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Engineering-seismometric monitoring of urban territories with railway transport

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Abstract. The paper addresses the geotechnical monitoring of the railway ground bed using seismometric monitoring of vibrations caused by the passage of trains, which makes it possible to detect changes in soils at the depth of several meters at an early stage. The identification of processes, which are hazardous for urban territories with a railway network, is important for safety in cities.

1 Introduction

The sustainable development of large urban agglomerations directly depends on the creation of appropriately arranged engineering infrastructure, systematic management of the urban economy, developed transport network, etc. Let us review the problem using Moscow as an example. The urban transport system includes the underground subway, the Moscow Central Circle (MCC) replacing the Little Ring of the Moscow Railways, and the Moscow Central Diameters (MCD) — a system of off-street railway lines, based on the existing infrastructure of the Moscow Railway Junction. The transport network development in the recent decade made it possible to connect the capital with 17 regional cities (Table 1).

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Table 1. Connection the capital with 17 regional cities.

Designation End stations	Length, km	Number of stations, pcs.
MCD-1 Lobnya–Odintsovo	52	28
MCD-2 Nakhabino–Podolsk	80	38
MCD-3* Zelenograd–Ramenki	83	43
MCD-4* Zheleznodorozhny–Aprelevka	86	38
MCD-5* Pushkino–Domodedovo	72	34
* prospective railway lines		

By 2023, an overground and underground subway with a total length of 1000 km is planned to be constructed, which is three times more than in 2010, with passenger traffic of about 500 thousand people per day or 391 mln passengers per year.

The integration of the overground railway transport and the underground subway into a single network requires a systematic review of the development of all parts, including the issues of urban planning, environment and safety, technology, design solutions, etc. All these issues shall be reviewed prior to the construction of new residential complexes in the territories in close proximity to the transport infrastructure. It is important that investments into the transport system increased the demand for the territories, which had been little used before.

The housing with convenient transport access to transfer hubs and stations is attractive for investors and developers; the demand for both residential and commercial real estate is growing. For example, multi-story residential complexes Life Botanic Garden, Yes Botanic Garden, and Silver were built after the commissioning of the MCC/subway Botanichesky Sad stations. Large and highly comfortable complexes are located near Ulitsa Narodnogo Opolcheniya, Aminyevskoye Shosse, Nagatinsky Zaton (Korabelnaya), Tekhnopark, and Lefortovo stations.

However, there are still a number of unresolved issues, one of which is the assessment of the mutual impact of large-scale construction and intensively operated railway lines. The urban planning renovation, i.e. the active development of outskirts and unoccupied industrial areas for large-scale construction, changes the relief and properties of soils in rather large territories. On the one part, it causes changes in the properties of the railway ground bed, which may lead to a reduction in the bearing capacity of beds, i.e. an increase in the accident rate. On the other part, the constant growth of the passenger and freight traffic intensity requires stricter safety measures related to railway transport. Therefore, it is necessary to detect hazardous processes in soils at an early stage of negative phenomena development and perform continuous instrumental monitoring.

Until recently, it has been very difficult to meet these requirements due to a number of reasons. First of all, due to the sensitivity of monitoring methods. The issues of earth bed surveys were considered in a number of fundamental studies [1-3]. As a rule, conditions close to the emergency ones are detected in soils already in the first meters of depth. The changes in the groundwater regime caused by construction may cover greater depths and affect the properties of the top layers. Therefore, the first requirement for engineering-seismometric monitoring is to identify minor changes in the properties of the environment and not only in the top of the earth bed. The capability to identify seasonal and weather changes shall be one of the criteria of monitoring method sensitivity. We assessed the required sensor sensitivity in the course of modeling [4, 5].

Another reason is the need for continuous monitoring. There are almost no such seismometric methods used in the transport industry. At present, various modifications of surveys are used: the passage of a special-purpose car, shallow seismic survey, etc. Besides their sporadic nature, they are expensive and require specialized data processing. The use of rolling stock as a source of vibration for radiographic inspection of soils can solve the problem. The idea is not new, but previously only the high-frequency part of vibrations was considered. Our priority is the use of the long-period component of vibrations from a train for monitoring.

