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DEVISING A PROCEDURE FOR ASSESSING THE SUBGRADE COMPACTION DEGREE BASED ON THE PROPAGATION RATE OF ELASTIC WAVES

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This paper reports the analysis of the methods for estimating the technical condition of the subgrade underneath a constructed railroad track or road during its operation. The study results have proven that the issue related to monitoring and controlling high-quality compaction of a heterogeneous subgrade remains relevant and requires the construction of reliable experimental methods for assessing the subgrade degree of compaction.

A procedure for determining the compaction of subgrade in the laboratory has been devised, based on inertial microcomputer technologies, which makes it possible to assess the degree of compaction of subgrade soils depending on the propagation rate of an impact's elastic waves.

An experimental study has been performed into the propagation rate of elastic waves across a homogeneous subgrade made of coarse-grained sand and a heterogeneous subgrade made of coarse sand with a layer of clay in the middle of the prism. The study results established that the propagation rate of an elastic wave in a heterogeneous subgrade accepts a lower value than the rate of wave propagation in a homogeneous subgrade.

Through the dynamic interpretation, by using a discriminant statistical analysis, the characteristic features have been defined in the distribution of accelerations in the body of the homogeneous and heterogeneous subgrade, depending on the degree of compaction, which would make it possible to monitor the state of the subgrade during operation. As the degree of the subgrade soil compaction affects the technical condition of roads

Keywords: subgrade, impact's elastic wave, inertial study, wave propagation rate, density

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1. Introduction

The development of railroad transport aimed at improving the throughput capacity and increasing the speed of trains, by utilizing the resources of existing infrastructure, is possible only if the subgrade sore spots are strengthened. When exploiting the subgrade, which is the basis of roads, under conditions of increasing loads, as well as the adverse effects of natural factors, it accumulates deformations with the occurrence of irregularities. Depending on the characteristics of the soil, deformations of the subgrade may occur such as ballast bed, splashes, which leads to a loss of its stability. Therefore, the stable operation of the railroad track depends on the state of the subgrade. However, the technical condition of the subgrade is studied by a small number of scientists.

It should be noted that assessing the technical condition of the subgrade reveals certain difficulties due to the impact on its operation exerted by many factors, namely: the physical and mechanical properties of soils, moisture, vibration, elasticity, which tend to change over time. The experience of railroad operation shows that the greatest danger to the movement of trains is the deformation of the subgrade composed of clay soils. Deformations are long-term processes and their surface detection is preceded by internal processes that reduce the strength of soils in the subgrade and contribute to the formation of weakened zones and hidden cracks. Such processes manifest themselves in the form of sudden deformations.

An important characteristic of soils is their density. The degree of compaction of the soil directly affects the deformation characteristics of the subgrade. The higher the density of the soil, the smaller the deformations of the subgrade. With increasing density, the characteristics of shift resistance also increase. Deformations constantly occur in the subgrade exposed to the vibrodynamic effect of moving load, and it is important that they are elastic. If residual deformations occur, recessions may be formed on the main platform of the subgrade. Moisture accumulates in these recessions, which leads to the softening of clay soils and rapid growth of deformations, as well as damage to the subgrade.

To prevent sudden deformations, an important task is the timely detection of the subgrade sites that are potentially dangerous for trains. To this end, it is necessary to continuously diagnose all embankments that are exploited over a long time by involving modern methods and technical means.

If a heterogeneous subgrade forms, there is an issue related to the premature disarrangement of the railroad track geometry in the form of the accumulation of vertical and horizontal irregularities on the track. This affects the subsequent service life of track elements and their premature decommissioning. Therefore, the issue of monitoring and controlling the proper compaction of the heterogeneous subgrade is relevant and requires devising an experimental and theoretical methodology for assessing the degree of its compaction during the railroad track life cycle.

Taking into consideration the nature of the effect exerted by the rolling stock on the subgrade, it is a relevant task to study those processes that are manifested in the form of oscillation propagation in it. The process of elastic wave propagation in the subgrade underneath a railroad track under the action of the rolling stock depends on its physical and mechanical characteristics and reflects the actual technical condition of the track.

Establishing the dependence between the propagation time of the elastic wave at the different compaction of a heterogeneous subgrade would make it possible to analyze its bearing capacity during railroad track exploitation.

Therefore, as one of the options, we investigated the possibility of using inertial methods to assess the technical condition of the railroad track subgrade.

