Experimental Study of the Influence of a Defective Ground Surface, on Increasing the Acceleration and Movement of Sleepers during the Action of Railway Rolling Stock

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Abstract: A review of the research on the study of the outflow of heterogeneous roadbed of railway tracks on the development of irregularities on the track and its impact on the increase in dynamic impact on the track is carried out. The device and methodology for determining accelerations and displacements of railway sleepers depending on the dynamic load of railway rolling stock and taking into account the technical condition of the roadbed and crushed stone ballast of the railway track are proposed. The experimental measurements of acceleration on a railway track sleeper were also carried out, depending on the type of rolling stock and the technical condition of the roadbed. The sleepers were deposited on a section of track with a defective roadbed and on a section of railway track with a technically serviceable roadbed, taking into account the action of the type of rolling stock. It is established that the number of accelerations and displacements that occur on the sleeper when passing freight and passenger trains through a defective roadbed is higher than the passage of rolling stock through a technically serviceable roadbed. That in order to ensure a stable geometry of the railway track, it is necessary to keep the crushed stone ballast layer of the track and the roadbed in a technically serviceable condition, to prevent the development of subsidence, especially on sections of the track that are experiencing waterlogging; that the indicator of changes in the technical condition of the railway track with a defective roadbed is the amount of accelerations and subsidence of the track that occur during the passage of rolling stock of railways.

Keywords: railway track; roadbed; ballast layer; dynamic loads; rolling stock; acceleration; displacement

1 Introduction

In most countries of the world, rail transport accounts for the bulk of freight and passenger transport. However, the increased speed of movement and the load on the axle makes it necessary to maintain the railway track more reliably to ensure traffic safety and uninterrupted traffic. One of the most important structures of a railway track is the roadbed, since it can withstand the load from the upper structure of the track and the action of rolling stock. However, the roadbed is not paid proper attention when repairing the track and a sufficient number of surveys and studies of the load-bearing capacity of the roadbed are not carried out.

Waterlogged sections of the track and the effect of dynamic loads from railway rolling stock have a significant impact on the loss of load-bearing capacity of the roadbed. The amount of dynamic load of railway rolling stock on the track largely depends on developing irregularities in the ballast layer (Fig. 1), which is proven by the experimental studies [1].

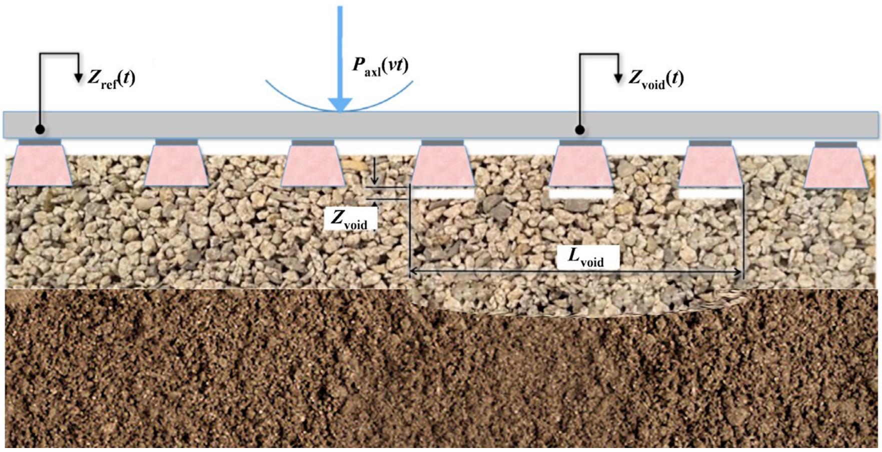


Figure 1

Subsidence of railway track ballast with the formation of voids under the sleepers [1]

As a result of the conducted research in [1], it was found that sections with backlashes are characterized by a dynamic effect during the passage of rolling stock wheels, that is, the amount of backlash Z_{void} has a significant impact on increasing the dynamic addition of forces to the track. This requires identification of such track faults and their immediate elimination. It is also noted that multi-point measurements using high-speed visualization are necessary for railway track diagnostics. The proposed method for estimating the parameters of track backlash involves taking into account the local stiffness of the track, which is considered as a possible cause of its (backlash) origin and development.