Finally, monitoring the condition of rather large territories (e.g. for the MCC, MCD) requires automation of data collection, processing, and transfer, and all this shall be done in real-time.

Our goal was to present the fundamentals of the new seismic method for the continuous monitoring of transport route beds using trains. The main task was to identify the parameters of seismic records that are sensitive to changes in the environment.

2 Materials and methods

2.1 Field observations

The study is based on the experimental data obtained in the course of several field seasons at the Northern Railway in the area of Onega town. A complex of geological and geophysical surveys was conducted in order to identify the structure and properties of the environment [6]. Seismometric observations near the railway bed (about 5 m) at a depth of 1 m were used as the materials for the paper. Below we discuss the results of recording vibrations from passing trains with a three-component seismic velocimeter sensor TRI (Trillium Compact 120s with a Centaur recorder (Nanometrics, Canada)). The horizontal components were oriented longitudinally (X) and transversely (Y) to the embankment. The observation results allow us to obtain the absolute level of vibration velocity. The specific feature of such a type of sensors as compared with normally used ones is the capability to record low-frequency vibrations (below 0.1 Hz), which has not been done previously in railway bed surveys.

New capabilities let us obtain new results. A train passage record was made in a broadband range (0.008–100 Hz) and using a low-frequency (LF) filter (0.1 Hz and less). A high-frequency (HF) filter in a 5–8 Hz band was also used for processing. These filters are the most informative as the results of their use provide rather detailed waveforms for various types of trains.

In the course of continuous observations from April 24 through June 16, 2019, the passage of 1957 trains of various types (freight, passenger, etc.) was recorded, which, on the one hand, became a great opportunity for statistical processing and, on the other hand, allowed us to create algorithms for the automation of processing seismic records regardless of the train type.

The first step of the automation was to identify the record part corresponding to the train passage. For this purpose, we used the STA/LTA algorithm, which is applied in seismology and based on amplitude ratios in short and long time intervals [7]. Then the recording parameters were calculated, which were selected as shown below. The assessment of the informative value of the parameter describing soil condition is based on modeling and experimental data on the parameter/time dependence (in our experiment, at the variation of meteorological conditions).

2.2 Modeling

At the beginning of our studies, we used numerical modeling to understand the roles of various significant changes in the soil condition affecting the values of displacements in soil [4, 5]. Such an approach makes it possible to gain a qualitative understanding of the problem and determine the required sensor sensitivity for the identification of processes in the environment. Taking into account the diversity of soil conditions and situations of their changing, we have to consider a vast number of models to determine if it is possible to monitor hazardous phenomena at an early stage, but it will not provide any clarity in what can be observed experimentally. A more effective way is to obtain analytical solutions for the embankment deformation problem, including parameters characterizing soils.

Two models were selected: No. 1 — a homogeneous deformable half-space with a train as a moving force creating displacements in the set point of the soil — the Boussinesq problem [5] and No. 2 — an elastic layer on a viscous half-space, where stresses develop in the environment incorporating the embankment and subsoil and are distributed horizontally according to the diffusion laws — the Elsasser model [8].

Model No. 1 is applicable to waveforms of the vertical component of displacement velocities in the LF filter:

$$\frac{dw}{dt} = -\frac{PV^2t}{4\pi\mu}\left(\frac{3z^2}{R^5} + \frac{2(1-\nu)}{R^3}\right) \tag{1}$$

where $R = \sqrt{(Vt)^2 + y^2 + z^2}$ is determined by the sensor coordinates (y, z), V is the train speed, P is the train weight, μ is the shear modulus, ν is the Poisson's ratio. As was shown earlier [5], this model describes the specific features of waveforms for the vertical component, but it does not fit to describe the horizontal components.

Model No. 2 describes the distribution of stresses in the top layer [9] depending on the distance from the bed and time after the train impact. This corresponds to the situation observed for the horizontal components and will be discussed below.

