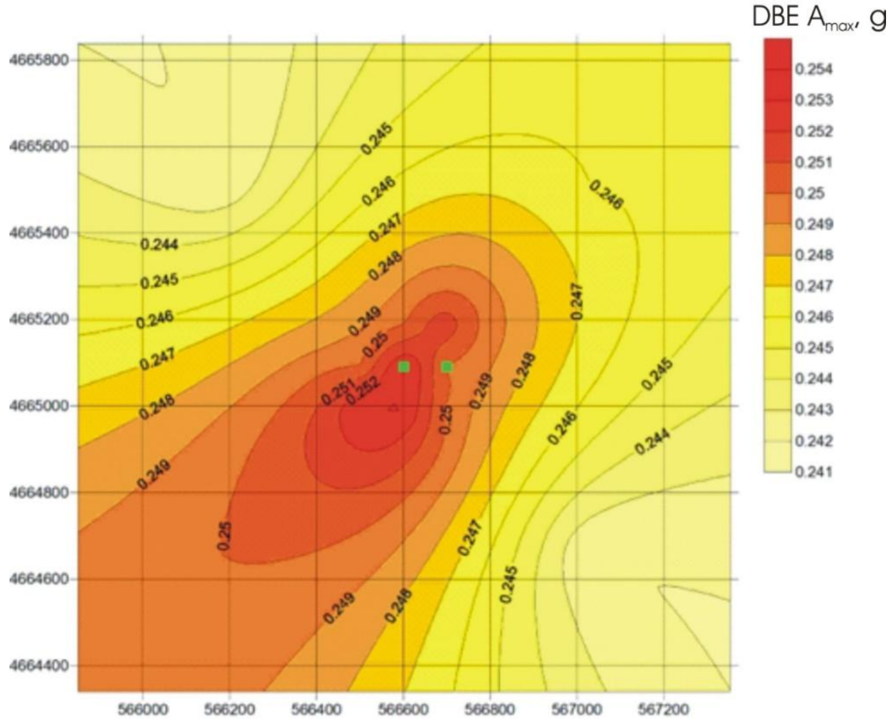

Figure 8: *Distribution of the amplitude of the maximum acceleration of the bottom soil A_{max} in fractions g in the southwestern part of the Zhenis site. Well locations are shown in green boxes*

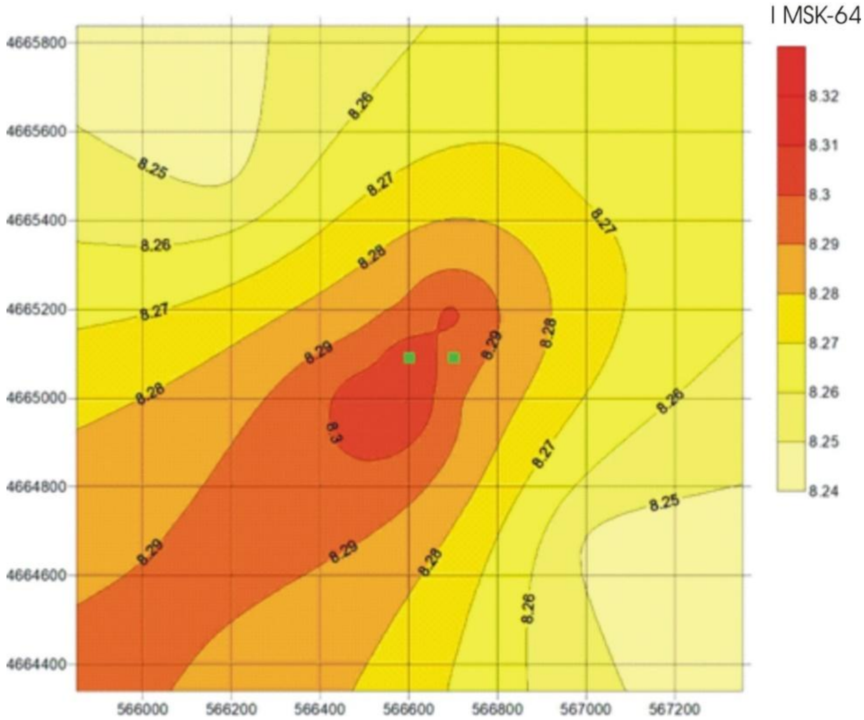

Figure 9: *Distribution of seismic impact intensity on the bottom soil surface in MSK-64 scale points in the southwestern part of Zhenis site for SSE. Well positions are shown in green squares*

The SMZ calculations to take into account the influence of bottom soils on seismic parameters were performed using two different methods: the method of seismic rigidity and the calculation method using the NERA program [4]. For the first method, seismogeological sections constructed to a depth of 35 m using seismic data were used.

For the calculation method, geotechnical cross-sections were also used. All calculated seismic parameters, taking into account the influence of bottom soil, were plotted on the SMZ maps.

