Slow Strain Waves in Rocks as Potential Precursors to Seismic Hazard

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Abstract. The article reports on instrumental monitoring of rock deformation in the South Baikal geodynamic test site. Based on the analysis of the time series of data sets, two groups of strain components are distinguished by differences in their origin and wave properties. Strain components in the first group are caused by external factors, such as lunar-solar tides and atmospheric pressure variations. The second group includes non-periodic, random and periodic (constant) components generated by internal tectonics. Non-periodic components are manifested as single deformation impulses that differ in intensity and form, and are related to slow displacements along large active faults, which occur outside the monitoring sites. Besides, non-periodic components are related to fast displacements at block interfaces within the monitoring sites. The periodic (constant) component is related to the India-Eurasian collision. It is represented by slow strain waves, which lengths amount to 400–500 m, with amplitudes of few microns, and periods of (1–3)·10^{-4} Hz. The strain wave directions and rates of their migration in space vary with time. The identified trends of changes of the wave parameters in the South Baikal geodynamic polygon can be related to the preparation of a strong earthquake.

1. Introduction
The problem of slow strain waves (SW) in the lithosphere has been in the focus of scientific interest since Ch. Richter [1] and K. Mogi [2] suggested that migration of earthquake foci in the zones of large seismically active faults is triggered by unidirectional spatial migration of slow inelastic strain waves. A number of recent publications are devoted to this problem [3-6]. According to estimations using the model of V. Elsasser [7] and its modified versions, the SW velocity may range from 0.1 [8] to 3650 km/yr [9]. Estimations from the instrumental observation data in different geodynamic settings show that the SW velocity values can amount to dozens of kilometers per year and vary from 10 to 100 km/yr [3, 5, 10, 11]. Two main types of slow SW are distinguished [12]. Intraplate SW that occur between faults belong to the first type. Such waves are caused by interactions between plates [13, 14], generated by the ‘lithosphere – asthenosphere’ system [15], and occur due to other factors of the global scale. SW inside faults belong to the second type. Such waves can occur as a result of the transformations of the first-type SW passing through the zones of major faults. Besides, the second-type SWs can be generated by the faults during displacements along these faults.

Until recently, it was commonly believed that displacements along large faults are realized by two deformation modes: rapid displacements of fault wings relative to each other with the occurrence of a seismic effect, and slow aseismic creep [14, 16]. Modern high-precision geophysical and geodetic
techniques have detected, in addition to creep, slow displacements along faults. Such displacements differ in their duration and the amplitude-frequency spectra of generated waves [17-20]. Initially, these displacements were attributed to subduction zones [21-23]. Later on, they were found in large fault zones of other types [24].

A strict classification of slow displacements has not been proposed yet. Nonetheless, silent (‘slow’) earthquakes, episodic tremor and slip, episodic creep events, slow slip events, low-frequency earthquakes are distinguished [19, 25-29]. In early papers, slow displacements were described as triggered ones and generated by strong earthquakes, but later it was found that slow displacements can occur in aseismic periods, as well as precede an earthquake [10], [30-32]. Despite the fact that the problem of slow displacements has been studied for a quarter of a century and discussed in a large number of publications, the origin of slow displacements has not been thoroughly investigated yet, and their role in the overall strain dynamics of faults remains unclear. Poorly studied is the generation of slow SW by slow displacements, and parameters of such SW need to be discovered and estimated.

This article reports on comprehensive monitoring studies conducted in the South Baikal geodynamic polygon (SBGTS) and presents new data on the sources, types and dynamics of slow strain waves.

2. Monitoring equipment and techniques

In the SBGTS, original monitoring sets designed by the authors [33] are installed on four monitoring sites – Tyrgan, Listvyanka, Talaya, and Mondy (figure 1). On the Tyrgan site, two monitoring points are established on a profile oriented across the Primorsky fault; strain measurement are carried out by rod sensors (10 m base), one installed horizontally at a depth of 2.5 m at the point closest to the fault (figure 2A), and a vertical one in a borehole at the second point located at a distance of 120 m from the first point (figure 2B). On the Listvyanka and Mondy sites, vertical rod sensors (10 m base) are used (figure 2B). On the Talaya site, a network of ten sensors launched in a mining tunnel includes nine rod sensors (6 m base) installed horizontally on the floor of the tunnel and one vertical rod sensor (2 m base) (see figure 2C).

Figure 1. Locations of monitoring sites Tyrgan, Listvyanka, Talaya, and Mondy (yellow circles) in the South Baikal geodynamic polygon. Red circle - 29.03.2019 earthquake foci (K= 3.3).

The time series of monitoring data were processed using an original software package that filters initial data sets, separates specified components of the oscillation process, identifies and removes a trend
component, and calculates correlation functions [34]. At the start of processing of a selected time series a daily component associated with lunar-solar tides and the trend are excluded. To eliminate instrumental and other high-frequency noise, the filtered time series are averaged using a two-hour sliding window (10 second increment). For each position of the window, which includes 720 strain values, an average value is calculated. The processed data sets are used to calculate correlation functions for each pair of points in order to detect a time shift in the manifestation of strain of the same type. This data processing procedure aims at isolating the wave component of the deformation process and, if periodic SW are detected, makes it possible to evaluate their main parameters – wave length, period, and velocity of spatial migration.

**Figure 2.** Strain monitoring site. 1 – fault zone; 2 – mining tunnel; 3 – horizontal (a) and vertical (b) red sensors; 4 – distance between rod sensors

3. Results and discussion

The analysis of the obtained time series of strain data shows that deformation occurs as an oscillatory process characterized by a wide range of oscillation periods [33, 34]. In the deformation structure, two groups of components differing in origin are distinguished.

