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Analysis of Changes in the Seismic Regime at Engineering Facilities Under the Influence of Natural and Man-made Factors

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Abstract: The experience of studying the consequences of strong earthquakes indicates that intensity and type of seismic effects are determined by local features of the geological environment, which can change over time under the influence of natural and man-made factors. The results of long-term systematic experimental studies on the study of changes in seismic conditions over time in the soil complexes of the Imereti lowland and the site of the Balakovo NPP are presented. This made it possible to carry out long-term forecasting of changes in seismic conditions during economic development of territories.

Keywords: seismic microzonation, seismic properties, seismic forecast, calculated accelerograms, man-made changes.

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1. Introduction

In the seventies, the problem facing engineering geology was formulated — the need to take into account the role of exogenous processes and engineering and economic activities in space and time [*Sergeev et al.*, 1974]. In particular, it was noted the need to develop methods for forecasting and combating the disturbance of the natural balance in the Earth's crust under the influence of anthropogenesis. This task has been given attention by many seismological researchers when considering the problem of seismic microzonation (SMZ) [*Aleshin*, 2010; *Dzhurik et al.*, 1988; *Krieger et al.*, 1994; *Wight*, 1974; *Zaalishvili*, 2009] and others]. In [*Dif et al.*, 2018; *Johnson et al.*, 2020; *Mindel et al.*, 2003; *Prasad*, 2011] the features of the seismic properties of dispersed soils and the manifestation of the seismic effect on them were studied. In [*Kapustyan et al.*, 2007; *Mindel et al.*, 2005; *Pavlenko*, 2005], the consequences of man-made impacts on changes in seismic conditions at a number of nuclear power plants and urban areas were considered in details. Let us note the work [*Ozmidov*, 2014] devoted to the influence of ground conditions on the characteristics of vibrations on the surface using the example of Sochi. The study and assessment of the risk of seismic liquefaction of the geological base of the Olympic facilities sites in Sochi was carried out in the paper [*Bardet et al.*, 2001].

The purpose of this article is to show how the seismic properties of dispersed soils at the base of buildings and structures have changed over time under the influence of engineering activity. And as a result of these changes, to investigate and evaluate the magnitude of the seismic effect on them. The possibility of improving seismic conditions using engineering training methods was also considered. These studies are illustrated by the example of the Imereti lowland (Sochi area) during the construction and operation of

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Olympic facilities, as well as by the example of the Balakovo NPP for more than 35 years of its existence.

2. Materials and methods

The author's analysis was based on the results of engineering, geological and seismic studies conducted during different observation periods. The research results served as the basis for the construction of seismic models. Accelerograms, amplification factor graphs $\beta(T)$, and amplitude-frequency response characteristics were calculated using these models using the well-known programs NERA [*Ratnikova et al.*, 1967] and COEF-9 [*Aleshin*, 2015; *Ratnikova*, 1984]. Methods of engineering and geological analogies and seismic rigidities were used to build maps of seismic microzoning (SMZ) [*Aleshin*, 2010; *Detailed seismic zoning…*, 2019; *Ulomov et al.*, 1999].

3. Results and discussion

3.1. Analysis of changes in seismic conditions in the Imereti lowland (Sochi)

Based on the GSZ-97(OCP-97) database for the Sochi region, V. I. Ulomov [*Balabanov*, 2010; *Ulomov*, 2005] performed a probabilistic analysis of seismic hazard in the parameters of seismic intensity (I) in the MSK-64 scale and peak acceleration values (in $\mathrm{cm/s^2}$) for various periods of earthquake recurrence on soils of category II according to seismic properties. The results of earlier tectonic and seismological studies conducted in 1998–2000 by a team of PNIIIS[1] specialists (V. N. Averyanova, I. I. Barkhatov, S. A. Nesmeyanov, A. I. Lutikov, L. S. Shumilina et al.), potential earthquake foci (PEF) zone scheme was drawn up for the Sochi area on a scale of 1:1,000,000 with the Sochi and Sukhumi PEF zones most dangerous for the territory under consideration. They correspond to the two lineaments that are most dangerous for the Sochi region from the OSR-97 database according to [*Ulomov*, 2005]. Based on these studies, the authors synthesized initial accelerograms for the near “Sochi” and remote “Sukhumi” PEF zones for calculations. At sites where Olympic facilities are located, it is necessary to take into account the features of the geological structure not only of the upper 30-meter soil layer, but also of the entire low-velocity Quaternary sediments [*Averyanova*, 1985; *Balabanov et al.*, 2011]. The geological structure of the Imereti lowland, with its thickness (up to 100 m) and horizontal stratification, have a major impact on the amplitude level and frequency composition during seismic vibrations on the daytime surface.

