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POSSIBILITIES OF SEISMIC METHODS FOR ESTIMATION OF RAILWAY SUBGRADE STATE IN CONDITIONS OF FAR NORTH

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Abstract. The article presents results of monitoring state of railway subgrade using seismic methods in the Far North area.

Purpose: The purpose of the studies is to find out reasons of subgrade subsidence in turfed soils of Onezhsky District of Arkhangelsk Oblast.

Methodology: Studying soils in foundations of subgrade, a complex of active and passive methods was used, including: seismic exploration of refracted waves, multi-channel analysis of ground waves, and engineering seismic analysis based upon spectrum analysis of seismic noises. This complex enabled considering and estimating the system “subgrade-soils of foundations”.

Results: A relative high capacity of weak soils, probably containing turf, lying under subgrade. Sections of increased water saturation in subgrade soils were found out. Loads from passing trains and resonant effect in weak soils cause its compression resulting in emergence of subsidence. Resonant effects whereby are not that strong, whereas passing trains have a more significant impact on the state of subgrades.

Practical significance: Elaboration of technology of quick estimation of state of railway subgrade for immediate detection of a dangerous defect at an early stage of its development is a topical and acute challenge.

Keywords: railway track subgrade, seismic vibrodiagnostics, passive seismic methods, Far North.

Introduction

In the territory of the Russian Federation, in the regions of permafrost soils, more approximately 5 thousand kilometres (including the Baikal-Amur Mainline and most part of the Trans-Siberian Railway) of railways are operated [1]. Industrial exploration of the Far North and Siberia territories requires extending railway tracks with their simultaneous operation. A distinguished feature of subgrade foundations with permafrost, swampy and karst sections is an increased proneness to deformation of tracks caused by cryogenic, karst and suffosion, and suffosion processes in subgrade soils.

In order to increase traffic safety, JSC “RZD” pays special heed to development and implementation of different methods for monitoring subgrade by virtue of mobile devices. Order of works in unstable places is set individually basing on data of instrumental and visual monitoring, on-site and engineering nd geological (geophysical) investigations, calculations of strength and operation reliability of objects. In recent years, in Russia and abroad field measurements of soils have been gaining their popularity. These are, first and foremost, cone penetration test (CPT) and standard penetration test (SPT). It should be noted that, despite these methods being very efficient, they are not able to perform constant (uninterrupted) control of subgrade and soils under it. It is significant to detect failure at its early stage of development which is complicated when only one single method is used on dangerous/problematic sections. There is a necessity in much deeper study of the issue.

The amount of information about upper part of section (UPS) of the Earth crust could be significantly increased by virtue of new geophysical technologies, employing integration of different methods. In recent time, with development of instrumental and methodological bases, application of passive seismic methods, mainly microseismic, have been gaining more significance in studies [2, 3, 4]. The main advantages of such methods are lack of necessity in special sounding signal sources, relative simplicity and realisation accessibility.