2. Literature review and problem statement

The soil density in the subgrade body, in the layers above the pipes, and on the sides of pipe backfill is the most important characteristic that defines their safe exploitation and should be closely monitored. During operation, the soils work in the elastic-plastic stage with the elastic or residual deformations occurring in them, depending on the loads. Such processes lead to soil compaction or loosening [1, 2]. Thus, soil density directly affects the technical condition of a structure. The normative document regulating the requirements for the coefficient of soil compaction in the subgrade underneath the railroads of Ukraine is [3], in which it is recommended to determine density by the method of standard compaction.

Normative document [4] regulates determining the soil density by three methods. These include a method of standard compaction using the SoyuzdorNDI device (Ukraine); a method for determining the maximum density according to Proctor, and the modified density method by Proctor. Mostly, the latter two methods are used in all countries of the European Union, USA, Canada, etc. [5–7]. These methods imply building a compaction curve, which reflects the dependence of the density of dry soil on its humidity when compacted by ramming [8].

The authors of work [9] report the results of comparing the three methods of determining soil density that established that the best density indicators could be derived when using a method for determining the modified density according to Proctor. The authors noted that the use of the standard method of estimating soil compaction is impossible due to the absence of shear stresses in the soil sample. It should be noted that the standard compaction device was designed by changing the structure of the Proctor device (USA).

Today's construction volumes [10] require devices that could quickly and reliably determine soil density since the existing procedure [4] takes quite a long time and does not make it possible to perfectly check the soil density throughout the site.

In work [11], in order to assess the technical condition of the heterogeneous overwetted railroad track subgrade, the authors applied a georadar method. However, a given method requires the use of expensive equipment and makes it possible to determine only the boundaries of the properties of the soil environment of the subgrade.

The authors [12] designed a portable device that makes it possible to automatically determine the actual and asymptotic module of soil deformation; it has its own energy carrier and enables the measurement and processing of results in an automated mode.

There are a large number of devices in the world market for determining the stamping module of elasticity (deformation) of the soil through dynamic testing (by dropping a load). Software is used for the correlation of values linking short-term modules to a static module and a compaction coefficient. However, the analysis of papers reveals the variety of all methods and the large time cost of research, which emphasizes the relevance of the development of a device for determining the density of subgrade soils based on a pulse response.

Study [13] found that the nature of wave propagation in the subgrade soil is influenced by its transverse profile and the types of soil arrays involved in the compaction process.

When oscillations are excited in an elastic environment, a source located near the surface forms two main types of waves – volumetric and surface. Volumetric waves in elastic solid media spread in the form of two types of oscillations depending on the direction of shear of particles, which are longitudinal and transverse. When a longitudinal *P*-wave propagates, the particles of the medium oscillate along the direction of the wave propagation; the deformation of the environment occurs. When a transverse *S*-wave propagates, the particles oscillate in a plane perpendicular to the direction of the wave propagation; the deformation of the shape occurs [14].

Surface waves, depending on the plane of particle oscillation, are divided into two types – the waves by Love and the Rayleigh waves. The Love waves are the polarized waves in which particles oscillate along the surface of the medium perpendicular to the direction of the wave propagation. These waves occur in a layered environment when the wave speed in the lower layer is lower than that in the top layer [14].

The Rayleigh waves occur near the free surface of the medium. Fluctuations of particles occur in the direction of the wave propagation in the plane that is perpendicular to the surface [14]. Both types of waves demonstrate dispersion, that is, the dependence of the phase velocity on frequency [13]. The propagation depth of the oscillations of a surface wave is directly proportional to the wavelength (inversely proportional to the frequency). A wave with a high oscillation frequency quickly fades and has a slight penetration depth; reducing the frequency makes it possible to increase the depth of propagation [13, 14].

In recent years, the European Union has been actively using and developing a method for determining the speed of transverse wave propagation based on the analysis of the dispersion characteristics of surface waves [15, 16]. A given method was devised in 1983; it is called SASW (Spectral Analysis Surface Waves).

To date, many variants of the SASW method have been developed, differing in the type of waves being studied, the mode of observation (active, passive), and the frequency range of measurements. Solving the set task is possible using the Monte Carlo method and the statistical method of maximum plausibility.

The speed of transverse waves is closely related to the deformation characteristics of soils, such as the modulus of elasticity and the shear module [14, 17].