In the late 80th, the territory of the Imereti lowland (the site of the future Olympic facilities) was an artificially irrigated state farm fields. The soils of the territory under consideration were classified as category III in terms of seismic properties [*Averyanova*, 1985; *Balabanov et al.*, 2011]. The maximum acceleration values calculated by authors according to COEF-9 program were: from close dangerous zones of potential earthquake foci (PEF) (Sochi) Amax = 450 $\mathrm{cm/s^2}$; from the far Sukhumi PEF zone Amax = 465 $\mathrm{cm/s^2}$ [*Balabanov*, 2010; *Ozmidov*, 2014]. Based on the results of geophysical research in 1986–1996 SMZ map was constructed (1996), where most of the territory of the Imereti lowland was assigned to areas with seismic intensity I = 9 points.

11 years after the engineering preparation of the territory for construction (removal of swampy lagoon sediments), according to the results of research for the purpose of placing Olympic facilities, the SMZ map (2007) was compiled. The SMZ map of 2007 has changed compared to 1996. Compared with 1996, areas with soils of category II–III with seismicity I were allocated = 8.5 points and with Amax = 305–330 $\mathrm{cm/s^2}$ from the PEF close zones and Amax = 300–335 $\mathrm{cm/s^2}$ from the PEF Sukhumi zone. After 4–5 years, studies have shown a deterioration in soil properties under the influence of man-made factors as a result of intensive construction and operation of constructed structures. The studied soils of the II–III categories have become closer to the soils of the III category in terms of their seismic properties. According to calculations, the maximum acceleration values increased

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to Amax = 380 cm/s^2 (from close PEF zones) and Amax = 380–390 cm/s^2 (from the far PEF Sukhumi zone). On the 2014 SMZ schematic map (Figure 1), after the construction and operation of Olympic facilities, compared with the 2007 map, there was an increase in the territory with soils of category III and seismicity I = 9(9*) points.