In work [2], it is noted that the technical condition of the roadbed and ballast layer significantly affects the state of the track geometry and the cost of its maintenance, which can reach up to 30% of the total cost of current track maintenance.

When the load on the axle increases, geometric deviations and residual deformations occur in some areas that were previously in excellent condition. The main reason for these phenomena is that stress limits occur in relatively weak elements of the ballast layer and roadbed. The soil of the roadbed penetrates the ballast layer, due to which the load-bearing capacity of the roadbed is significantly reduced. Therefore, assessing the influence of the ballast layer state on the dynamic load of rolling stock on the track is an urgent task of scientific research.

Of particular importance is the assessment of dynamic characteristics and determination of the safety margin of an existing heterogeneous roadbed that is used for a long time.

To assess the impact of a faulty roadbed on the dynamic load of the track, the paper proposes a method based on measuring accelerations on the railway track sleeper during the passage of railway rolling stock and determination of the sleeper displacements depending on the technical condition of the roadbed.

For the study, it is necessary to perform experimental measurements of accelerations and movements of the railway track sleeper depending on the technical condition of the roadbed and the type of rolling stock of the railway and analyze the results of field experimental studies.

2 Analysis of Literature Data and Problem Statement

With increasing loads on crushed stone ballast and roadbed and waterlogging of the roadbed, the subsidence and deformation of the railway track increases in areas with a long service life [2], which causes an increase in the dynamic impact on the railway track from railway rolling stock.

In works [3] [4], laboratory studies of railway track ballast subsidence under dynamic load are presented, depending on the method of ballast lining. It is established that the type of lining has a significant impact on the ballast compaction, which ultimately causes the stable operation of the ballast layer of the railway. However, the works do not study the effect of a defective roadbed on the dynamic interaction of track and rolling stock of railways.

In work [5], the dependences of the passage of the impact velocity through a ballast prism are established as a function of the degree of ballast compaction. It is established that when the degree of the ballast compaction increases, the speed of passage of the elastic shock wave increases, which is an indicator of evaluating the effectiveness of lining the track ballast.

The results of numerous experiments [6] indicate that the poor technical condition of the roadbed is the reason for limiting high speeds.

Nowadays, there are many calculated models of ground bases, which take into account deformations of the ground surface under the action of dynamic load from rolling stock, which causes defects of the ground surface, reducing its load-bearing capacity and creating a backlash under the sleepers.

In work [8], the disorder of the railway track geometry due to uneven subsidence of the ballast layer is studied. And in work [9] it is indicated that the amount of ballast subsidence is significantly influenced by the quality of repair work in the track, which is associated with the type of ballast lining used.

In work [10], a model for determining the stress-strain state of a railway track is proposed based on the Wave Theory of stress propagation, which can be used to justify the design of the track or establish permissible values of traffic speeds depending on the state of the track.

In work [11], a method for calculating the stress-strain state of the roadbed and railway track during their joint work is presented based on an axisymmetric columnar model of the soil base, which takes into account heterogeneity (layering) in depth. At the same time, the proposed algorithm makes it possible to determine both the displacement of the base and the stress state, which, in turn, allows estimating the load-bearing capacity of an inhomogeneous roadbed.

In work [12] it is proved that in case of poor-quality compaction of railway track ballast, there are additional dynamic loads on the roadbed of the railway. And this ultimately causes an increase in the dynamic load on structures made of metal corrugated structures of the railway track. Therefore, for the stable operation of transport structures made of corrugated metal structures, it is necessary to keep the railway track ballast in a technically sound condition. However, the paper does not present studies of track subsidence over structures under the action of railway rolling stock.

In work [13], the stress-strain state of the roadbed of a railway track reinforced with tubular drains was studied. It is established that tubular drains cause decompression of the roadbed of the track, and this, in turn, leads to an increase in the dynamic effect on the track. However, studies of increasing the dynamic effect of rolling stock on the track due to loosening of the roadbed were not made.