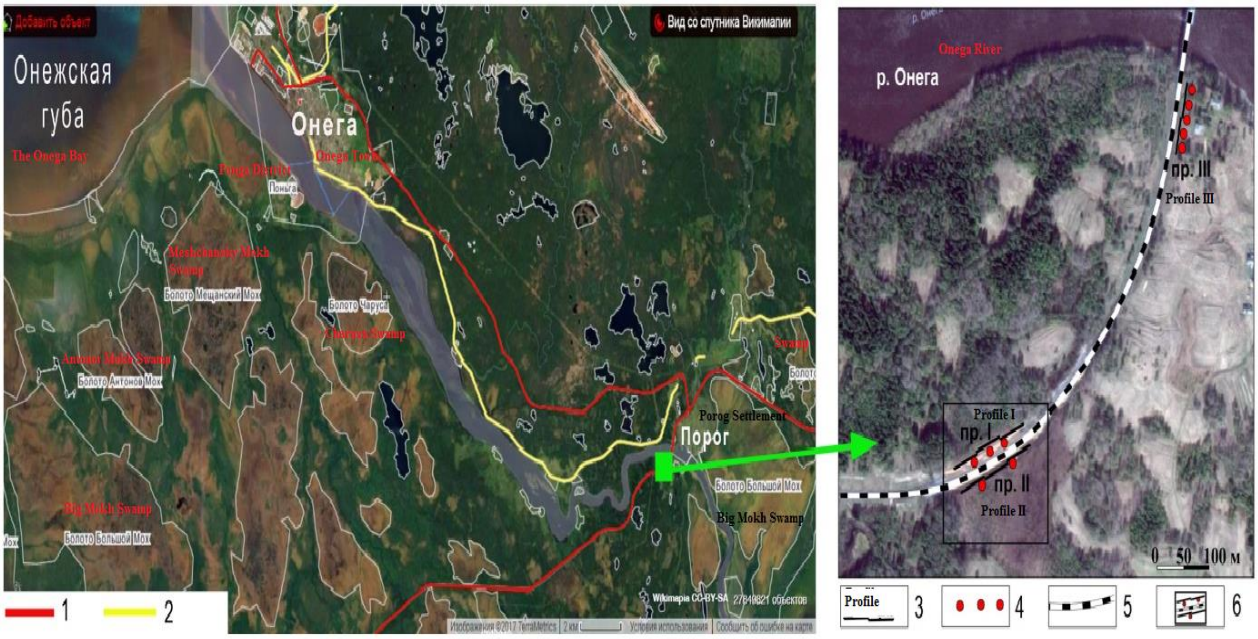
The notion “microseismic monitoring” encompasses a whole range of technologies, based upon analysis of waves of different origins and types (seismic emission, technology-related signals, surface waves, etc.). We are exploring methods of investigating UPS by means of picking out “necessary” signals from microseisms. It is essential to mention, that for getting fundamentally different information about the sphere, the captured wavefield may be simultaneously processed by different methods based on different “useful” constituents of microseisms.

Elaboration of technology of microseismic monitoring may be used either individually for acquiring quick estimation of subgrade state, or in combination with conventional methods for getting a picture of all alterations in the geological terrain in the area of railway construction.

Setting of the task

Mainline operation length of the Severnaya Railway (Northern Railway) makes approximately 1045 km, most of which is located in the conditions of the Far North. Development of issues of technology of microseismic monitoring and methods of data processing was carried out in a section of the Severnaya Railway, Onezhsky District of Arkhangelsk Oblast.

The object for investigation is subgrade of railway in the area of turfed soils. During the investigation, a task was being solved to find out reasons of soil subsidence (pic. 1).



Pic. 1. Scheme of works carried out: 1 – railway line; 2 – automobile mainline; 3 – engineering seismic survey; 4 – places of installment of seismic equipment; 5 – railway in the area of the works; 6 – area of investigation

Engineering and geological conditions of the area near Onezhsky District are dictated by flat and slightly undulating features of terrain, development of sand and clay glacial deposits, sand and clay sediments of latest marine transgressions of different intensity [5, 6, 7].

A significant fact, on which the railway subgrade is dependent, is engineering and geological features of soils, groundwater level, and lithological composition of underlying rocks. Generally, according to Russia's Design and Construction Specifications 11-105-97 (СП 11-105-97) [8], the territory belongs to II category of complication in terms of engineering and geological conditions. It is our believe, that the section under investigation is located in area of depositional plain of glaciolacustrine deposits, seacoast lowland. In the lowland plains, there are basically non-homogeneous, thin-layered, flowing clay water-saturated deposits with the capacity varying from several to 10 metres [7].

Peculiarities of the region (excessive hydration) and lithological composition low permeable blanket deposits characterise shallow deposition of groundwater (less than 2 metres). The surface of groundwater contours outline of undulating relief and at some places, in pits between hills and ridges, converge with swamp water. In wetlands, turf capacity varies, as a rule, from 3 to 6 metres, or even 8-10 metres in some places. Turf is usually underlain by soft soils.

Accepted assumptions

For this section, due to lack of information about engineering and geological surveys and type of subgrade, bearing in mind common data on the region of the work conducted [5, 7] and Construction Specifications 32-104-98 (СП 32-104-98), let us assume that a subgrade is up to 3 metres high. It has been designed and constructed after full or partial removal of turf layers from foundation being later replaced by mineral ground (sand and gravel mixture).

