RT&A, Special Issue No 5 (75)
Volume 18, November 2023

ON THE INFLUENCE OF SEISMIC INTENSITY IN A ROCK MASS IN THE DESIGN OF TRANSPORT TUNNELS

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Abstract

The results of experiments on simultaneous recording of seismic signals from various sources on the Earth surface and at a depth of up to 250 m are stated. The peculiarities of change with depth of the spectral composition of teleseismic earthquake and microseismic oscillations have been studied, which testify in favour of a significant decrease in the level of seismic effects on underground structures in a wide range of frequencies in relation to buildings and structures on the daylight surface.

Keywords: seismic intensity, earthquakes, underground structures, Earth surface

I. Introduction

In seismically hazardous areas, when designing transport tunnels, the materials consumption of supports and linings is greatly influenced by the level of seismic hazard. In many cases, accounting for the design seismicity requires a strong reinforcement of linings, which leads to a significant increase in the cost of construction.

At the same time, the consequences of earthquakes in the world show that underground structures do not suffer from destructive effects unlike buildings and structures on the Earth surface. Thus, in the 1985 Mexico City earthquake, more than 1,500 buildings and structures were damaged. The subway stopped working only on the day of the earthquake. As of the next day, the subway was operating, only 32 stations out of 101 stations were closed not because of damage to the subway itself, but because of emergency rescue work on the surface and debris removal.

Earthquakes in Japan show the appearance of flaws in parts of tunnels where the lining is unreinforced, while buildings and structures on the earth surface experience significant damage. The results of field studies of the impact of earthquakes on underground structures [1-7] in Japan, China, Taiwan and other countries indicate that the seismic intensity in the tunnel is less than on the Earth surface.

Studies of the consequences of earthquakes on the Circum-Baikal railway [8] have shown that earthquakes that occurred in the Baikal rift zone affected the integrity of frame-type galleries, tunnel-type galleries and near-portal sections of tunnels up to 10 meters deep. No violations were recorded in other sections of the tunnels.

The currently practiced methods of seismic microzoning (SMZ) already have theoretical prerequisites and methodological guidelines that make it possible to assess how much the level of seismic impacts will decrease in points if they are calculated not on the surface, but at some buried point. In particular, the seismic impedance method is based on the concept of the difference between the seismic properties (transverse wave velocity and rock density) of soils at the surface and some reference (benchmark) soils, which are usually classified as Category I in terms of seismic properties. In practice, soils that are close in their properties to the reference ones (rigidity R=2000 t/(m2·s) according to SP 283.1325800.2016) are usually found at a certain depth, which gives grounds to consider the seismic intensity for them on average 1 point lower than for soils of category II, most often found on the surface.

Other SMZ methods (method of earthquake recording or microseism) also theoretically allow obtaining grade increments for soils at depth, but in reality all field observations are always carried out on the soils accessible on the earth surface and the SMZ results are brought also to the earth surface.

It is important to note that all SMZ methods focused on obtaining intensity increments in points provide only a limited opportunity to see how the spectral composition of impacts can change. According to RSN 65-87, there are three intervals of periods (0.1-0.3 s, 0.3-0.5 s and 0.5-2 s) for which it is necessary to determine the score. However, this approach allows only indirectly taking into account the influence of different-frequency oscillations on seismic intensity, because the determination of the frequency characteristics of soils still occurs from the surface.

The present paper is aimed at obtaining the initial data, allowing getting a real and only true idea of the change of seismic vibrations with depth when they affect soils at different depths. For this purpose, synchronous measurements of seismic vibrations on real objects (adits, boreholes, tunnels) were specially organized. Waves from teleseismic earthquakes and microseismic oscillations were used as signals. It is expected that microseisms, when compared to results based on earthquake recordings, will provide similar results in a shorter time frame because they are recorded at any time.

II. Research at the test sites

A significant part of the data on earthquakes was obtained at the test site of the Geophysical Service of the Russian Academy of Sciences in Obninsk, where, in addition to the surface instrument, one was located in an adit at a depth of 30 m, directly below point on the earth surface. Broad-band seismometers TC-120 (Nanometrics) with a natural period of 120 s were used in the experiment. Recordings were made over 4 months (from April to July 2023) with 100 Hz digitisation (frequency range 0.008 to 40 Hz). Similar data were also obtained earlier in the period from 2012 to 2022 on numerous tunnels in the area of Sochi, where there was a difference in height between the measuring points from 50 to 250 m.