Promising means of assessing the technical condition of the track are measuring the stiffness of the track by using systems installed on the track or vehicles [14]. There are train-based measurement systems for measuring hardness, such as the rolling stiffness measurement wagon (Rolling Stiffness Measurement Vehicle) of the Swedish railway; Chinese gauge system (The Chinese Track Stiffness

Measurement System); American Track Loading Vehicle; (Swiss Track Stiffness Measurement Vehicle).

In work [15], a method for measuring ballast layer sedimentation using measuring devices installed on railway rolling stock is proposed.

Measurement systems allow identifying voids under sleepers by the nonlinear stiffness of the track; however, the system has many technical limitations, such as low speed and measurement accuracy. Frequent use of the systems is limited by the high costs that arise due to the need to use special measuring systems.

Systems for measuring the technical condition of the track based on sensors installed directly on the track to determine the stiffness of the track in transition zones are given in work [16]. Three different measurement systems were used to measure the dynamic subsidence of sleepers: video recording, a laser device, and a geophone.

In work [17] to identify the operating conditions of the sub-fuel base, an onboard inertial measurement system installed on trains that are in operation is used. It is proposed to perform data analysis with multiple sources to ensure rapid monitoring of the entire railway network.

Monitoring of the technical condition of railway infrastructure based on data from distributed acoustic sensing and Fractal analysis of track geometry is proposed in works [18] [19]. This approach allows distinguishing the causes of unevenness in the track geometry: interaction between sleepers and ballast (hanging sleepers), poor performance or contamination of the ballast, or weak condition of the roadbed.

In work [20], a non-contact and non-destructive method is presented for evaluating the bending behavior of concrete sleepers under various conditions of the substrate. The method is based on laser spectrum imaging. This method was successfully implemented to determine deformations on railway tracks and tested in the laboratory. An approach to monitoring the state of the substrate using inertial measurements is presented in work [21]. This approach offers identification of sleeper deflection and track elastic modulus.

In work [22], a method of non-destructive testing of the degree of compaction of railway track ballast based on the pulse response method is proposed. It is established that increasing the compaction of the track ballast causes increasing the speed of the impact wave passage through the ballast prism.

In work [23], the dependence of railway track ballast compaction on the dynamic load on the ballast is established. It is established that the highest degree of ballast compaction on the track is achieved during the cyclic action of the load.

In work [24], the waterlogging influence of the roadbed of a railway track on its stability and strength is studied. It is established that waterlogging of the roadbed leads to forming hidden irregularities under the sleepers and ballast layer, which as a result increases the dynamic load on the railway track.

In work [25], the experimental studies were made to determine the distribution of compaction along the length of the sleeper. It is established that the ballast is compacted heterogeneously along the length of the sleeper under the action of a cyclic load. The ballast has the largest seal in the sub-rail base and the smallest in the middle of the sleeper.

In work [26], the experimental and theoretical studies of the effect of lateral ballast lining on the amount of its compaction under the sleeper in the sub-rail zone are presented. It was found that the sidelining seals the ballast well in the sub-rail zone.

A separate group of studies of the effect of ballast on the disorder of the geometry of switches is represented by the studies given in works [27-32]. In works [27] [28], the study monitoring of switches using inertial measuring systems located on railway rolling stock is carried out. A method for processing the measured signal using machine learning is also presented.

In the works [29] [30], it is established that the indicator of changes in the geometry of switches due to a disorder of the track ballast is the number of accelerations that occurs during the passage of railway rolling stock.

In the works [31] [32], studies of the dynamic characteristics of switches are carried out using stationary measuring systems. It is established that in the presence of backlash under the crosspiece bar, the number of accelerations increases under the action of the rolling stock of the railway and the disorder of the switch accelerates.

In the work [33], the authors conducted studies of the dynamic deflection of a rail by the method of propagation of elastic waves in a railway track.

In the work [34], the authors conducted studies of the operational suitability of tram tracks by dynamic measurements.

In [35], the problems of operating a modern railway are described.

In the work [36], FE Modeling of the Concrete Canvas was carried out for using in railway tracks.