3 Results

The following results are substantial for monitoring the condition of the railway bed in urban territories with the identification of hazardous processes at an early stage:

– the identification of seismic recording parameters that are sensitive to small changes in the soil condition, e.g. seasonal or meteorological changes. This guarantees monitoring success as it is obvious that the parameters describing hazardous processes are superior to seasonal parameters and the latter can be considered as noise or an estimation error,

– taking into account the areas covered with the railway network in the city, the identification of the parameters that will be informative for monitoring shall be automated, mainly at the observation point, in order to reduce the flow of data transferred to the data center.

Let us pay special attention to these issues.

3.1 Monitoring sensitivity. Vertical component

To compare the calculations for model No. 1 with the experimental data, the following parameters were set: $\mu = 10^9$ Pa, $\nu = 0.2$, $P = 25$ tons of force per bogie or individual axis, $V = 20$ m/s (72 km/h). The experiment provided the distribution of amplitudes with several maximum values (Figure 1). The obtained calculated values of amplitudes agree well with the experimental values of vibration velocity amplitudes within the 4.6–5.2 μm/s interval (the main maximum of the histogram), i.e. at the normal train speed.

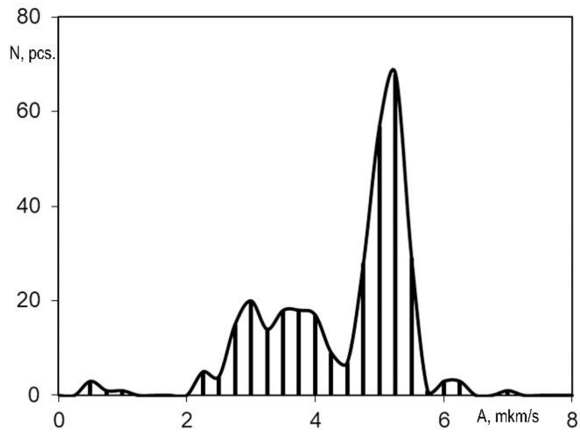

Fig. 1. Histogram of amplitudes of the SWF maximum for the vertical component at LF recording of train movement.

The ratio (1) shows that 10% variation of speed on the route (7 km/h at a speed of 70 km/h) gives the amplitude variation, which is also 10%, and which significantly exceeds the measurement error with a "good" sensor [4-6]. Besides, the collection of data on the train speed may be included in the scope of works during monitoring.

Let us determine what changes in the elastic properties of soils can be identified when monitoring the amplitude values in the Z component using LF filtration. The calculations contain the value $\mu = 10^9$ Pa, which is typical for aqueous cemented soils, frozen sands, and silty soils with frozen layers [10]. When soils thaw from -10 to -1°C, the value μ decreases by an order [10], i.e. the vibration amplitude increases by an order.

At the amplitude measurement error of 1% for a sensitive sensor, changes in the bearing capacity of such soil can be identified at thawing by 1°C, which is superior to the sensitivity of the known measurement methods. The reduction of the amplitude by 1.5 times at soil flooding in our experiments in 2017 and 2019 [4-6] corresponds to an increase in μ also by approximately 1.5 times, i.e. this parameter is reliably determined in the course of monitoring.

3.2 Monitoring sensitivity. Horizontal component

According to model No. 2, amplitudes of soil deformations were calculated depending on the position of the measurement point against the railway and the time of achieving the maximum deformation after stress relief (Figure 2). In our experiment, the distance is 5 m and the average time of achieving the maximum is 20 s.

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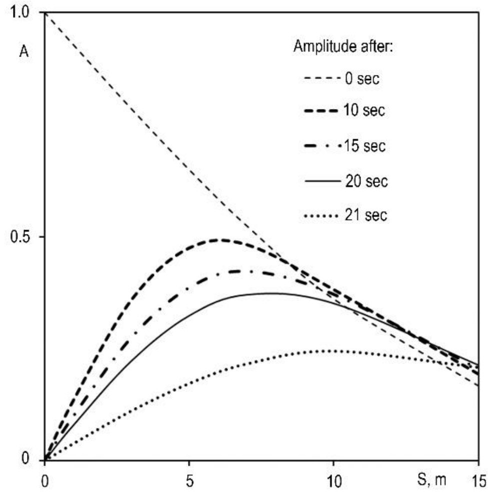

Fig. 2. Relationship between the amplitude and time of achieving the maximum in LF recording of the Y component (across the route) after the train passage, at a distance from the route.

