Mapping of changes in the stress-strain state of a landslide risk slope using an Earth’s natural pulsed electromagnetic field method

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Abstract. Among the wide range of hazardous natural processes and phenomena, the exogenic geodynamical processes stand aside. These events can either directly or indirectly provoke or amplify socio-economic or technogenic risks, and differ considerably in the time and space scales. The landslide processes can affect the environmental situation, decrease the durability of real estate objects, compromise the integrity of transportation and engineering infrastructure, and endanger the population safety. Among the reasons of soil plots destabilization are water cuts and technogenic stress on the geo-environment. As cities continue to grow, the environmental load increases. Global warming leads to an increase in precipitation and changes the regional hydrogeological conditions. Therefore, the problem of landslide research and forecasting becomes more urgent. This work presents results of a field research carried out on a site prone to intensive landslide process development, ravine erosion, and rain-wash by using an Earth’s natural pulsed electromagnetic field (ENPEMF) method. It has been demonstrated that the exogenic slope processes can develop rapidly and the occasional surveys alone are not enough to protect the infrastructure objects. It is necessary to establish an online ongoing monitoring of the stress-strain state (SSS) of the rocks. The ENPEMF method allows an instrumental real-time estimation of the soil stability and can be recommended for continuous monitoring of the SSS of the rocks.

1. Description of the problem

Tomsk region (Siberia, Russia) presents a wide variety of hazardous natural processes and phenomena. Such events, which may indirectly induce or amplify socio-economic or technogenic risks, exhibit considerably varying scales in time and space. Landslides are rather common phenomena in Tomsk region. This problem is most crucial in the localities of Tomsk, Kolpashevo, Kedrovka, Ust’-Bakchar, and others, where special town-planning regulations are introduced and special rules and regulations for territory management are enforced. Landslides have the major negative influences on the ecological situation in Tomsk. Landslide processes reduce the stability of real estate objects, compromise the integrity of transportation and utility infrastructure, and endanger the population safety. In the capital city of Tomsk region, the most probable reason for landsliding is the technogenic stress on the geological environment, and with the city growth the stress increases; hence, there is an increasing urgency to research and forecast the landslide activity.

During landslide surveys the following operations are usually performed:

- geotechnical survey of a terrain, establishing the parameters of revealed landslides and active focuses (landslide heads, rib spalling, sliding and pressure ramparts) and their influence on geodynamics;
- fracture-morphological survey of active landslides and adjacent slopes, distinguishing landslide tension fractures, tension and shear fractures, lowered tension and shear fractures, compression fractures and pressure ramparts, which provide evidence of development of
landslide processes. In both cases, surveys are occasional, and in the latter case results are subjective and heavily depend on the specialist’s qualification. To mitigate regional risks and socio-economic consequences caused by geodynamic events, it is necessary to develop and implement an objective instrumental method of SSS of rock monitoring.

2. Substantiation of the method

In 2019, we carried out a field research on the bank slope of the Tom River in the proximity of the Lagerny Sad. The goal of the research was to optimize active landslide mapping methods and work out instrumental detection of their hazard level. The Lagerny Sad is located in the southern part of Tomsk and includes a plot from the Communal Bridge over the Tom River to 19th Gvardeiskoy Divisii street. That plot is prone to intensive landslide process development, ravine erosion, and rain-wash. In 1979, to prevent the slope destruction and to protect the engineering infrastructure in that part of the city, a number of projects for landslide prevention works were developed. Their implementation allowed one to decrease the intensity of the landslide processes to some degree. Later, an “Integrated Project for Landslide Prevention Works on the Right Bank of Tom River in Tomsk” was developed. In accordance with this project, relevant works were carried out on the slope, and various landslide preventing constructions were built. Despite these efforts, the exogenic slope processes continue in the Lagerny Sad, and this brings forward the region’s need for the development of new methods of land movement forecasting. The plot chosen for the research features an external evidence of an active landslide, namely sliding fractures, landslide scars, marshiness, “drunken” forest, knobby terrain, a ruined building. A satellite image acquired in Google Earth (Figure 1) shows a site of areal measurements highlighted with a red frame. In the image one can see landslide scars and the evidence of recent ground movements with no vegetation. The landslide endangers the city infrastructure objects located in proximity.

![Figure 1. Satellite image of areal research site.](image)

The research used an Earth’s natural pulsed electromagnetic field (ENPEMF) method based on the
phenomenon of electromagnetic emission: the emissive ability of dielectric materials when they are acted on. Electromagnetic emission emerges in the process of charge generation and relaxation on fracture planes during the stress state of the rocks. Pulses emerge both when dielectric uniformity changes and when electrolyte-filled capillars rift. Observing electromagnetic emission allows monitoring of the stress-strained state of the rock formation [1]. In rock formations, there can be the following sources of natural electromagnetic fields: soil structure inconsistencies, unequally strained structures, fractures and microfractures. All these sources generate pulsed electromagnetic fields as a result of mechanic-to-electric energy conversion, strain waves from the mantle, tides, microseisms, winds, and technological loads, thus creating a natural electromagnetic background of lithospheric nature. Perennial measurement in various regions demonstrated that the lithospheric ENPEMF has distinguishable daily and seasonal variations. This can be explained by the fact that stress-related waves in Earth’s crust are related to Earth’s nonuniform rotation around its own axis and around the Sun [2]. Daily variations depend on the calendar date, geolocation, and the geophysical attributes of the location. Pulsed electromagnetic fields can change both with changes in the ground conditions and with changes in the influence of the field sources. For example, typical daily variations can be disrupted by changes in the Earth’s crust rhythmic movement as a result of separate crust blocks joining into a consolidated mass, prior to an earthquake or when the stress-strained state of the rock changes. Thus, ENPEMF recording can be a comprehensive integrated tool for geophysical survey, Earth’s crust geodynamic activity monitoring, and Earth sciences research.