In the work [37], the authors conducted studies of the effect of ballast reinforcement with geogrids on changing the geometry of railway tracks, and in the work [38] they conducted studies of the effect of humidity on the operation of railway track ballast.

Authors in the work [39] explore the relationships between mechanical and geometrical properties, particularly focusing on the interplay between the flakiness index, shape index, Los Angeles abrasion, Micro-Deval wear, and methylene blue assessments. This study rigorously investigates the interdependencies among a suite of crushed stone aggregate characteristics to enhance material selection for infrastructure projects.

The above literature analysis shows a wide range of studies on the effect of loosening the roadbed and ballast layer on increasing the dynamic effect of rolling stock on the track and changing the track geometry. However, most studies are based on theoretical studies with low experimental justification, since an inhomogeneous roadbed requires special research methods due to its complex configuration of physical and mechanical properties. Moreover, the physical and mechanical properties of an inhomogeneous roadbed tend to change rapidly when exposed to various factors such as moisture, vibrations, freezing, etc.

Thus, improving train safety depends on the technical condition of the railway track. A special impact on the track has the development of irregularities on the track, which is associated with the subsidence of the roadbed and the formation of voids under the sleepers (backlashes), which lead to increased loads and disruption of the geometry of the railway track.

Therefore, this work studies the influence of a defective roadbed and the type of rolling stock on changes in dynamic indicators (accelerations, displacements) when railway trains move along the track. For this purpose, the experimental measurements of accelerations that occur on the upper platform of the sleeper on a section of track with a serviceable and defective roadbed are carried out.

The objective of the work is to make the experimental studies of the influence of a defective roadbed on the change in the accelerations and displacements of the sleeper under the action of railway rolling stock, which will allow setting up the dependence of the accelerations and displacements of the sleeper on the technical condition of the roadbed and the type of railway rolling stock.

To achieve this objective, the following tasks were needed:

- Develop a device for experimental study of accelerations and displacements of railway track sleepers under the action of railway rolling stock
- Make full-scale experimental studies of accelerations and displacements of sleepers on track sections, depending on the technical condition of the roadbed and the type of rolling stock of the railway

3 Materials and Methods for Studying Accelerations and Displacements of Railway Track Sleepers under the Action of Rolling Stock

3.1 Description of a Railway Track Section for Experimental Measurements of Sleeper Accelerations and Displacements

One of the manifestations of a waterlogged decompressed roadbed is the subsidence of the rail-sleeper grid and contamination of the ballast with soil particles due to the dynamic operation of the structure. Also, an important indicator of the presence of a defective roadbed is the friction of ballast material particles with each other or grinding, which manifests itself in the form of white spots on the ballast. These phenomena are observed on sections of railway track where there is a defective roadbed for a significant length of several sleepers, which causes large deflections of the track and wear of the ballast material. One of these problem areas of the railway track is shown in Fig. 2.

Figure 2
Defective section of the railway track with a technically faulty subgrade

The studied section of the railway track consists of reinforced concrete sleepers of the SB 3-0 type weighing 280 kg, 2.7 m long and rails of the P65 type weighing 1 m – 64.88 kg, cross – sectional area-82.65 sm^2. Ballast layer is the crushed stone with a height of 45 cm. The roadbed is defective, with solid bulges at a length of about 50 m.

To study the accelerations and displacements of a reinforced concrete sleeper on a railway track, these parameters are measured using the developed device (see Section 4.1). Accelerations are measured on the sleeper using high-frequency acceleration sensors when passing railway rolling stock.

3.2 Method of Experimental Measurements of Accelerations on Railway Tracks

The method of full-scale experimental measurements of accelerations provided for measurements on a section of a railway track with a defective subgrade and a serviceable one. The scheme of experimental measurements of railway track accelerations is shown in Fig. 3.

