Spatio-temporal variations of short-period S wave attenuation field in a region of the North Korea Punggye-Ri nuclear test site

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Six underground nuclear explosions (UNEs) were conducted at the DPRK nuclear test site in 2006-2017. We analyzed seismograms of UNEs and near earthquakes, obtained by stations MDJ and VLA at distances of ~270-450 km to investigate characteristics of the attenuation field. We studied the ratios of maximum amplitudes of Lg and Pg waves (Lg/Pg parameter). Narrow-band filter with central frequency of 1.25 Hz was used. According to the UNEs data, Lg/Pg parameter diminished essentially from 2006 to 2017. It was shown that in 2017-2024 the mean value of the Lg/Pg parameter for the earthquake recordings is higher essentially than for UNE data in 2017. We compared the new data with data obtained earlier for the Semipalatinsk test site (STS). The mean value of the Lg/Pg parameter for the Balapan site in the STS diminished essentially from 1980 to 1989. The most natural explanation of temporal variations of the attenuation field connected with ascending deep-seated fluids from the uppermost mantle into the earth's crust as a result of intensive influence of the powerful UNEs on the geological medium.

SnT 2025 8 SEPTEMBER ONLINE DAY 9 TO 12 SEPTEMBER AT HOFBURG PALACE, VIENNA & ONLINE
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P2.4-675

Introduction

The works [Kopnichev, Sokolova, 2001; Kopnichev, Sokolova, 2022; Kopnichev et al., 2013; Berezina et al., 2024] show that in the areas of three largest nuclear test sites (Nevada (USA), Semipalatinsk (former USSR), Lop Nor (China)) significant spatio-temporal variations in the attenuation field of short-period S-waves were observed, most likely associated with the migration of deep fluids. The characteristics of the attenuation field in the area of the relatively small Punggye-ri nuclear test site, located near the northern border of the DPRK, are studied in this report. For comparison, some characteristics of the UNE records at the Semipalatinsk Test Site (STS) are considered.

Brief geological and geophysical characteristics of the study area

Punggye-ri is a nuclear weapons test site in the DPRK, located in a mountainous area near the Baekdusan volcano (Fig. 1). The volcano formed in the Pliocene, then its activity resumed in the Holocene. Currently, hot water and gases are released in the lake located in the caldera at the top of the stratovolcano.
The distance from the test site to the Sea of Japan is about 50 km, and to the Baekdusan volcano - about 110 km. Jurassic granites with inclusions of diorite, dolomite, limestone, gneiss and quartz porphyry is dominated at the test site area.

Six UNEs were conducted at the test site from 2006 to 2017, the yield of these explosions increased over time [Adushkin et al., 2021; Adushkin et al., 2025].