3. Technique for processing of Earth’s natural pulsed electromagnetic field recorded parameters and interpretation of research results

Natural rhythmic movement of Earth’s crust is only revealed robustly when a certain optimal recorders’ sensitivity is used. If the sensitivity of the equipment is too high, the atmospheric noise components and interference dominate in the pulse flow. If the sensitivity is too low, only the most powerful pulses caused by thunderstorm discharges are recorded and lithosphere originated pulses are missed. Therefore, the sensitivity of recorders should have certain optimal settings, depending on the properties of the geologic environment, on the situation with atmospheric phenomena at the recording site, and on the problem being solved [3]. Before the start of the work, all multichannel geophysical recorders were set to identical sensitivity taking into account the local geological conditions and technogenic interference. The settings were made at a distance not exceeding the wavelength from the preassigned survey tracks of ENPEMF measuring in the central part of the site. To set optimal sensitivity, we used specially developed calibrating dependences accumulated based on a multiyear research of the ENPEMF in various regions of Eurasia, the Windows applications “MGR-Protector”, “MGR_Analiz”, and “MGR_Field”. All software listed above was developed by the authors and registered in the national software registry.

During the survey works, a recorder 0003 was used as a reference recorder to measure background ENPEMF variations in a continuous mode. Recorders with numbers 0004 and 0005 were used to perform route surveys of ENPEMF time-space variations on preplanned survey stakes.

Each of the route recorders and the reference recorder measured the ENPEMF parameters in two channels of predominant reception in directions N-S and W-E. The measurements at each of the survey stakes were taken for 2 minutes with a sampling interval of 1 second. The reference recorder measured continuously with the sampling interval of 1 second. The recorders were synchronized in time before the work started.

The spatial distribution of the ENPEMF intensity was chosen as an informative feature for the calculation of ENPEMF anomalies. To calculate this, first we performed a comparative analysis of the data recorded by the variation station and the route station. Then the high amplitude pulses recorded by both stations at the same time were excluded. These pulses were considered to be generated by distant sources non-relevant to the local geological structures, e.g. tropical thunderstorms. After this the average intensity of the pulse flow was calculated for each measuring waypoint, as well as for the
variation station for the same time frame. Dividing the waypoint intensity by the reference station intensity, we obtained a ratio representing a spatial change in the ENPEMF for each waypoint.

Negative anomalies in the ENPEMF structure are usually associated with zones of compression or tectonic dislocation centerlines, since they are filled with low-radiating gouge. Thus, major active geological splits are distinguished in the ENPEMF as a bay anomaly with a positive excess in the ENPEMF intensity of 10 or more times on the fault side and a decrease in the intensity compared to the background values over the centerline. Plots with a complicated stress-strained state of the rocks are usually indicated by a positive anomaly in one of the ENPEMF reception directions and a negative anomaly in the other direction channel. Such plots are prone to possible landslides, cavings, and other local geodynamic processes.

To summarize, during the field survey described above we used the following criteria as a hazard indicator of geodynamic structures of different kinematics:

- 10 or more times excess of the ENPEMF compared to the background values: extremely active structures;
- 1.3 - 10 times: low active structures or associated with the zone of jointing;
- Differing from the background values by 30% or less: non-active structures.

Background values: values equal to 1.

4. Mapping of geophysical anomalies

The areal survey, in total, was carried out on the site selected. In order to do that, the site was divided into 4 tracks with the distance between the tracks of 40 m, and each track was divided into 15 survey stakes with a distance between stakes of 15 m. Hence, the total number of stakes was 60.

The ENPEMF anomaly map acquired on August 7 using two mutually orthogonal directions is shown in Figure 2. The survey demonstrated that a large part of the slope is in a compressing stress state, while the riverfront zone is in a tension stress state. It is worth noting that the weather conditions in the summer of 2019 in the survey site were arid. Low level of the groundwater and weak water content facilitated a stable state of the rock formations on the slope.
A repeated survey was carried out on the same stakes a week later. Instrumental measurements demonstrated that rains which took place in the time between the surveys have changed the stress-strain state of the rock formation within the surveyed site (Figure 3). A snapshot of the field is shown in Figure 4. The ENPEMF anomaly map reveals 2 plots with a tension stress state. These plots soundly reproduce the outlines of two landslides revealed by geomorphological analysis and separated by a sliding rampart, which was situated in the center of the survey site. The outlines of these landslides are shown by a dotted line on the anomaly map (Figure 4).
5. Conclusions

The above field research and survey on the slope have demonstrated that the exogenic slope processes can develop rapidly and occasional surveys are not enough to protect the infrastructure objects. It is necessary to establish permanent online monitoring of the stress-strain state of the rock formation. The ENPEMF method allows estimating the stress-strain state instrumentally in real time and can be recommended as a method of continuous monitoring of the ground state.

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