Seismic equipment

Measuring microseisms in the region of subgrade location and traffic-induced impacts on subgrade soils, the Güralp CMG-6TD broadband seismometer (Great Britain) [10] and the Nanometrics Trillium Compact 120s (Canada) [11] were used. The sensors were deployed as in picture 1. Axes were located along (X) and across (Y) the subgrade. The distance between the sensors was set 15 metres on the basis of prospective depth of sounding of the UPS.

For shallow seismic surveys of UPS the "GEOSINGAL Ltd." TELSS-402 telemetry seismic surveying system was used [12]. Receipt of P-waves and S-waves was carried out by vertical and horizontal sensors. Waves were induced 8 kg hammer being pounded on a flat metal plate. Scheme of profile location can be seen in picture 1. The distance between receiving channels was 2 metres, total length of profile was 15 metres. Processing of received data was carried out in programmes "RadExPro 2016" [13].

Materials and methods of studies

The main source of strong seismic vibrations in the region of the Severnaya Railway track is railway transport. When resonant frequencies of rock system "subgrade and underlying soils" equal seismic vibrations frequencies of passing trains, dynamic load on subgrade significantly rises, which may result in emergency situations.

In the conditions of possible variations of subgrade soils state (karst regions, swamp areas), if it is impossible or not reasonable to carry out its reconstruction works, the most optimal would be to uninterrupted monitoring of resonant frequencies of soils. In this case, changes in resonant frequency would mark processes of changes in soils. Therefore, there arises a necessity of estimation of resonant frequencies of soils, which can be calculated both theoretically and experimentally.

Theoretical calculation of resonant frequency is carried out, provided that the information about speeds of transversal waves in the soils being surveyed is available, according to the formula [14]:

$$f_{rn} = \frac{(2n+1)V_s}{4Z},$$

where V_s – average speed of waves in the upper layer; Z – upper layer thickness; n – mode number.

The main advantage of theoretical calculation is that it provides the possibility of modeling, which allows to estimate alteration of values of natural frequencies when the state of the system “subgrade and underlying soils” changes (for example, because of water saturation, depth of freezing, etc.) and/or (for example, because of alteration of thickness of subgrade, changes of construction material properties, etc.). Thus, results of theoretical calculations could be used while planning works aimed at reconstructing and reinforcing railway subgrades.

The empirical studies were based upon a combination active and passive seismic methods.

For calculation of resonant frequency by passive seismic surveys, there exists a range of methods:

1. Engineering and seismic methods based upon spectrum analysis of seismic noise, allowing us to single out signals from the whole spectrum of microseisms corresponding to harmonic sources of oscillations [15]. Estimation of dynamic property of the record is based upon obtaining power spectrum $S_{ij}(f)$ for each of components of registration (i, j = X, Y, Z) and coherence function $K_{ij}(f)$ in pairs for components:

$$K_{ij}(f) = \frac{|S_{ij}(f)|}{\sqrt{S_{ii}(f) \cdot S_{jj}(f)}},$$

where $|S_{ij}(f)|$ – mutual averaged spectrum. Coherence function is practically a correlation coefficient for each frequency constituent, present in registration component [16].

For monitoring dynamics of microseismic process of alterations in time of changes of these estimations are analysed. Calculations are carried out in moving average, spectral time diagrams (STD) are built up – $S_{ij}(f, t)$ for corresponding records.

2. H/V Methods – the relation of the horizontal to vertical components of microseism. This method has been described in the studies [17] and is based upon the fact that resonant frequency of fundamental mode can be determined from the relation of spectra of horizontal and vertical components of seismic noise:

$$f_{r0} = \sqrt{\frac{S^2(\omega)_{NS} + S^2(\omega)_{WE}}{2S^2(\omega)_V}},$$

where $S(\omega)_{NS}$, $S(\omega)_{WE}$ – spectra of horizontal components of the record; $S(\omega)_V$ – spectrum of vertical component of the record.

Thus, bearing in mind dependence upon conditions, we can use either theoretical or empirical approaches to determination of resonant frequencies of railway subgrade soils.