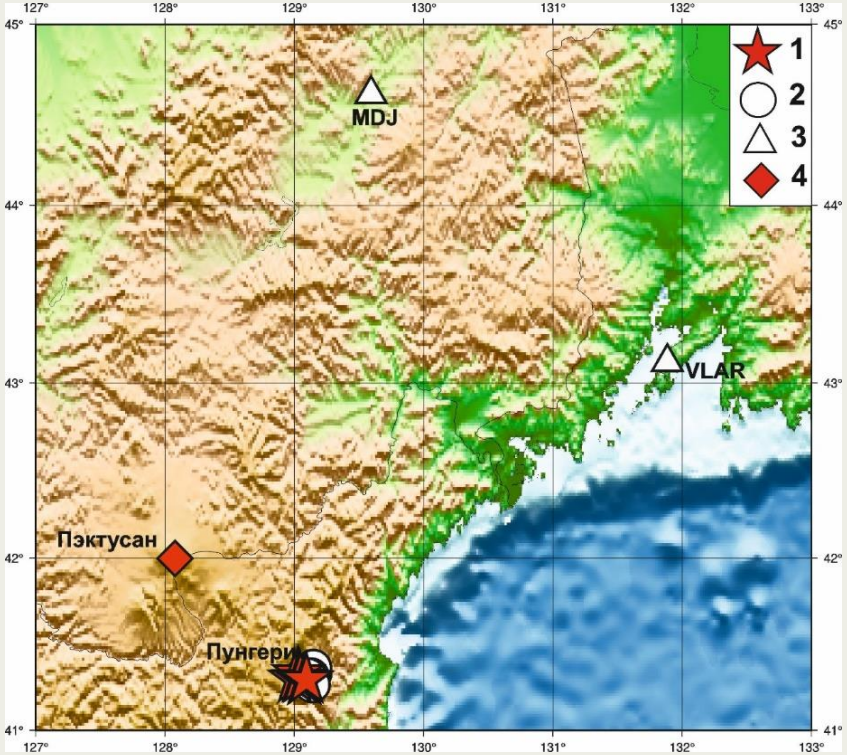

Fig. 1. Map of the study area.
1 – epicenters of UNEs at Punggye-ri, 2 – epicenters of aftershocks, 3 – seismic stations, 4 – Baekdu volcano

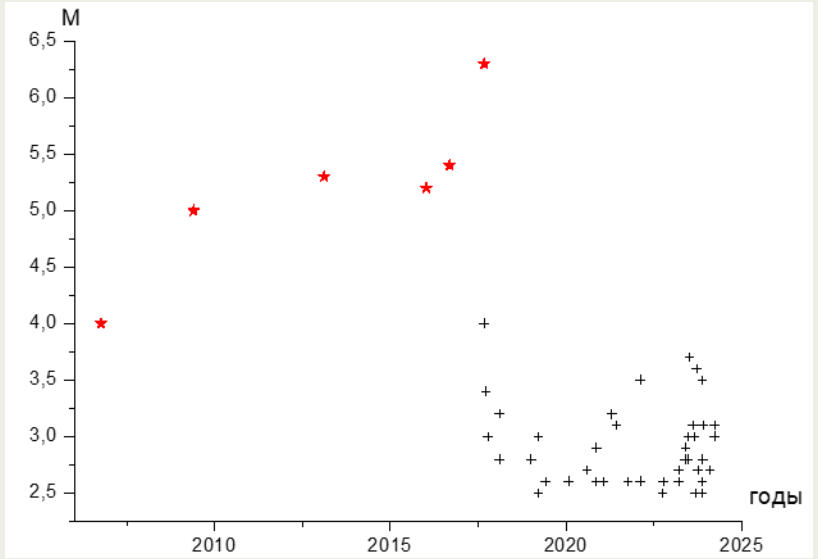

Fig. 2. Realization of seismic events from the Punggye-ri test site area in time.
Asterisks – UNE, crosses – earthquakes

After the two most powerful UNEs, conducted on September 9, 2016 and September 3, 2017, large number of relatively weak aftershocks were observed. Fig. 2 shows the dependence of the magnitudes of seismic events from the Punggye-ri test site on time. It is evident that there has been a significant increase in the number of earthquakes in recent years (more than seven years), while the duration of aftershock sequences during UNE usually does not exceed 25 months [Adushkin, Spivak, 1995

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Materials and research methods

We used records from two seismic stations VLA (Russia) and MDJ (China) located at distances from the Punggye-ri test site of ~ 320 and 370 km, respectively (Fig. 1). Records of six UNEs and 11 earthquakes for the period of 2006–2024 were processed.

A comparison of the attenuation field characteristics was carried out for two test sites: the Punggye-ri and the STS. For the STS area, UNE records were used, which were obtained by the TLG station (Northern Tien Shan region). It should be noted that for the path from the STS to the TLG station, Lg waves propagate along the stable Kazakh platform, the lithosphere of which is characterized by relatively weak attenuation of short-period S-waves [Kopnichev, Sokolova, 2001] (Fig.5). More than 200 records obtained at distances of ~730–770 km were processed in total. A filter with a central frequency of 1.25 Hz and a width of 2/3 octave was used. Based on the records of UNEs and earthquakes, the ratios of the maximum amplitudes in the Pg and Lg waves were found (parameter Lg/Pg).