Observations in adits and wells are more representative, since they are long-term and, moreover, allow analyzing data along with information about the deep structure. These objects are well studied and there are both lithological columns and a known velocity profile for them.

In total, several hundred teleseismic earthquakes were recorded at the Obninsk test site during the entire observation period. For processing, 14 records from earthquakes with a magnitude of mb≥6 were selected (Table 1).

There is a sedimentary layer of rocks with a thickness of 30 m between the two instruments on the test site. Information about the seismogeological model for the near-surface rock mass to a depth of 40 m is given in Table 2 and in Fig. 1.

An example of one of the records of a strong earthquake near the East coast of Kamchatka on April 18, 2023 (M=6.4, epicentre distance 6824 km) (Fig.2) demonstrates how strongly the oscillations recorded in one set at different levels from the earth surface differ. Since the analysis involved predominantly strong and only teleseismic earthquakes, they quite representatively cover the frequency range from 0.5 to 10 Hz used in estimating seismic intensity increments. The equipment used in this frequency range does not introduce distortion.

Table 1: *Catalog of registered earthquakes*

Item	Time [UTC]	Width, degrees	Longitude, degrees	Depth, km	mb	Region
1	04/14/2023 09:55 AM	-6	112.05	600	6.5	Java Sea
2	04/15/202315:01 PM	-33.84	56.17	10	5.8	Southwest Indian Ridge
3	04/18/202302:40 AM	54.15	159.79	120	5.9	Eastern coast of Kamchatka
4	04/18/2023 04:31 AM	-22.33	179.41	580	6	South of the Fiji Islands
5	04/21/2023 10:21 AM	2.75	127.12	33	6.2	North of the Molucca Sea
6	04/22/2023 08:23 AM	-5.32	125.51	33	6.0	Banda Sea
7	04/24/2023 00:41 AM	-30.06	-177.84	50	6.9	Kermadec Islands, New Zealand
8	04/24/2023 20:00 PM	-0.59	98.68	10	6.5	South Sumatra, Indonesia
9	04/28/2023 03:13 AM	-25.35	178.69	600	6.4	South of the Fiji Islands
10	05/10/2023 16:02 PM	-15.45	-174.59	210	6.6	Tonga Islands
11	05/18/2023 18:58 PM	34.95	24.29	15	5.6	Crete, Greece
12	05/19/2023 02:57 AM	-23.25	170.75	33	7.1	Southeast of the Loyalty Islands
13	05/19/2023 15:15 PM	12.74	49.09	10	5.8	East of the Gulf of Aden
14	05/20/2023 01:51 AM	-23	170.52	33	6.9	Southeast of the Loyalty Islands

Table 2: *Parameters of the seismic-geological model for the Obninsk test site*

Layer no.	Soil characteristics	Vp, m/s	Vs, m/s	Density, g/cm^3	Layer thickness, m
1	Top soil	305	178	1.75	2.3
2	Sand, loam	458	255	1.81	8.3
3	Hard-plastic loam, sand	475	284	1.83	4.8
4	Sand, loam	679	395	1.86	13.5
5	Limestone	1949	1129	2.52	∞

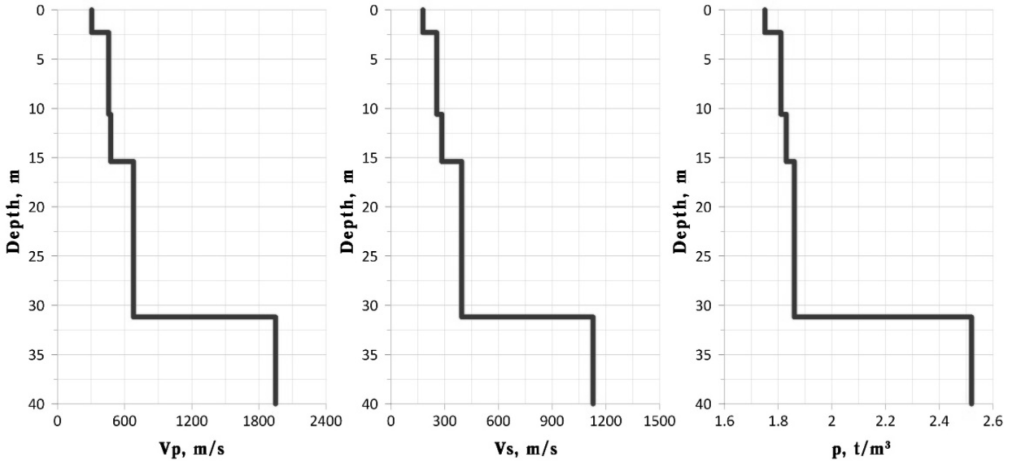

Fig. 1: *Velocity and density profile in the area of the adit in Obninsk to a depth of 40 m*