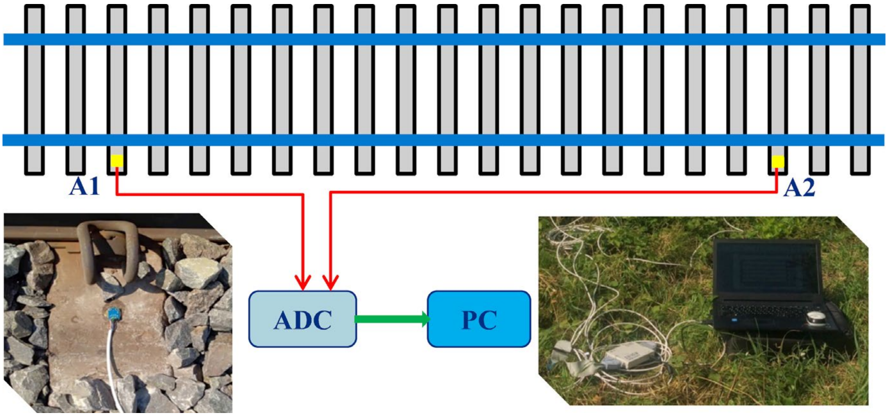


Figure 3
The scheme of experimental measurements of railway track accelerations

Accelerometer A1 was located on a reinforced concrete sleeper on a site with a serviceable roadbed and a well-compacted ballast layer, and accelerometer A2 was located on a reinforced concrete sleeper with a defective roadbed and compacted ballast, approximately in the center of the defective place where the maximum deflection of the rail was observed.

When passing the operational rolling stock of the railway, accelerations were recorded simultaneously from two acceleration sensors.

When analyzing the measured acceleration values, digital signal filtering is used, under the recommendations given in works [40]. High-frequency components in the input signal spectrum are excluded and frequencies corresponding to the natural vibrations of the rolling stock-track system are selected.

Then, according to the obtained values of the acceleration signal $\boldsymbol{a_z}$, we determine the speed by an integration method according to the trapezoidal approximation [41] by the formula:

$$V_z = \sum_{i=1}^{n} \left[\frac{\left(a_{z_{i-1}} + a_{z_i}\right)}{2} \cdot \Delta t \right] \tag{1}$$

where Δt are the time interval between acceleration values; a_z – values of vertical accelerations.

To get the values of sleeper displacement the speed values Vzare integrated by the formula:

$$S_z = \sum_{i=1}^{n} \left[\frac{\left(V_{z_{i-1}} + V_{z_i}\right)}{2} \cdot \Delta t \right]. \tag{2}$$

where V_z – speed.

Thus, having twice performed the integration of the acceleration signal, respectively, using formulas (1) and (2), we determined the displacements of the sleeper under the action of railway rolling stock, depending on the number of accelerations.

4 The Results of Experimental Studies of Accelerations and Displacements of Railway Track Sleepers under the Action of Rolling Stock

4.1 The Device for Making the Experimental Studies of Railway Track Accelerations

To make the experimental studies of accelerations and displacements of railway track sleepers under the action of railway rolling stock, a measurement system is proposed. It is based on measuring accelerations at the ends of railway track sleepers using high-frequency sensors during the movement of railway rolling stock.

The proposed device for experimental measurements of railway track accelerations is shown in Fig. 4. When performing experimental acceleration measurements, the signal from analogue sensors A1 and A2 is transmitted to an analogue-to-digital converter (ADC). With special software, the parameters of the measured signal are recorded and processed and displayed on the screen of a personal computer (PC).

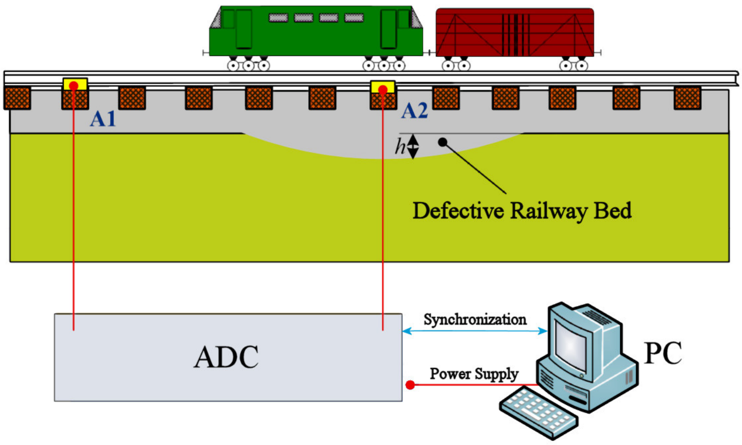


Figure 4
The device for experimental measurements of railway track accelerations is proposed: A1, A2 are accelerometers, ADC is an analogue-to-digital converter, PC is Personal Computer

Further, the measured signal for the entire period of specific measurements is stored in the computer's memory for further desk processing and analysis.