By virtue of multichannel analysis of surface waves on the basis of field records of wavefield, velocity models of alteration of transverse wave speed value have been obtained. This method was first described in the studies [18, 19, 20] and was further improved in the study [21]. The method allows obtaining one dimension velocity models of geological terrain along linear seismic profiles on the bases of analysis of dispersive properties of surface waves. The multichannel method of surface waves analysis is based upon the spectral-wave (f-k) signal transformation followed by its addition in all channels [22].

As the active seismic methods, engineering seismic tomography was used for refracted and reflected waves [23], which was used for geological and geophysical profiles, identification of possible zones of inhomogeneities and determination of velocity properties of terrain. The refracted waves method is based on determination of refracted wave travel time (longitudinal or transverse) from the source of its excitation till the registration point. One of the conditions for this method to be applied is to increase velocity of transverse waves with depth. The depth of occurrence is calculated by the system of catching and counter travel time, combined by methods t_0 and time fields, refracting boundaries are created; boundary velocity in refracting layer and relation V_s/V_p characterise its lithology [24].

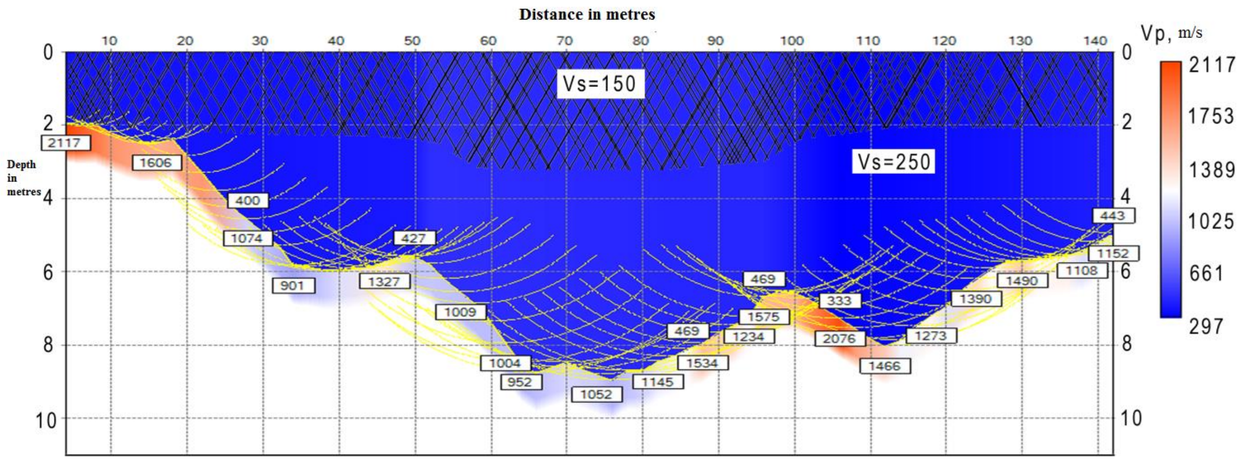
Result of the studies

In the picture 2 the generalised velocity depth profile I (scheme can be seen the picture 1) in the section with "subgrade and underlying soils" system of disturbances is shown. The integration of active seismic methods allows receiving a more detailed velocity profile. Using methods of multichannel analysis of surface waves, we achieved to detect lower boundary of subgrade, which was not possible to do by means of refracted waves method due to excessive noise contamination.

Thus, the first boundary is singled out in the depth from 0 till 3 metres, average transverse waves velocity, determined by method MASW (multichannel analysis of surface waves), made 150 m/s, relation was $V_s/V_p = 0.33 - 0.4$ and corresponded to sand and gravel layer [5, 7].

Refracted boundary is detected at the depth from 2 till 5 metres, with noticeable immersion in the centre up to 8−9 metres. Average velocity of transverse waves before the boundary $V_p = 333 - 443$ m/s, thus making it an aerated zone. The relation $V_s/V_p = 0.56$ makes it possible to assume that this layer is characterised by intercalation of sand, sandy loam and loam of ice age [5, 7].

Further below, there is a layer with increased velocities up to 2117 m/s, which corresponds to clay water-saturated depositions.