Fig. 3 shows the records of six UNEs (Punggye-ri test site) obtained by the VLA station. It is evident that for the UNEs records in 2006–2009, the level of the Lg group is significantly higher than Pg, and in 2017 the opposite view is observed.

Data analysis and discussion

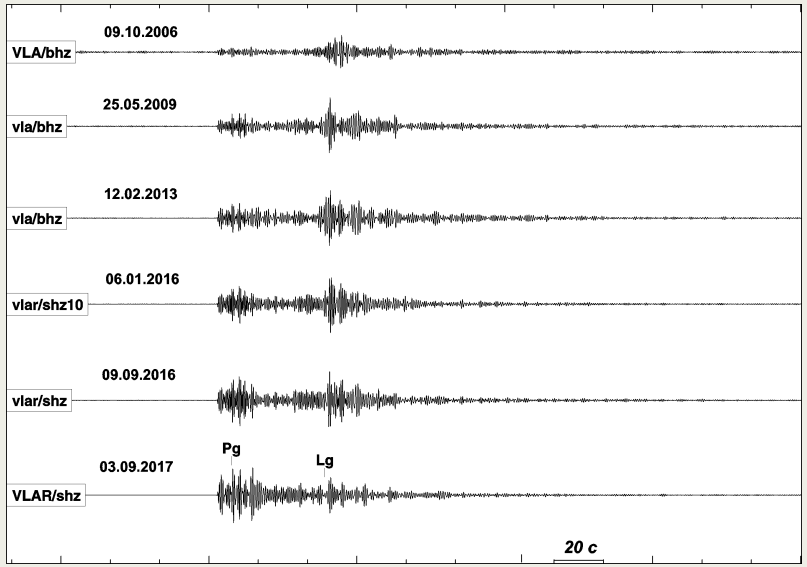

Fig.3. UNEs seismograms obtained by the VLA station. Z component, 1.25 Hz channel. Arrivals of Lg and Pg waves are marked

Fig. 4 shows the dependences of the Lg/Pg parameters on time based on the records of the VLA and MDJ stations. It is evident that from 2006 to 2017, according to the VLA station data, there was a monotonic decrease in the Lg/Pg values from 0.42 to –0.26 log units. According to the MDJ station data, the Lg/Pg values also decreased over time, especially sharply in 2016–2017 (from 0.20 to –0.20 log units).

Based on the records of aftershocks of the two most powerful UNEs that occurred in 2017–2024, [Adushkin et al., 2025] and recorded by the VLA station, the mean values of the Lg/Pg parameters were estimated as 0.58±0.09 log units. It follows from Fig. 4 that these values are significantly (by 0.68 log units) higher than the average for UNEs in 2016–2017. A similar result was obtained from the data for the MDJ station: the mean values of Lg/Pg are higher for aftershocks in 2017–2024 in relation to three UNEs in 2016–2017 by 0.28 log units.