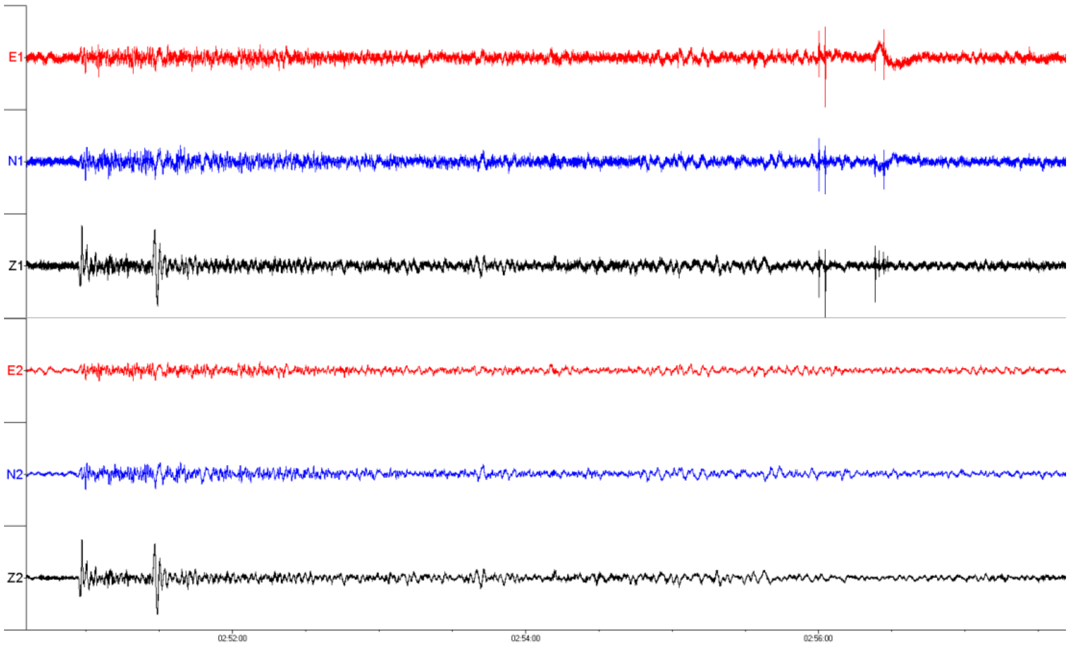

Fig. 2: *An example of teleseismic earthquake records obtained on the earth surface (three upper channels) and at a depth of 30 m (three lower channels)*

Fig.3 shows the results of calculations of the amplitude spectra for the displacement velocities of the horizontal E components recorded on the earth surface and in the adit. It can be seen that the level of seismic vibrations in the adit for the entire frequency range from 0.5 to 10 Hz is significantly lower. At the same time, with increasing frequency, the degree of difference between the levels of seismic vibrations increases.