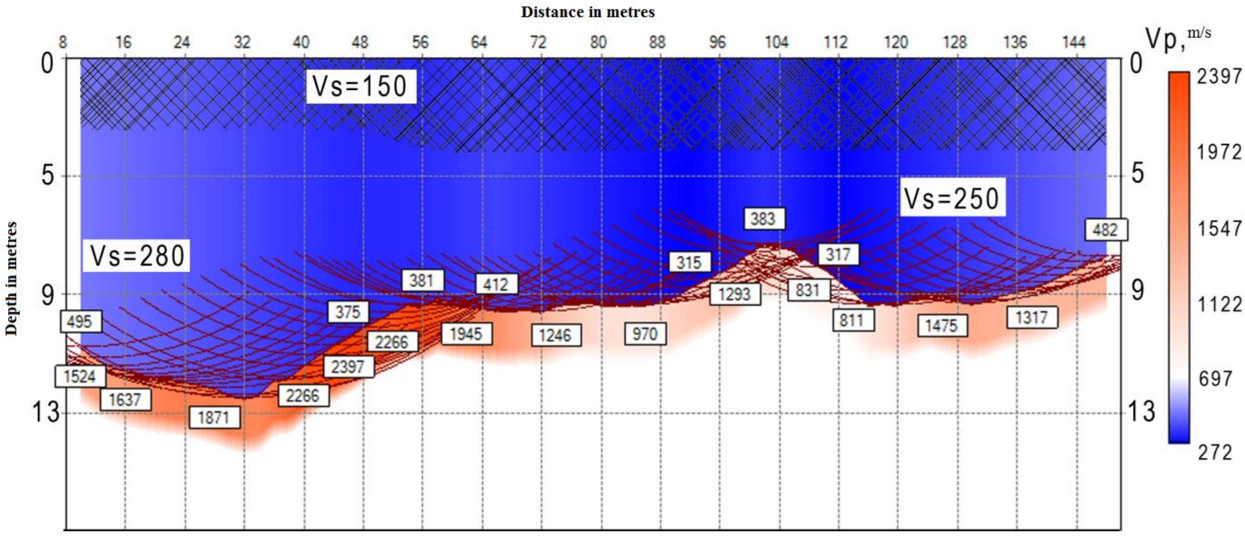


Pic. 2. Generalised velocity profile I. Hatched lines – lower boundary of subgrade, detected by virtue of MASW

In the picture 3, the velocity depth profile II (scheme is in the picture 1) in the section with “subgrade-underlying soils” disturbance system is shown, but on the other side of the subgrade with profile I. Just like profile I, the layer with crushed rock and sand depositions was singled out by means of MASW, at a depth from 0 till 4 metres, whereby average transverse waves velocities make 150 m/s, the relation is $V_s/V_p = 0.3 - 0.47$.

Refracted boundary is detected, according to both methods at a depth from 8 till 12 metres with deep submergence at the beginning of the profile. Average transverse waves velocities up to the boundary is $V_p = 315 - 495$ m/s, average transverse waves velocities(V_s) at depths from 3 till 13 metres are from 250 till 280 m/s, the relation is $V_s/V_p = 0.56$. It could be assumed that these properties correspond to intercalation of ooze, loam, sandy loam and sand of ice age.

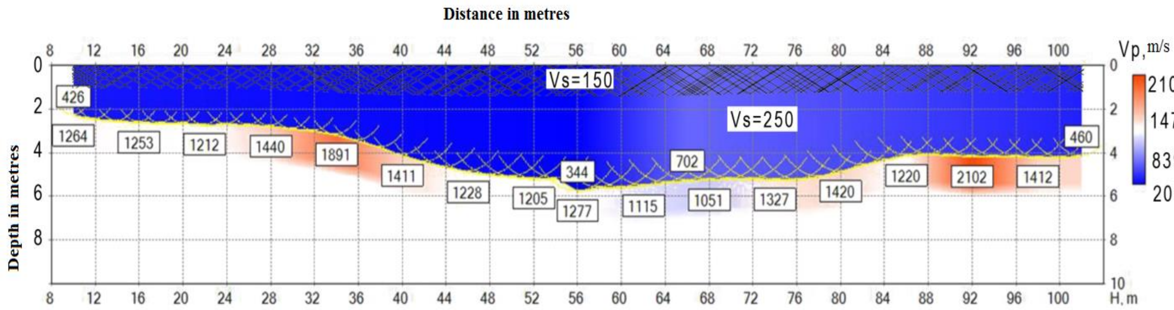
In the lower layer, high boundary velocities up to 2397 m/s are registered, which presumably correspond to clay water-saturated depositions [7].