Different methods are used to construct a theoretical dispersion curve. It is known that a Rayleigh wave has several forms of propagation (harmonics) with different values of phase velocities. Progressive inversion methods take into consideration the influence of the higher harmonics of the Rayleigh waves [18]. In some cases, it is necessary to take into consideration the effect of volumetric waves by using spectral analysis methods.

The Multichannel Analysis of Surface Waves (MASW) method was first introduced in 1999; it was published in the Geophysics journal [18]. The authors register the surface oscillations of Rayleigh waves from different sources, then these speeds are analyzed to construct a speed profile of the transverse waves.

The authors of [19] applied a method of multichannel analysis of surface waves (MASW) to measure a speed change in the Rayleigh waves. A Rayleigh wave speed depends on the soil shear module. It is also proposed to monitor changes in soil strength at certain intervals based on a change in the Rayleigh wave speed.

The authors of work [20] employed a method of inertial measurements to assess the quality of the subgrade layer underneath a railroad track. The study was performed on homogeneous gravel without inclusions.

Papers [21, 22] report the results of studying the degree of compaction of the ballast layer after the work of ballast machines of various designs. A seismic method was improved by the comprehensive dynamic and kinematic interpretation of the pulse response. In the dynamic interpretation, by using a cluster and discriminant statistical analysis, the authors defined characteristic spectral features corresponding to the degree of compaction of the ballast layer. The field measurements of the degree of compaction of the ballast layer after the work of different sequences of ballasting machines made it possible to establish the efficiency of compaction and the expediency of their use.

The authors of [23] studied the distribution properties of a ballast prism depending on the compaction of the ballast layer by a dynamic load. During the experiment, various boundary conditions for supporting the ballast layer were considered, from a complete spatial restriction of movement to the free arms of the ballast prism with a natural slope inclination. Ballast performance during loading cycles was assessed by the pressure measurements at the base of the ballast prism along the sleeper axis and, at the same time, by video registration of the movement of ballast particles through the transparent side walls of the gravel box. Measurements of pressure distribution were carried out using the developed microcomputer system of measurements and developed mesdosis, which make it possible to carry out multipoint stress measurements in a combination with measurements of accelerations and photogrammetry. The measurement results showed a significant impact of the compaction of the ballast layer on the distribution of stresses under the sleeper. The cited study opens up new opportunities for practical improvement of existing track design and the technology of making and compacting a ballast layer in terms of ensuring optimal working conditions for the ballast layer.

Work [24] reports the development and application of a method for determining the compaction of the ballast layer. The experimental study revealed a significant change in the properties of ballast in the process of its deformation under the sleeper. The work proved the possibility of applying multi-sensor sound meter measurements of a wave front propagation field instead of the complicated method based on accelerometers. The results of the measurements showed a significant local increase in the rate of longitudinal wave propagation in the ballast layer. These results are confirmed by many studies that show the existence of compaction zones under the sleeper.

Paper [25] reports a laboratory experimental study of the propagation of elastic waves depending on the magnitude of the dynamic compaction of the railroad track gravel ballast. The research results established that a significant dynamic load with a frequency exceeding 30 Hz leads to loosening the track ballast while the ballast prism becomes homogeneous. And the speeds of wave propagation along the length of the prism are the same. A new theoretical mechanism for the development of track irregularities was also proposed, which takes into consideration not only the residual settling of the ballast layer but also the occurrence of backlash under the sleepers. These factors lead to a local change in the elasticity of the track and the formation of a zone with heterogeneous compaction of the ballast layer.

The propagation of elastic waves across the grainy medium is determined by the mineralogical and granulometric composition of the grains and, to a large extent, the number of contacts between the grains, that is, the density of the soil layer. As experiments show [26], this dependence is linear. Thus, by measuring the propagation rate of elastic waves after each compaction of the soil, one can conclude about the degree of compaction.

Two important parameters that affect the speed of wave propagation across the soil are density and elasticity (shear module). Elasticity is related to shear strength via the structural matrix of the soil, which is affected by the size, shape, friction, and bonds between the grains that make up the soil skeleton [27]. Density and shear strength are interrelated with the compaction degree, which is often expressed by a soil porosity coefficient [19].

Paper [28] states that as the density of contact between soil grains and friction increases, porosity decreases. It was also established that the wave propagation speed does not directly depend on the shear strength but is considered as a qualitative indicator for assessing a change in shear strength, especially in heterogeneous soils. In coarse-grained soils, shear strength and transverse wave speed depend on the density of grains.