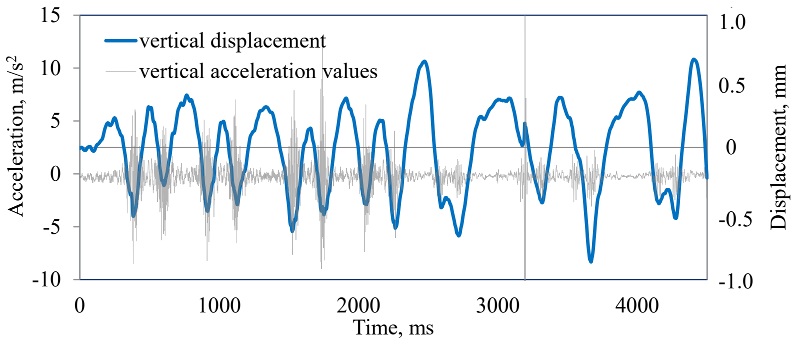
To power and ensure the operation of analogue acceleration sensors, an ADC is used, which outputs a voltage of 5V, which is sufficient to power the accelerometers, while the ADC is connected to a PC. Receives power from a personal computer and transmits the measured data from accelerometers.

An ESP 8266 microcontroller was used as an analog-to-digital converter, and ADXL 335 analog accelerometers were used to measure accelerations. Experimental measurements were processed in the Matlab software package.

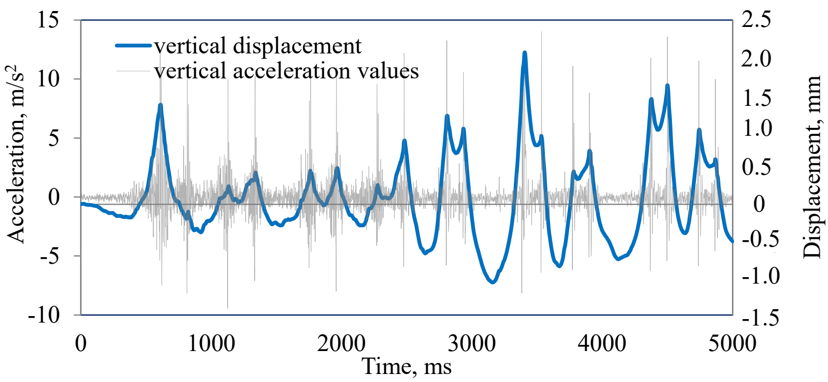
The proposed scheme of the device for measuring railway track accelerations ensures high measurement accuracy and stability of operation under operating conditions. It allows displaying real-time acceleration graphs that occur from the passage of railway rolling stock, which can warn in time about changes in the technical condition of the track due to a malfunction of the ballast of the railway track with a defective roadbed.

4.2 The Results of full-Scale Experimental Studies of Accelerations and Displacements of Sleepers on Track Sections Depending on the Technical Condition of the Roadbed and the Type of Rolling Stock of the Railway

In this experiment, the values of accelerations and displacements of sleepers during the passage of freight and passenger trains on a defective and technically serviceable roadbed are obtained. The frequency of discretization during experimental acceleration measurements was 1000 Hz. The speed of the freight train is 60 km/h, and the passenger train is 80 km/h. The load on the axle from the freight car is 116 kN, and the locomotive is 230 kN. The results of experimental measurements of track accelerations and displacements during the passage of a freight train are shown in Fig. 5.