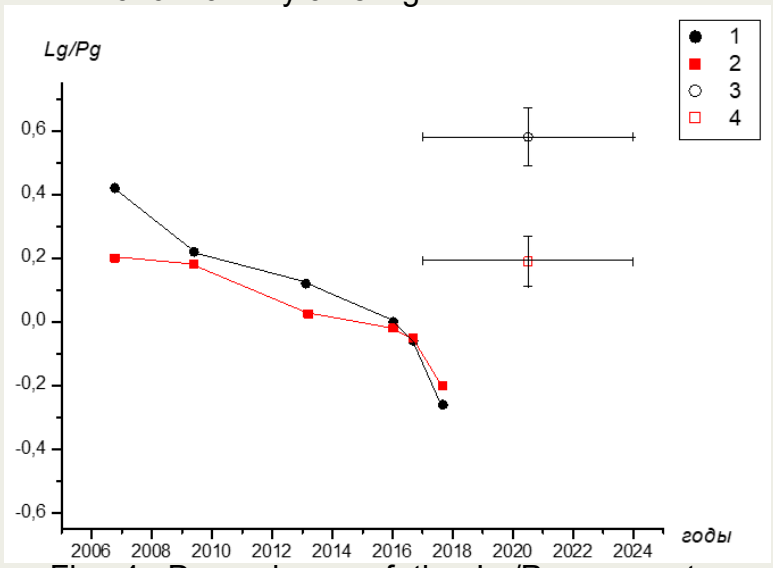

Fig. 4. Dependence of the Lg/Pg parameter on time.

1 – UNE (VLA), 2 – UNE (MDJ), 3 – earthquakes (VLA), 4 – earthquakes (MDJ). Average values, standard deviations and time range are shown for earthquakes

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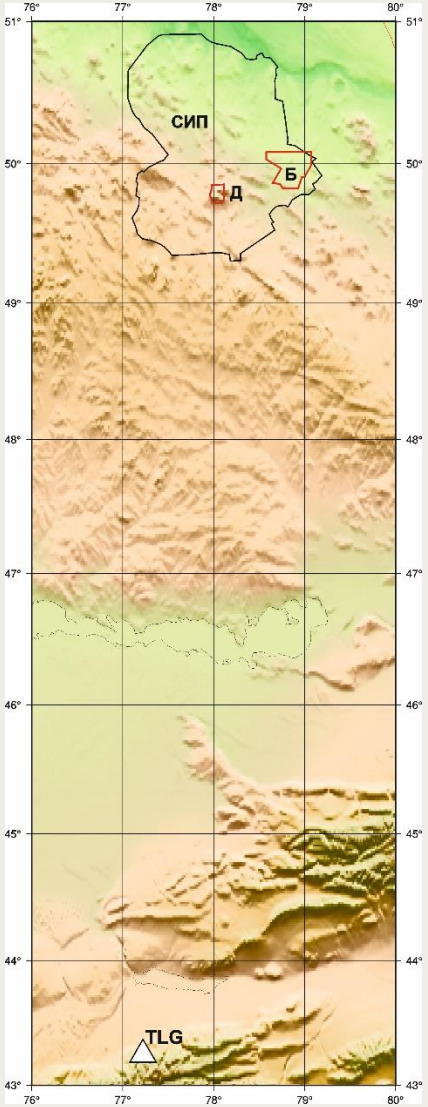

Fig. 5. Location of the Degelen and Balapan test sites at the STS and TLG station

Fig. 6 shows the time variations of the Lg/Pg parameter for UNEs at the two main STS sites: Degelen and Balapan. For UNEs at Degelen, from the mid-1960s to the end of the 1970s, the average Lg/Pg values increased significantly (up to 0.80 log units); then, until the end of the 1980s, they remained at approximately the same level. At the same time, for Balapan, starting in 1980, a gradual decrease in Lg/Pg values is observed, on average, they fall by the end of the 1980s by 0.4–0.5 log units, dropping to approximately 0.1. In this regard, at the end of the 1980s, the difference in the average values of this parameter for UNEs at Degelen and Balapan reached 0.6 log units. It is important to note that the minimum Lg/Pg values for the Punggye-ri test site are significantly lower than for the Balapan site and especially for Degelen.

The Lg group represents a set of shear waves reflected beyond the Mohoroviči boundary [Kopnichev, 1985], and Pg are longitudinal waves propagating in the earth's crust. In this regard, the Lg/Pg parameter is a measure of the integral attenuation of short-period S-waves in the earth's crust. The sharp drop in Lg/Pg values for UNEs at the Punggye-ri test site over time is most likely explained by the rise of deep fluids in the lithosphere in the test site area, associated with intense technogenic impact on the earth's crust.