Pic. 3. Generalised velocity profile II (4-6), hatched lines – lower boundary of subgrade, detected by virtue of MASW

Thus, in an unfavourable section a layer of soils (from 4 till 8 metres) with decreased velocities is singled out; this section has various gradients – relied made by glacial deposits. This peculiarity is also underlined by increased velocity properties – water saturation of clay rock, which is presumable is one the reasons of this sections soils' subsidence.

In the picture 4, one can see the velocity depth profile III for a favourable section without any disturbances in the system "subgrade-underlying soils". A layer of crushed rock and sand was detected by virtue of MASW at 1.5 metres. Refracted boundary is detected at depths from 2.5 till 4 metres with a slight 5 metres sag in the centre. Average transverse waves velocities up to the boundary are $V_p = 344 - 702$ m/s. Average transverse waves velocities in the upper level (V_s) are from 150 till 250 m/s/, the relation is$V_s/V_p = 0.35 - 0.43$. It could be assumed that, these properties, just like in the previous section, correspond to intercalation of crushed rock and sand layer, loamy ooze, sandy loam, and sand of ice age [7]. Below, there lies a layer of presumably water-saturated deposits (velocities from 1212 till 2102 m/s).

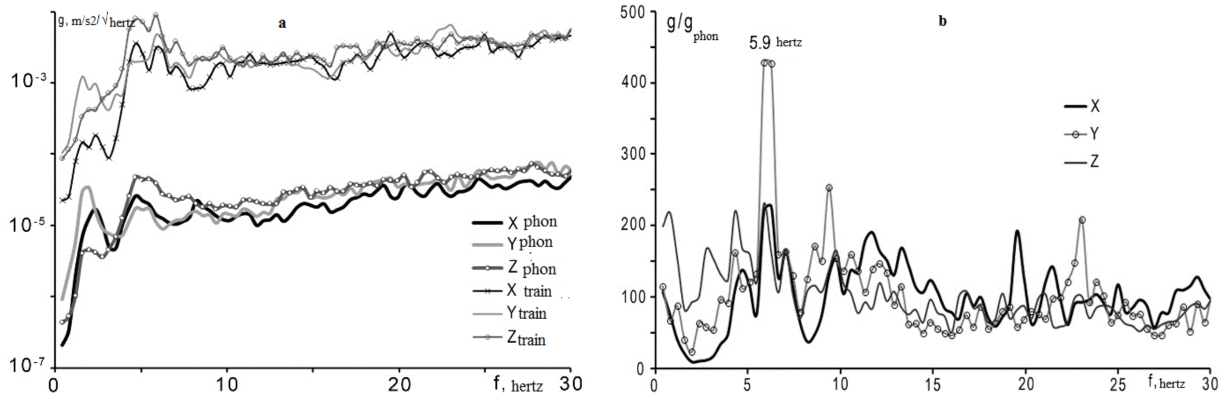


Pic. 4. Generalised velocity profile III (7-8), hatched lines – lower boundary of subgrade, detected by virtue of MASW

As it is seen from the picture 4, this section's layer with decreased velocity has significantly lower capacity and relatively flat boundary, and values of velocity increase are solitary. This fact indirectly indicates that this section soils have stronger bearing capacity.