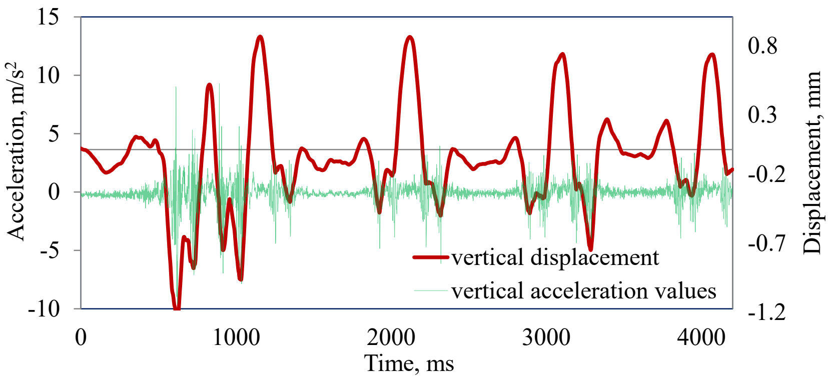
a



b

Figure 5
The record of accelerations on the sleeper when passing a freight train when:
a is a technically sound roadbed; b is a defective roadbed

In Fig. 5 it can be seen that higher values of accelerations and displacements of sleepers are observed on a section of track with a defective roadbed. When a freight train passed through a technically sound roadbed, the maximum number of accelerations was 9 m/s^2, and the maximum sleeper movement is 0.92 mm. At the same time, the number of accelerations that occur when a freight train passes through a defective roadbed was 13 m/s^2, and the maximum sleeper displacement is 2.1 mm.



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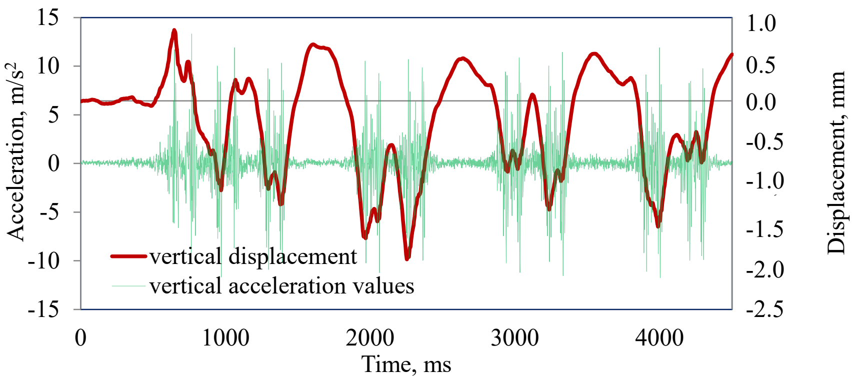

b

Figure 6

The record of accelerations on the sleeper when passing a passenger train when: *a* is a technically sound roadbed; *b* is a defective roadbed

In Fig. 6 it can be seen when a passenger train passes through a technically serviceable roadbed, the maximum acceleration value was 7 m/s^2, and the maximum sleeper displacement is 0.8 mm. At the same time, the maximum number of accelerations that occur when a passenger train passes through a defective roadbed was 13 m/s^2, and the maximum sleeper movement is 1.9 mm.

From the studies, it was established that the number of accelerations and displacements that occur on the sleeper when freight and passenger trains pass through a defective roadbed is higher than the passage of rolling stock through a technically serviceable roadbed. In addition, the track receives higher draft values when passing a freight train. Although the difference in the value of the maximum acceleration values that occur from the action of freight and passenger trains is within a small range of 1–2 m/s^2.

Analysis of experimental data shows that sections of the track with a defective (heterogeneous) roadbed are characterized by a large value of rail displacement, which is associated with an increase in dynamic impact. The dynamic effect can be seen in the results of measuring the accelerations of the sleeper in a section with a non-uniform roadbed, the accelerations increase rapidly. Also, to predict the development of the behavior of an inhomogeneous roadbed, it is necessary to consider various calculation options using mathematical modelling to determine the loads from the wheel to the rail.

5 The Discussion Results of Determining Accelerations and Displacements of Railway Track Sleepers under the Action of railway Rolling Stock

During the operation of the railway track on sections with a defective roadbed, the development of permanent deformation of the track and an increase of dynamic load from rolling stock of the railway take place. The first sign of deterioration in the geometry of the railway track is the subsidence of sleepers, which is a consequence of the development of inhomogeneities and defects in the roadbed.