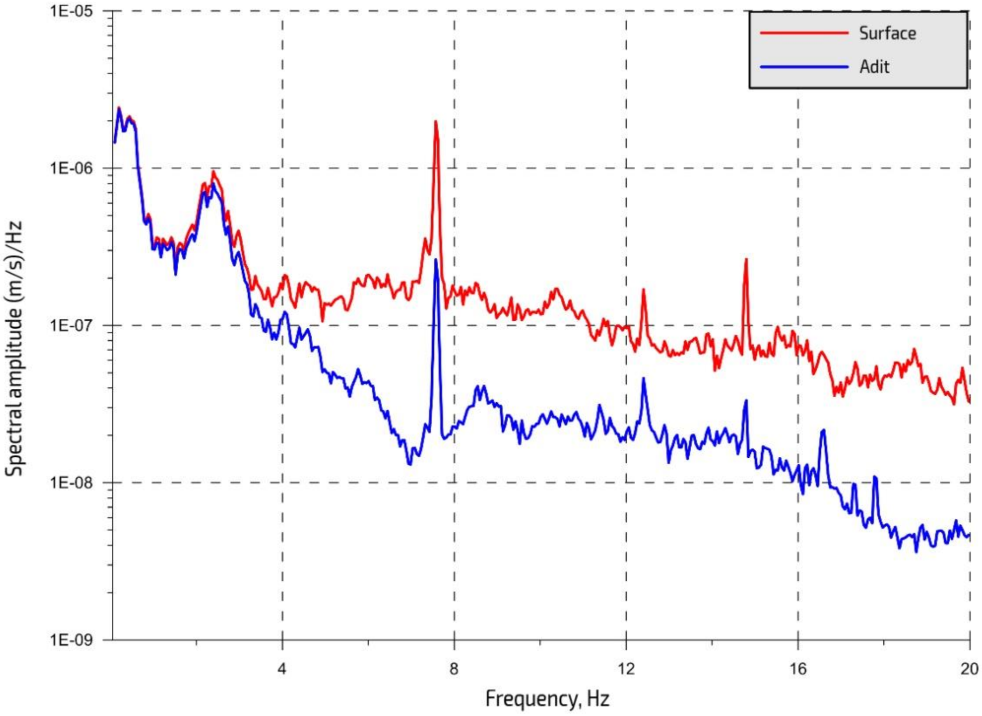

Fig. 3: *Comparison of the amplitude spectra of the records of the horizontal E component of the earthquake in Fig. 2, obtained on the earth surface (green curve) and at a depth of 30 m (red curve)*

For each record, calculations were made of the ratios of the spectral amplitudes measured on the surface (A_{sur}) and in the adit (A_{ad}), for all motion components. The measurement results are presented in Table 3. It should be noted that for the horizontal components, in general, there is a higher level of A_{sur}/A_{ad} ratios compared to the vertical component, therefore, the values presented in Table 3 characterise mainly the horizontal oscillations. The ratios calculated for different horizontal components differ to a lesser extent. The table contains data on those components where the highest A_{sur}/A_{ad} ratios were obtained. The average values for the horizontal components A_{sur}/A_{ad} for all events match reasonably well, especially at low frequencies. Variations do not exceed 0.7 % for low frequencies, 3.5 % for medium frequencies, and 27 % for high frequencies.

Table 3: *Ratios of spectral amplitudes of displacement velocities A_{sur}/A_{ad} for earthquakes (see Table 1)*

Record no.	Frequency range, Hz		
	0.5-2.0	2.0-3.3	3.3-10
1	1.22	2.27	8.62
2	1.22	2.29	6.11
3	1.23	2.38	6.58
4	1.23	2.25	8.67
5	1.22	2.27	6.46
6	1.22	2.24	7.99
7	1.22	2.29	6.09
8	1.22	2.37	6.04
9	1.23	2.35	6.32
10	1.22	2.26	6.87
11	1.22	2.33	5.68
12	1.23	2.27	6.41
13	1.23	2.26	6.82
14	1.22	2.31	5.45
Average	**1.22±0.01**	**2.30±0.08**	**6.7±1.8**

Similar measurements and calculations performed for weak microseismic oscillations give similar results (Table 4). In general, they completely repeat the estimates obtained earlier at the same object in 2013 [Malovichko, Pyatunin, 2013], and the differences between the results of different methods do not exceed 2 % for low frequencies, 9 % for medium frequencies, and 13 % for high frequencies. Relatively large discrepancies for high frequencies can be associated with the influence of local microseismic sources, which are not always possible to get rid of. Nevertheless, the values of the ratios themselves, even with such significant random deviations, are statistically significant (>3σ).

Table 4: *Comparison of the ratios of amplitudes of displacement velocities A_{sur}/A_{ad}, obtained by various methods*

Calculation option	Frequency range, Hz		
	0.5-2.0	2.0-3.3	3.3-10
Asur/Aad for earthquakes	1.22	2.30	6.72
Asur/Aad for microseisms	1.24	2.49	5.84

The amplitude ratios obtained can be further easily converted into seismic intensity increments. The conversion is performed using the following formula [RSN 65-87]:

$$\Delta I = k\frac{A_1}{A_0},$$

where instead of the ratio of amplitudes A_1/A_0 on the investigated and reference soils the ratio A_{sur}/A_{ad} was used, and the value of the coefficient *k* is taken as 2.5. The coefficient *k*=2.5 instead of *k*=3.3, adopted in RSN 65-87, most adequately matches the difference of 1 point, which is obtained when the amplitudes change by 2.5 times according to recent studies [Aptikaev, 2012].