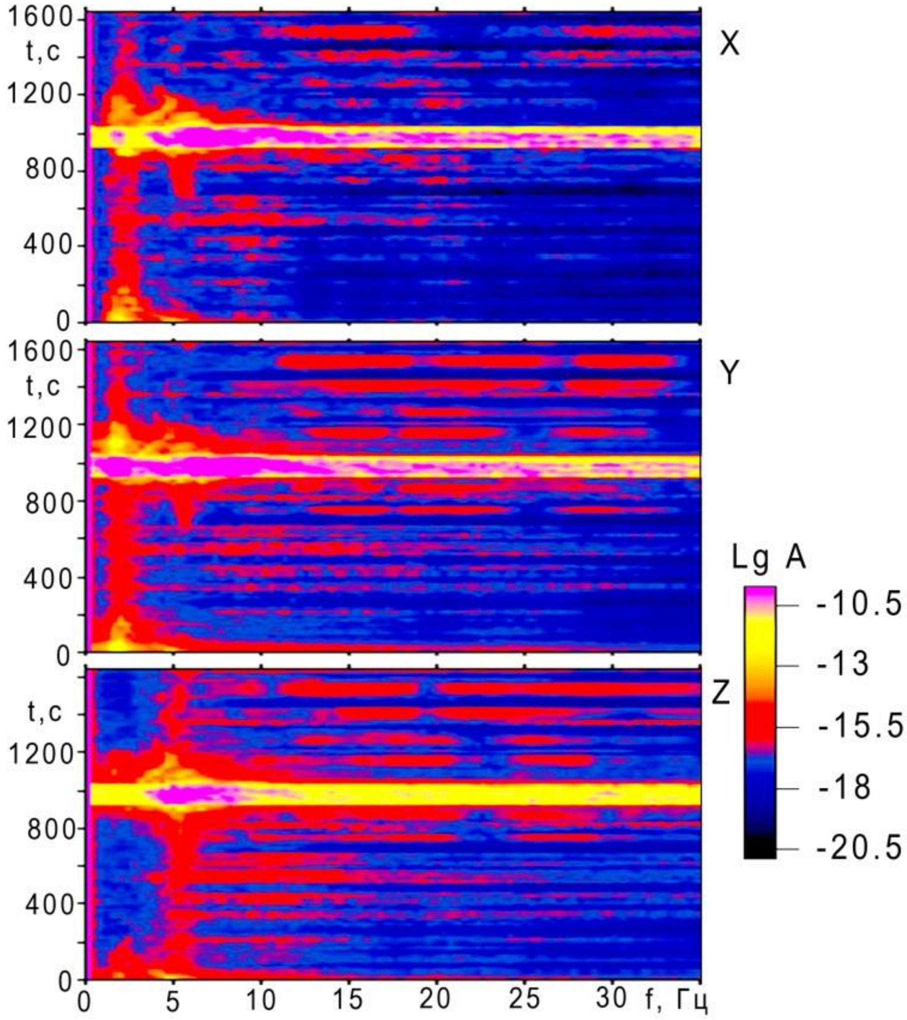
Thus, application of active seismic methods enabled obtaining velocity model of the system "subgrade-underlying soils" to a depth of 22.5 metres.

Let us carry out integration of the received information with the results of passive seismic methods. We will consider results of spectral analysis based on the data of passive seismic methods. For evaluation of levels of impact of train for the section of survey acceleration spectrums before and during the train traffic were compared (Picture 5). Two wide-range peaks, corresponding to the first and the second modes of oscillations in the system "subgrade-underlying soils", are singled out, with their ranges being equal to 1.6-2.4 hertz and 4.7-5.5 hertz. On average, passing freight trains increase general level of the system oscillation 100 times (Picture 5a), whereby the second mode is subjected to the most of the amplification of acceleration amplitude. The most "vivid" is the frequency 5.9 hertz, coming up when the greatest load of the rolling stock is exerted on the system "subgrade-underlying soils". At the same time, the amplitude of the transverse component increases twice with respect to increases at other components and for other frequencies, related to train traffic (Picture 5b). This is presumably due to curvature of the track section surveyed (Picture 1).



Picture. 5. Spectra of impacts before and during freight train traffic for unfavourable section of subgrade (a) and spectra of acceleration during train traffic (b)