To get accurate information about the condition of the railway track, to further assess the load-bearing capacity of the roadbed, a device for estimating the accelerations and displacements of the sleeper is proposed, based on high-frequency measurements of the acceleration values on the railway track sleeper.

From the experimental studies of sleeper accelerations and displacements (Fig. 5 and Fig. 6) depending on the technical condition of the roadbed and crushed stone ballast and the type of passage of railway rolling stock, it can be seen that the number of accelerations and displacements that occur on the sleeper when freight and passenger trains pass through a defective roadbed is higher than the passage of rolling stock through a technically serviceable roadbed.

It is established that the highest value of accelerations and displacements that occur on the sleeper is achieved when passing a freight train. However, it should be noted that the maximum number of accelerations that occur when a freight and passenger train passes through a defective roadbed has similar values that differ in the range from 1-2 m/s^2. In the case of passenger and freight trains passing through a technically defective roadbed, the maximum number of accelerations reached 13 m/s^2. When a passenger train passed through a technically sound roadbed, the maximum amount of acceleration was 7 m/s^2, and when passing a freight train – 9 m/s^2.

A railway track sleeper gets a greater value of displacement when passing freight rolling stock compared to a passenger one. The maximum amount of sleeper displacements that occur when a passenger train passes through a technically serviceable roadbed was 0.8 mm, and when a freight train passes through 0.92 mm. In the case of passenger and freight trains passing through a defective roadbed, the sleeper displacements were 1.9 mm and 2.1 mm, respectively.

Therefore, it is established that to ensure a stable geometry of the railway track, it is necessary to keep the crushed stone ballast layer of the track and the roadbed in a technically sound condition, to prevent the development of subsidence, especially on sections of the track that are experiencing waterlogging.

From the experimental studies of accelerations on a section of track with a defective and technically serviceable roadbed, it was found that accelerations on a defective section fade much more slowly than on a serviceable section of the sleeper track (Fig. 5 and Fig. 6). This is one of the identifiers for assessing the technical condition of the roadbed. And it can make recommendations on the need to perform repair measures of the roadbed or ballast layer on a certain section of the railway track.

Therefore, developing the methods for diagnosing the underlying base, monitoring and further planning of railway track maintenance are among the ways to reduce the cost of current track maintenance.

One of the disadvantages of the study is the failure to take into account the depth of backlash (unevenness) under the sleeper and its impact on the dynamic load from railway rolling stock and taking into account the physical and mechanical characteristics of the roadbed soils. It should be noted that taking into account the real characteristics of soils in mathematical modelling in combination with experimental tests will increase the accuracy of design solutions, which, in turn, will lead to an increase in the reliability and durability of the roadbed and railway track as a whole. These tasks are planned to be solved in the next research works.

Conclusions

A device for experimental measurements of railway track accelerations was developed, which consists of an analogue-to-digital converter, accelerometers and a personal computer. It allows for measuring accelerations on the sleeper with high accuracy and stability of operation, under operating loads. In addition, it can display real-time acceleration values that occur from the passage of railway rolling stock, in the form of graphs. This makes it possible to warn, in real-time, about changes in the technical condition of the track, due to a malfunction of the ballast of the railway track with a defective roadbed.

From the full-scale experimental studies of accelerations and displacements of sleepers on track sections, depending on the technical condition of the roadbed and the type of rolling stock of the railway, it was established that the highest values of acceleration and subsidence were recorded on track sections with a defective roadbed.

The experimental studies established that when a passenger train passes through a technically serviceable roadbed, the maximum acceleration value was 7 m/s^2, and when passing a freight train – 9 m/s^2. In the case of passenger and freight trains passing through a defective roadbed, the acceleration value was about 13 m/s^2.

It was established that when a passenger train passed through a technically serviceable roadbed, the maximum amount of sleeper movements was 0.8 mm, and when a freight train passed through 0.92 mm. In the case of a passenger train passing through a defective roadbed, the maximum amount of sleeper movements was 1.9 mm, and when a freight train passed, the number of sleeper displacements reached 2.1 mm.

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