III. Analysis of research results

Thus, for the seismogeological conditions of the test site of the Geophysical Service of the Russian Academy of Sciences, at a depth of 30 m, a decrease in seismic intensity is achieved by 0.2 points for low frequencies, by 0.9 points for medium frequencies, and about 2 points for high frequencies.

Obviously, in other seismogeological conditions, it is possible to expect other ratios of amplitudes and, as a result, other increments of seismic intensity. However, with rare exceptions, seismic properties still improve with depth, that is, there is a fundamental similarity of soils in the upper part of the section in different areas due to the same susceptibility to weathering processes. In this regard, the general trend of decreasing intensity with depth will continue.

The above is confirmed by the results of synchronous measurements performed in numerous tunnels in the area of Sochi (Fig. 4). A special feature of the data obtained in and above the tunnels is that it extends the range of investigated depths up to 250 m. Seismogeological conditions for different observation points did not differ in stability. This allows us to look at the results obtained in general, abstracting from the structure of the array in each individual case. On average, for low frequencies, a decrease in seismic intensity by 0.4 points was obtained, at medium frequencies the difference was 0.7 points, at high frequencies – 0.8 points.

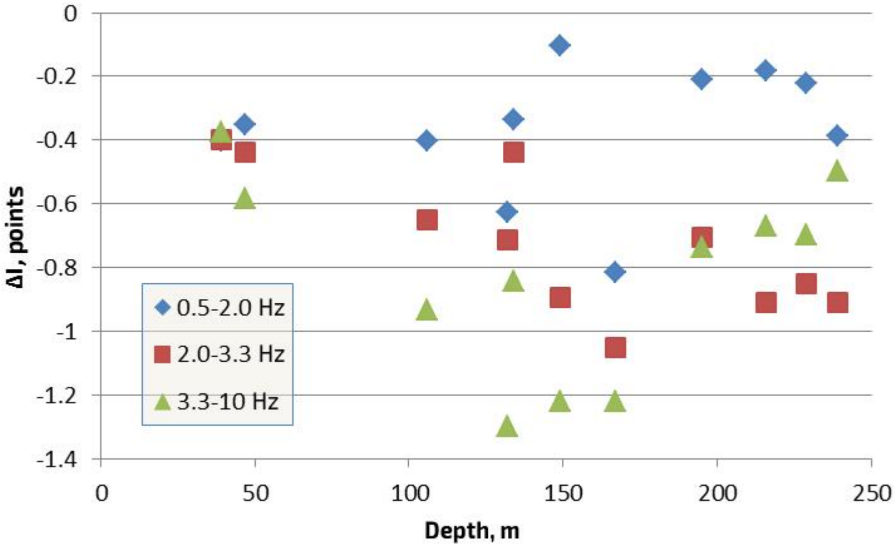

Fig. 4: *Ratios of increments of seismic intensity in three frequency ranges for different excavation depths*

It can be noted that low-frequency oscillations turned out to be weakly affected by the depth of excavation: most of the increments of ΔI are kept in the range from -0.4 to -0.2 points. Mid-frequency oscillations show some tendency of increasing the absolute difference of increments with depth. In the considered range of depths, it can be approximated by the equation $\Delta I = 0.68 - 0.29\ln(H)$, where H is the excavation depth in metres. High-frequency oscillations also show a similar trend down to a depth of 170 m, however, further it is broken, which casts doubt on its existence. Obviously, for the final conclusions regarding the quantitative description of the effect of depth on the increase in intensity, additional data are required.

IV. Conclusion

As a result of experimental studies at the Obninsk test site and a number of tunnels in Sochi, the features of the change in the spectral composition and intensity of oscillations were established when comparing records of teleseismic earthquakes and microseisms obtained on the earth surface and in the research adit. The most stable results were obtained for the frequency range up to 3.3 Hz, although in general, even up to 10 Hz, the revealed effects significantly exceed the measurement errors.

The performed studies also showed that the difference in oscillation level increases with the increase of frequency as well as with the depth of underground excavations. Nevertheless, there are still many questions regarding the impact of earthquakes on underground structures. To solve them, it is necessary to develop a methodological base with the implementation of the tasks in seismically active areas. One of the tasks is the installation of downhole systems for earthquake control, which will allow measurements at different depths, as well as equipping underground structures with automated monitoring systems to obtain spectral characteristics of seismic effects at the time of earthquakes.

The revealed patterns of seismic intensity decrease with depth can serve as the basis for the development of a special regulatory framework in order to reduce the cost of designing and building deep underground structures, in particular, transport tunnels.

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