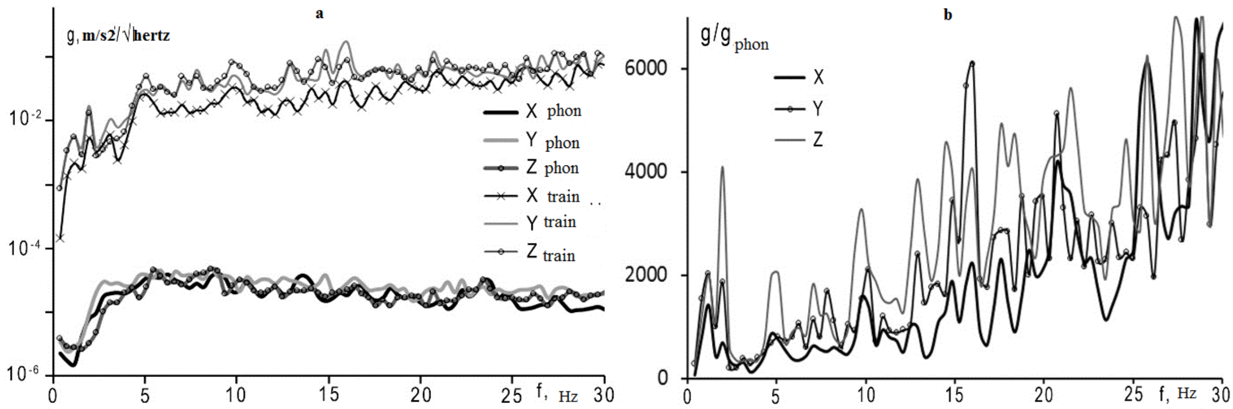
In spectral-time analysis (STAN) diagram of power spectrum of displacement velocity for unfavourable section (show in the Picture 6) two vertical lines of 2 and 5 hertz are singled out. They reflect oscillation dynamics of the system "subgrade-foundation soils". The signal is most vividly seen at frequency of 2 hertz (one of the oscillation modes of the system) for horizontal constituents (X, Y), which is due to constructive peculiarities of the subgrade. The signal at the frequency of 5 hertz is better seen in the vertical component Z, whereas in the horizontal components the signal comes up during train traffic (bright wide-range horizontal signal), which reflects occurrence of resonance during train traffic with the system “subgrade-foundation soils”.



Picture. 6. STAN – diagram of the system “subgrade-underlying soils”. Bright wide-range horizontal signal is the passing train

For comparative analysis, let us consider the same situation but for a favourable section (Picture 1), where the level of the edge of subgrade does not exceed 0.4 metres. In the Picture 7, impact spectra before and during freight train traffic in this section of the subgrade and spectra of acceleration during train traffic.

Analysis in the Picture 7 shows sufficiently equal distribution of load by frequencies. The difference of power levels of microseism phones in the state of rest and during train traffic is more than three orders of magnitude than for unfavourable sections. In the spectra, during train traffic in this section the most vividly seen peak is at 2.0 hertz, which is most like due to resonance with the system “subgrade-foundation soils”. Yet, absolute level of impact is low and does not significantly influence the state of the system considered.



Picture. 7. Spectra of impact before and during freight train traffic for favourable section of the subgrade (a) and spectra of acceleration during train traffic (b)

Discussion of the results

The dangerous physical and geological processes in the described territory along the Severnaya Railway are:

– presence in the upper layer of geological section of physically unstable oozy sandy loams and sands up to 8-12 metres;

– bog development, caused by geomorphologic location of some track parts, high level of groundwaters, presence of loose depositions of low-permeable clay depositions in the section.

Results of active seismic methods enabled singling out relatively thicker of softened soils, probably with turf, which lie under the subgrade. Sections with excessive water saturation in the foundations soils have been identified. Impact by trains, as well as resonant effect, causes its compression, leading to occurrence of subsidence. At the same time, resonant impact is not significant, whereas loads of passing trains contribute more to the state of soils.

Monitoring of the state of the subgrade for resonant frequency analysis is possible with the use of one sensor, preferably with accelerometer with lower frequency from 1 hertz. At the same time, application of short-range velocimeter will also be sufficient.

Another stage of these surveys will be assigning the calculation model and considering different situations with changes of physical properties of underlying soils and train impact.

The final stage of these studies predisposes creating functional model of technology of express evaluation, including experimental components: equipment, process of accumulation, processing and transmission of data, and decision algorithms. Implementing the theoretical task, we plan to obtain new ideas of interaction of the system “subgrade-underlying soils” and create data base of changes of bearing capacity of soils under real natural and man-caused impacts. It necessary to work out methodology of prognosis of subgrade behaviour in different options of climate changes and different loads.

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