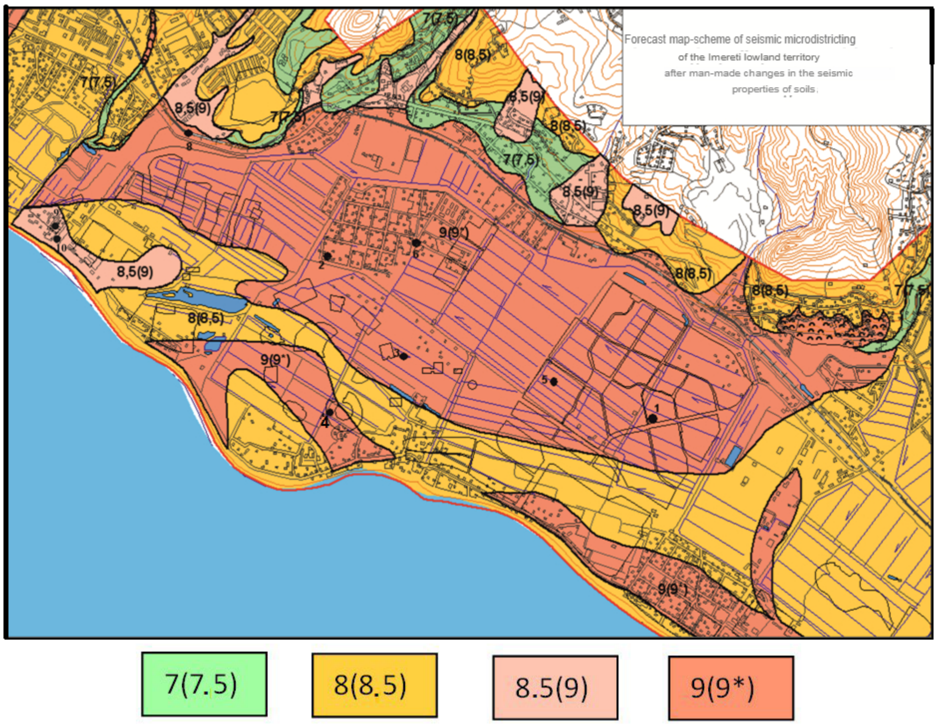


Figure 1. A schematic map of the seismic microzoning (SMZ) of the Imereti lowland territory after man-made changes in the seismic properties of soils (after research in 2010–2014) with bold dots indicating the locations of experimental engineering and geophysical research, indicating their numbers. Earthquake intensity values (I) in color zones with a recurrence of earthquakes 1 time in 500 years and intensity values in brackets with a recurrence of 1 time in 1000 years.

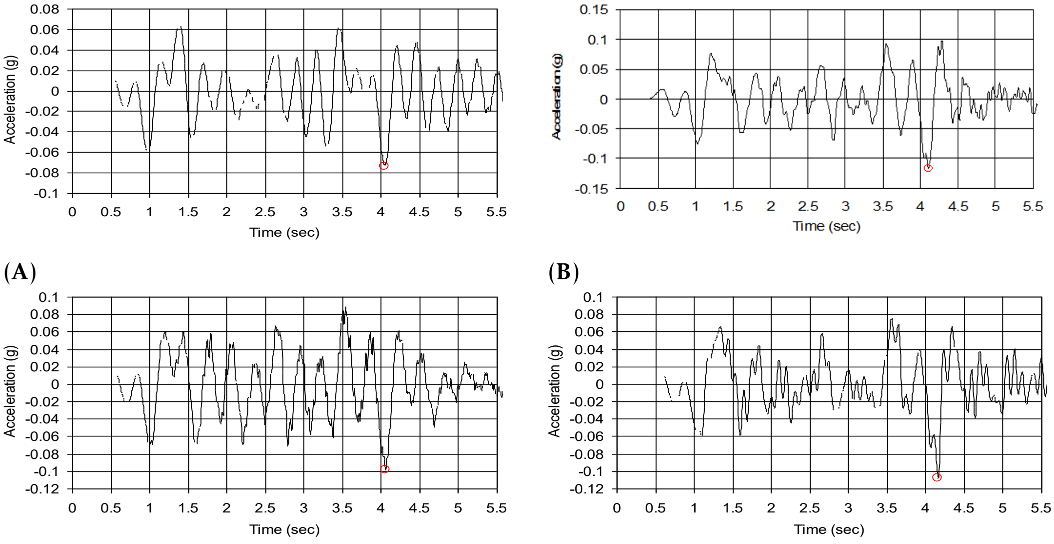
The results of studies of the seismic properties of soil complexes in various construction sites of Olympic facilities in the Imereti lowland, conducted before the start of construction in 2007 and after 4–5 years, showed changes in the initial seismic conditions due to the deterioration of the seismic properties of soils in the upper part of the section as a result of intensive construction and long-term operation of the constructed Olympic facilities.

For possible construction on soils of the III category of the Imereti lowland, experimental studies were conducted to assess the improvement of seismic conditions of the soils of the base under the foundations of structures by creating a pile field. The artificial massif created by a field of reinforced concrete piles on a grid of 2 × 2 m and 1.5 × 1.5 m increased the seismic rigidity of the massif and improved the seismic conditions of construction. Results of calculation of accelerograms on typical soil complexes composing most of the Imereti lowland, according to the COEF-9 program show a tendency to decrease the Amax values and improve the seismic properties of the base soils when pile fields are created in them (research sites No. 1, 2, 3, 5, 6 and No. 4, where the risk of seismic soil liquefaction is possible). Similar results we obtained when calculating using the NERA code. The values of Amax accelerations decreased by 25–30% from close PEF zones and by 10–14% from earthquakes from the far PEF Sukhumi zone.