Group 1 includes strain components caused by external factors, such as lunar-solar tides and atmospheric pressure variations. Lunar-solar tides are reflected in strain variations taking place within 12 or 24 hours. The 12-hour variations, that were clearly recorded only on the Talaya site, are modulated into in two-week cycles. Tidal deformation values range from few microns to the first dozens of microns. The deformation response of rocks to atmospheric pressure changes differs depending on the amount of
such changes. A sharp increase in atmospheric pressure can cause clearly recordable deformation impulses from few microns to the first dozens of microns (figure 3). In case of gradual changes of atmospheric pressure or sharp pressure drops, the deformation response of rocks is either weak or absent. The second group includes non-periodic, random and periodic, constant components generated by internal tectonics. Non-periodic components are manifested as single deformation impulses that differ in intensity and form (figure 4), occur sporadically, and are recorded as single strain waves passing through the monitoring sites. The velocities of wave migration are variable and, in most cases, range from the first centimeters to dozens of centimeters per second. In our study, we distinguish two types of strain waves differing in main parameters.

![Figure 3](image3.png)

**Figure 3.** Variations of atmospheric pressure (A) and deformation response of rocks (B).

![Figure 4](image4.png)

**Figure 4.** Examples of impulse changes of rock deformation caused by strain waves of the first (A) and second (B) types.
Strain waves of the first type are detected in the time series as asymmetrical impulses. Their amplitudes are to dozens of microns, and wave lengths are hundreds of meters (figure 4A). These SW pass through all the monitoring sites and, generally, are accompanied by residual deformation of few microns. Their sources are located outside the monitoring sites. Probable sources are slow displacements along faults [19]. Figure shows a deformation impulse recorded by the network of sensors on the Talaya site on March 27, 2019 (figure 5). It was initiated by tremor-like shearing along the Tunka seismically active fault, which took place prior to the main seismogenic slip along this fault and an earthquake of March 29, 2019 (K= 13.3; epicenter coordinates: latitude 51.71, longitude 101.54) (figure 5). The monitoring records of the Talaya site show the strain wave migration velocity of 1.3 m/s, the strain wave amplitude of 10–20 μm, and the wave length of 250 m. The attenuation amounted to 0.005 m/km, and the estimated velocity of displacement along the fault was 2 m/s.

![Figure 5. Deformation impulse on the Talaya site on March 27, 2019](image)

Strain waves of the second type are represented in the time series by symmetric or asymmetric impulses with the amplitudes of few microns and wave lengths of the first dozens of meters (see figure 4B). In contrast to the first-type SW, the second-type SW occur more frequently and are not accompanied by residual deformation. It is probable that such waves are generated by local sources related to stress redistribution in the fault-block structure of the upper crust. It was noted that the frequency of their occurrence significantly increased before the earthquakes.

Group 2 includes periodic wave components that are constantly present. Such a component has a wave length of 400–500 m, amplitude of few microns, and period of 2-10-4. Our study shows that SW migrate in space in varying directions, and their migration velocities vary with time. For instance, an average vector of SW migration in space was oriented from southwest to northeast at azimuth 50о in 2016, and rotated clockwise in 2017–2019 (see the increased sectors of azimuthal directions of SW migration in figure 6). The azimuth 50о coincides with the direction of the current compression from Indostan collision [35]. In tectonic studies aimed to assess seismic hazard, of particular interest are periodic wave components resulting from internal sources, namely, single tremor-like impulses and slow strain waves that are constantly present. Both the laboratory [36, 37] and instrumental observations [38], [30-32] give evidence that tremor-like impulses are indicative of the beginning of seismogenic activity on a fault.
Monitoring data show that the SW migration velocity is variable in both short and long-time intervals. Variations of this parameter were recorded within a short time interval before the earthquake (K=10.4) of July 29, 2016 (figure 1). Its epicenter was located in the Obruchev fault zone, 90 km from the Talaya site. The SW migration velocity increased sharply from 50 mm/s to 430 mm/s three days before the seismic event, then decreased to 17 mm/s, and recovered to its initial value (50 mm/s) before the earthquake (figure 7).

Figure 6. Change the direction of the average vector of SW migration on Talaya site in 2016–2019yy.

Figure 7. Variations of the SW migration velocity in July 2016 before the earthquake.

In the long-time intervals, the SW migration in space is variable and generally tends to increase. This is confirmed by the observation that the average SW migration velocity increased from 50 to 500 m/s in
the period from 2016 to 2018, and began decreasing in 2019 (figure 8). An increase in the SW migration velocity with time indicates a stress increase in the fault-block medium [39].

![Figure 8](image-url) Changes of the average SW migration velocity in 2016–2019 (Talaya site).

4. Conclusion
The instrumental monitoring data from the SBGTS show that the rock deformation pattern includes several components generated by external and internal sources. The single-act impacts of external sources, such as lunar-solar tides or atmospheric pressure variations, can cause a weak deformation response in rocks. However, due to the long-term periodic effects of such external sources, especially lunar-solar tides, a cumulative deformation response can be considerable. In tectonic studies aimed to assess seismic hazard, of particular interest are wave components resulting from internal sources, namely, single tremor-like impulses and slow strain waves that are constantly present. Both the laboratory and instrumental observations give evidence that tremor-like impulses are indicative of the beginning of seismogenic activity on a fault. Slow strain waves are a permanent factor contributing to the accumulation of deformation and stress in the lithosphere and need to be investigated as the indicators of the stress state of the fault-block medium. In the fault-block medium, a dominant direction of the active deformation vector is marked by an azimuthal direction of the SW spatial migration. An increase in the SW migration velocity with time indicates a stress increase in the fault-block medium.

Using a network of specially equipped monitoring points, it becomes possible to detect the tremor-like impulses and calculate the coordinates of a possible earthquake source location.

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