The migration of melts in the crust may also play a role, since the test site is located near the Baekdusan volcano. However, this role is most likely not very significant, since the viscosity of fluids is many orders of magnitude lower than the viscosity of melts or simply heated rocks. The difference in the Lg/Pg parameters for UNEs and aftershocks is associated with the features of focal radiation; it is obvious that during earthquakes much larger share of energy is radiated in the form of shear waves. The obtained data indicate that on the paths from the Punggye-ri test site in 2016–2017, despite a significantly smaller epicentral distance, much higher attenuation of S-waves in the earth's crust was observed than on the paths from the STS to the Northern Tien Shan before the end of the 1980s, primarily for the Degelen site. In our opinion, to explain this effect, it can be assumed that the earth's crust in the vicinity of the Punggye-ri test site has much higher fluid content than in the STS area.

This hypothesis is supported by the existence of the Baekdusan volcano at relatively short distances from the test site, whose eruptions were observed in historical time, as well as sharp drop in the Lg/Pg parameter over time for the paths from the test site to the VLA and MDJ stations. In addition, as shown in [Shchukin, Ryaboy, 1987], the attenuation of short-period S-waves in the continental lithosphere generally increases as it approaches the boundaries of seas and oceans.

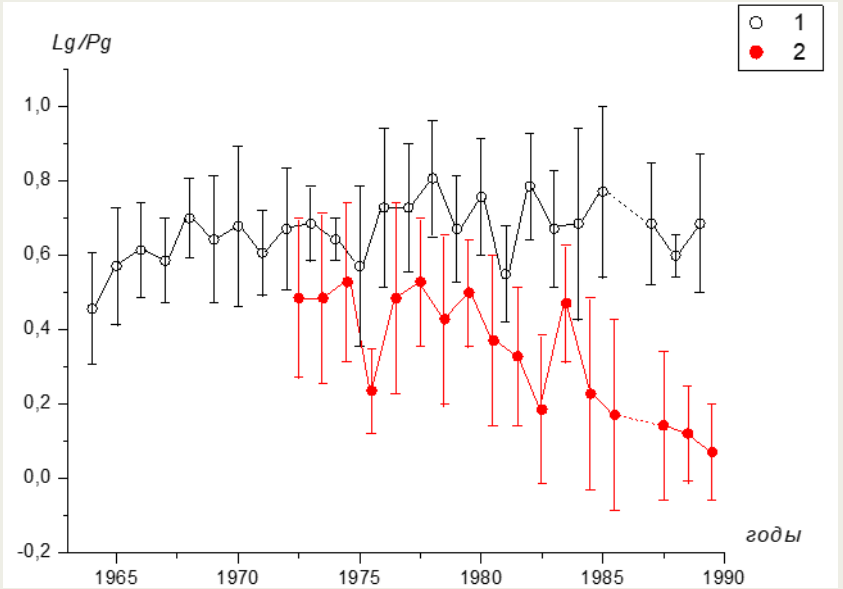

Fig.6.Temporal variations of the Lg/Pg based on TLG station records.1 – Degelen, 2 – Balapan. Mean values and standard deviations are shown

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Conclusion

The spatiotemporal variations in the structure of the shear-wave attenuation field in the area of the North Korean Punggye-ri nuclear test site were considered. The records of UNEs and earthquakes obtained by two stations, VLA and MDJ, at distances of up to 400 km were processed. The ratios of the maximum amplitudes in the Lg and Pg groups for the frequency of 1.25 Hz were determined. It was found that, according to the UNE records, the Lg/Pg parameter values decreased sharply from 2006 to 2017. It is assumed that this effect is associated with the rise of deep fluids in the lithosphere, caused by the intense technogenic impact of UNEs on the geological environment. In addition, it was shown that the mean values of the Lg/Pg parameter are significantly higher for UNE aftershocks than for explosions. A comparison was made of the characteristics of attenuation fields in the areas of the Punggye-ri test site and the Semipalatinsk test site.

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