3.2. Analysis of changes in seismic conditions on the territory of the Balakovo NPP over more than 35 years of its operation

The Balakovo NPP was built on the left bank of the Saratov reservoir in the area of the junction of large geostructures of the East European Platform: Caspian Depression, Volga-Ural and Voronezh anteclises, Pachelma aulacogen, and Volga dislocation system [*Ogadzhanov et al.*, 2009]. The base of the NPP is Cenozoic (Q, N, Pg), sandy-clay strata underlain by Cretaceous carbonate deposits.

The engineering-geological and seismic situation as a result of the manifestation of man-made human activity at the NPP site has been changing since 1980. (the beginning of the design) for 2004–2010 (construction of power units) and in 2019 (after 9 years of NPP operation). After leveling the construction site to the planning mark of 34 m, the natural dense soils were replaced with man-made backfilling (tQIV) of the III category according to seismic properties. The initial seismic conditions of the territory deteriorated (Figure 2A and B). When calculating using the NERA program, an accelerogram (horizontal VS component) borrowed from the materials of OJSC "Atomenergoproekt" in 2010 for the Balakovo NPP with Amax = 0.057 g was set as the input signal at the boundary of the elastic half-space (Cretaceous limestone roof at a depth of about 140 m). Four our calculations of the accelerogram set on a conditional rock base on the surface (calculations A, B, C, D) were performed.



(A) **(B)**

(C) **(D)**

Figure 2. The results of our calculation of accelerograms for Balakovo NPP site using NERA code [*Bardet et al.*, 2001]: model A — before the start of construction in 1978–1980 on the surface of the site at the initial natural state of the soil, Amax = 0.073 g; model B — after the engineering preparation of the territory in 2004–2010 on the surface at the planning mark of 34 m, Amax = 0.116 g.; model C — on a free surface next to power unit No. 5, a section with waterproofing side clay locks and a crushed stone cushion on which the foundation rests in 2012, Amax = 0.098 g; model D — in the same place in 2019, Amax = 0.108 g.

The deterioration of the initial seismic conditions (Figure 2A) after the preparation of the construction site (Figure 2C) caused the need to lay slabs with a 4-meter rubble cushion of compacted soils (dolomite rubble) at the base of the foundations of the Main Building with the engine room and reactor compartment (RC). Together with the water reduction and the device of clay locks, this made it possible to reduce the Amax value to 0.098 g (Figure 2C). There was a decrease in the values of accelerations relative to the surface by 16% (observations in 2012). 7 years after the start of operation of the RC power unit No. 5 of the study in 2019 showed a deterioration in the properties of the crushed stone cushion, which manifested itself in a change in the Amax values over seven years, respectively, from 0.098 g (Figure 2C) in 2012 to 0.108 g (Figure 2D) in 2019 (decrease in Amax relative to the surface was reduced to 7%).

The calculated accelerograms shown in Figure 2 for models describing the condition of the soil mass at different time periods illustrate the changes that have occurred not only in the Amax values, but also in their shape. At the same time, the calculated spectral characteristics have also changed — frequency response and amplification factor graphs $\beta(T)$ (Figure 3). The technogenic rise of groundwater level (GWL) and the destruction of clay locks affected the partial dissolution and swelling of the gravelly soils of the foundation cushion under the slab, which led to a deterioration of seismic conditions and further disruption of the stability of the bearing capacity of the foundation slab. Figure 3 below shows the change in the frequency response and the amplification factor graphs $\beta(T)$ for different stages of research at the NPP site (models A, B, C and D).