The variation of model parameters according to possible changes in soil conditions (shear modulus, viscosity) makes it possible to assess the method sensitivity. In order to identify the impact of soil below the top of the bed and not to account for the train weight, we considered the ratio between amplitudes of the maximum values in the horizontal components X and Y after the use of LF filtration. If the viscosity is set at 4%, the amplitude reduces by 20%, which can be easily observed. It should be mentioned that the coefficient of viscosity is the soil parameter in situ, which is the most difficult to determine.

3.3 Seismic recording parameters and automated monitoring algorithms

Based on models Nos. 1 and 2 of the environment and the comparison with the experimental data, the following parameters of recording at LF filtration were considered the most informative:

– the amplitude of the first SWF maximum for the vertical component,

– the ratio between the amplitudes of the first extreme values of the tail part (after the train passage) of the horizontal components (R),

– the time of achieving the extreme values (Δt).

At HF filtration in flooding, we previously demonstrated the informative value of the ratio between the median values of vibrations in the horizontal components (X, Y) and the vertical component (Z) during train passage (R_X, R_Y) for monitoring [11].

The calculations were automated using Python 3 interpreted programming language (https://www.python.org/). Python library ObsPy (https://docs.obspy.org/) and some standard Python languages were used to process seismic data. Data processing was comprised of two stages: preprocessing and monitoring. The first stage included the following (Figure 3):

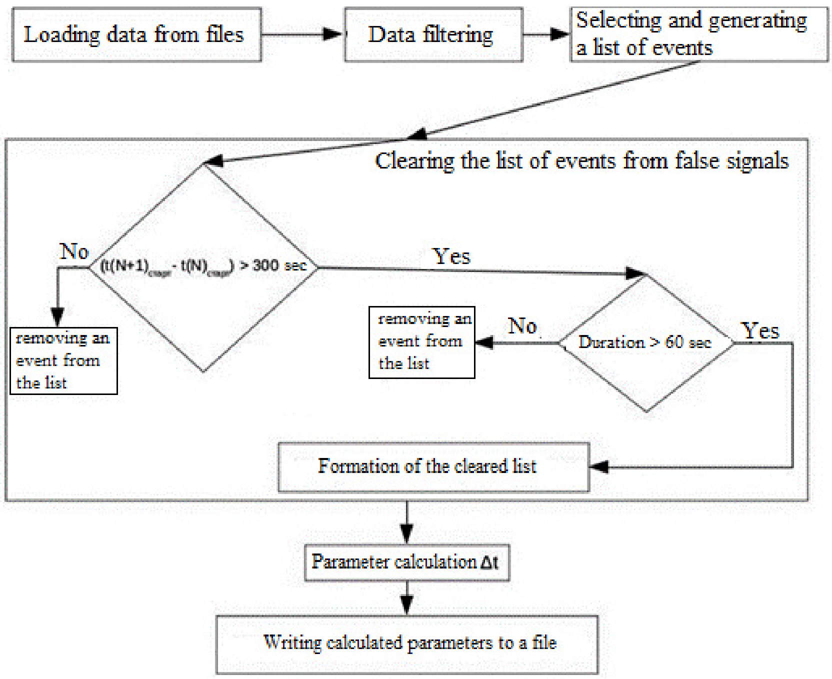

Fig. 3. Scheme of preprocessing.

– data downloading from files;

– data filtration using the filter function of the stream module in ObsPy library;

– selection of parameters for the STA/LTA trigger, identification of events, and calculation of their duration using the recursive_sta_lta function of the trigger module in ObsPy library;

– deletion of events with false triggers and trains with several cars from the list of events (short entry of an event). The final list included events with the duration of more than 60 s provided that the interval between the events (between trains) exceeded 5 min;

– calculation of the parameter (Δt) for each event;

– entry of the calculated parameters for each event into a text file.

The selection of automation methods for the assessment of changes in the soil condition over time is discussed below.