A NERA calculation was also performed for a cross-section developed to a depth of 140 m at the BHV well location. This calculation showed that the amplitudes of the maximum accelerations A_{max} are smaller than A_{max} calculated from the section to a depth of 35 m: 0.215 g and 0.253 g for the maximum design earthquake. These values are 8.08 and 8.31 points in the values of seismic shaking intensity on the MSK-64 scale. All this is true for the DBE.

This is not the case with the of operating-basis earthquake OBE. The A_{max} for the OBE plotted on a cross-section to a depth of 140 m is 0.1 g or 7 MSK-64. For another cross-section plotted to a depth of 35 m, the A_{max} is 0.073 g or 6.69 MSK-64.

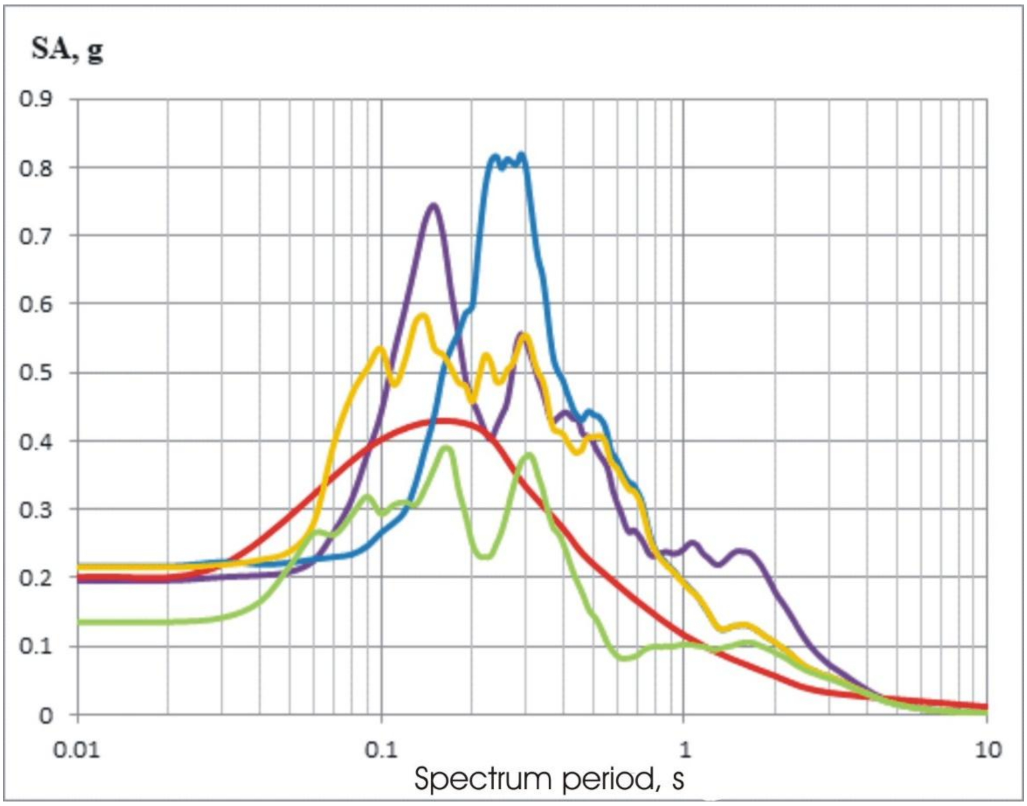

Figure 10*: Seismic response spectra with 5% attenuation for the Zhenis site for DBE. Red curve - initial seismic impacts, green curve - seismic response spectrum on the roof of Apsheron sediments (roof of basic soils); yellow curve - spectrum on the surface of the bottom soil of the well (74 m), calculated on the basis of the cross-section constructed without taking into account geotechnical data at the depth of 35 meters; blue curve - the same one for the section built with geotechnical data, purple curve - the same one for the section with geotechnical data built at a depth of 140 m to the reference soil roof*

This effect can be explained by the fact that for a OBE, seismic impacts are less intense than in the case of DBE. Therefore, the seismic signal is less affected by the non-linear properties of the ground, which weaken its amplitude.

For the OBE for the BHV borehole on the bottom soil surface of the Zhenis site, the maximum acceleration value A_{max}= 0.1 g or IMSK=7 MSK, as more conservative values, should be assumed for the OBE.

The results of using the seismic rigidity method were very close to the results obtained by the computational method.

Methods for assessing the potential for bottom liquefaction show a non-zero probability of this occurring. However, the burial of the anchors in the case of a semi-submersible drilling rig, or of the platform supports

in the case of a jack-up drilling rig, reduces this probability to zero. To the southeast of the Apsheron sill, a lineament structure can be traced, where earthquakes with M = 8 can occur, which, according to L. I. Lobkovsky's ideas, generates decomposition of gas hydrates.

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