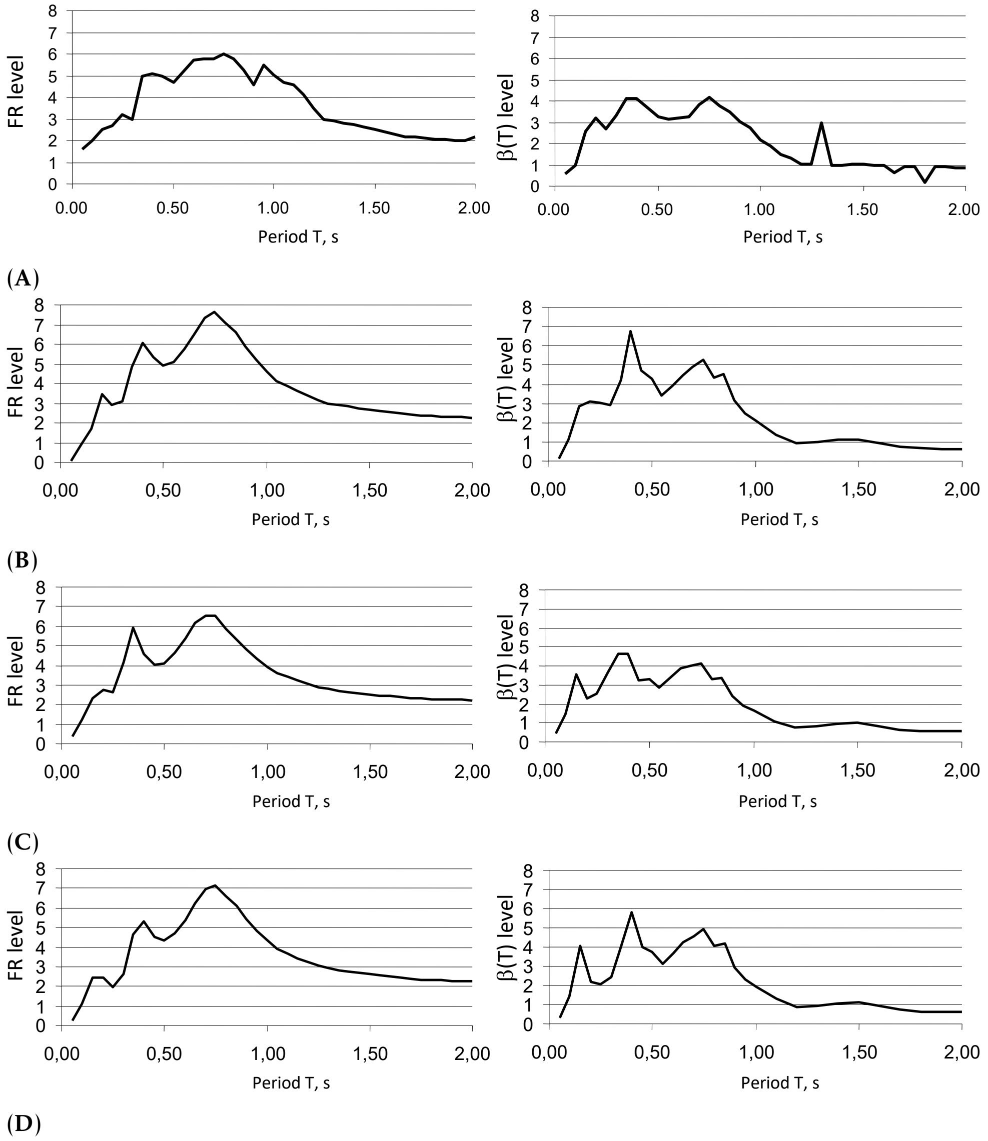


Figure 3. Calculated amplitude-frequency characteristics: FR-frequency response (left), according to COEF-9 and amplification factor graphs $\beta(T)$ (right), according to NERA on the surface site for different stages of research (see Figure 2).

The analysis allows us to assume a possible change in the engineering-geological and seismic conditions in the coming years, which may lead to a violation of the stability of the bearing capacity of the foundation plate, as well as to further deterioration of seismic conditions.

4. Conclusion

Systematic long-term studies of the seismic properties of soil complexes in territories affected by natural and man-made factors, such as the construction and operation of

Olympic facilities and Balakovo NPP, have shown how the seismic conditions of these territories has changed over time.

Based on the results of long-term research:

- a forecast map of the SMZ has been built on the territory of the Imereti lowland. It allows for long-term seismic forecasting during further urbanization of the territory of Sochi. It is shown that artificially creating an array of foundation soils using pile fields can significantly improve the seismic conditions of engineering and geological sections composed of category III soils in terms of seismic properties.
- changes in the seismic properties of soils have been shown at the Balakovo NPP site over more than 35 years of operation of previously built NPP power units and the construction of new ones, which make it possible to predict changes in seismic ground conditions.

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