4 Discussion

4.1 Time-related changes in the monitoring parameters

The time series of the parameters obtained after data preprocessing have similar patterns. Let us analyze one of these parameters: R_Y. The time course of the assessment is fluctuating but the histogram of the values corresponds to the Gauss distribution with a median of 1.3 and a standard deviation of 0.3. This allows us to replace a large values array for each train with an average daily value (approximately 10–15 trains per day). Figure 4 shows the time course of the assessments: the average daily and weekly. The comparison shows that 7-day (week) averaging improves the assessment since it eliminates fluctuations and decreases the resulting monitoring data array.

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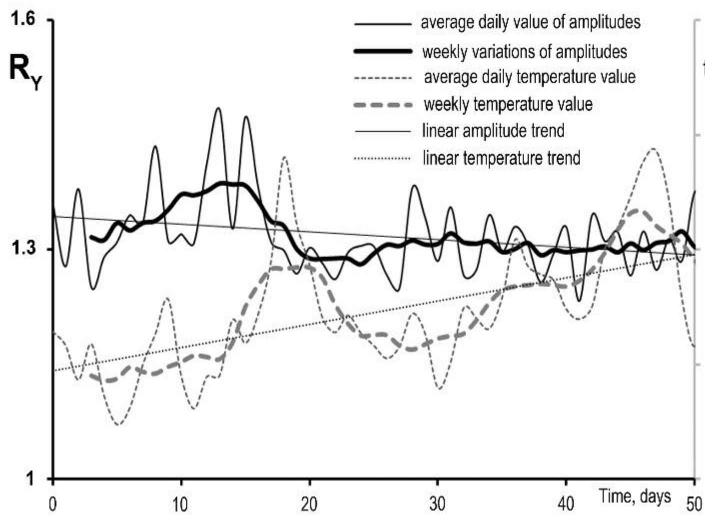

Fig. 4. Time course of the R_Y values and air temperature: average daily, average weekly, and linear trends, respectively.

But is such 7-day averaging legitimate and are all changes of the soil condition accounted for? Let us make a comparison with the average daily and average weekly temperature curves (Figure 4). Snow thawing at negative temperatures took the first 15 days, and then sharp warming was observed. The average weekly R_Y curve provides for the maximum value superseding the temperature course, which is obvious since the air temperature in the near-surface layer is determined by the soil condition. Thus, the assessment obtained for monitoring is highly sensitive to the soil condition.

It should be mentioned that when the weather and seasonal changes are settled (starting from the 30th day), the average weekly value of R_Y is almost constant, which corresponds to the results for other above-mentioned monitoring parameters with the use of seismometric observations of moving trains.

4.2 Basics of the seismometric method

The analysis of seismometric records for trains, which are informative for monitoring the condition of railway bed soils and suitable for automated processing, makes it possible to suggest the following average daily and/or average weekly values for continuous monitoring:

– the median value of ratios between vibration velocity values for the X, Y, Z components, calculated for the whole recording of the movement of each train at HF filtration at 5–8 Hz,

– the amplitude of the first maximum value of the Z component at LF filtration below 0.1 Hz,

– the ratio between the amplitudes of the first extreme values in the horizontal components immediately after the train passage (LF filter),

– the time intervals in the horizontal components after the train passage (zero line crossing) and the first extreme value (LF filtration).

The system hardware consists of the following:

1. Seismic station consisting of a broadband sensor, a digital recorder (can be integrated into the sensor), a GPS antenna or receiver, and a set of connecting cables. What is important is the following: the possibility to back up data in the internal data storage medium of the recorder; low energy consumption, the possibility of remote hardware control (setting, reset, etc.).
2. Power supply system (can be independent).
3. Data transfer systems: a cell modem/router and an antenna or a centralized unit.

5 Conclusion

The paper presents the basics of the seismic method for the continuous engineering-seismometric monitoring of the railway bed using seismic observations of vibrations created by passing trains. The basic monitoring parameters are the vibration signal amplitude and the time interval of soil relaxation.

We consider it reasonable to test the method and include it into the complex of activities to ensure transport safety in large cities, where the idea of using the existing railways for active passenger traffic is currently being developed. It is significant that the proposed system is easily implemented and can be automated.

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