However, our analysis of scientific papers has revealed that there are currently no procedures for determining the compaction of heterogeneous subgrade of the railroad track. Resolving a given issue would make it possible to assess the actual technical condition of the subgrade of the railroad track, the bearing capacity, and the mechanism that could forecast the subsequent disarrangement of track geometry depending on the degree of subgrade compaction.

3. The aim and objectives of the study

The aim of this study is to devise a procedure for assessing the degree of compaction of the subgrade beneath a railroad track using the inertial method. This would make it possible to assess the degree of compaction of the road subgrade soil.

To accomplish the aim, the following tasks have been set:

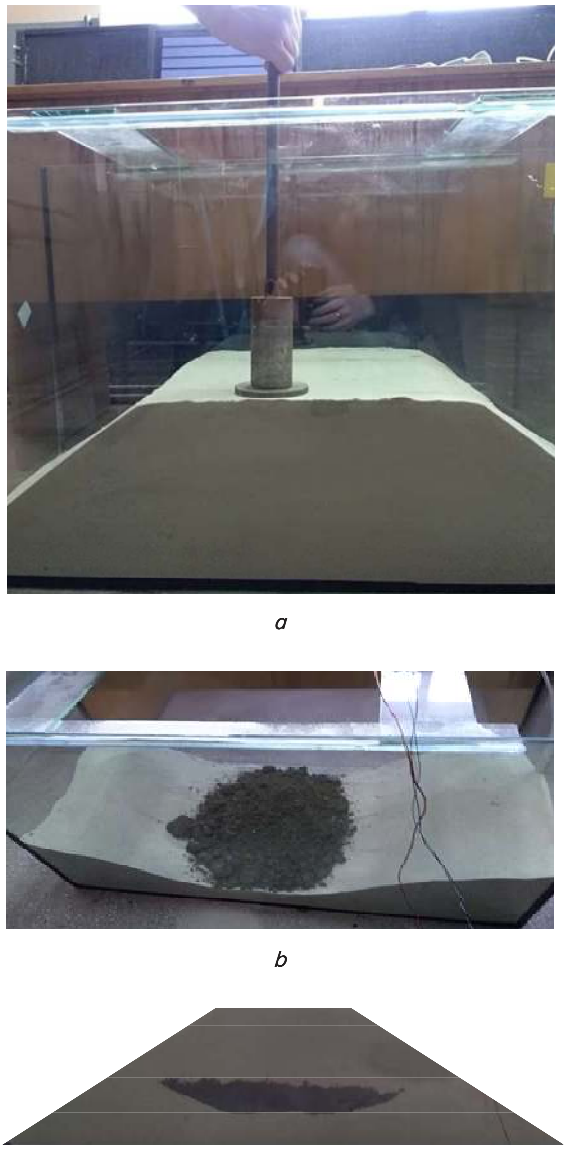
– to devise a laboratory procedure for assessing the degree of compaction of the homogeneous and heterogeneous subgrade;

– to determine the propagation rate of elastic waves in subgrade depending on the degree of soil compaction.

4. Devising a laboratory procedure for assessing the degree of subgrade compaction

The laboratory study of the subgrade included a sequence of cycles of the compaction of subgrade soils and the duration of passing the elastic waves of impacts. The pulse was set by a hammer through a round stamp placed in the center of the subgrade (Fig. 1).

The experiment was conducted in three cycles using two models. The first model is a homogeneous subgrade made of coarse-grained sand, the second model is a heterogeneous subgrade made of coarse sand and a layer of clay in the middle of the prism.


a

b

c

Fig. 1. The subgrade model in a laboratory experiment: *a* – soil compaction process; *b* – backfilling of a clay layer; *c* – heterogeneous subgrade made of coarse sand and a layer of clay in the middle of the prism

For each subgrade model, three cycles of experimental studies into the compaction of subgrade were carried out. Cycle No. 1 – the non-compacted state of subgrade; cycle No. 2 – an intermediate state of the subgrade compaction; cycle No. 3 – the most layer-wise compacted state of the subgrade.

After each compaction cycle, the measurements of the propagation of elastic waves across the subgrade were carried out using the designed inertial device. In order to optimally determine the subgrade density, we measured the propagation rate of elastic waves at five impacts in each cycle of the experiment.

The method of determining the subgrade compaction is based on measuring the propagation rate of elastic waves through a soil layer. The dynamic oscillations and their registration are carried out by the designed inertial device whose structural diagram is shown in Fig. 2.

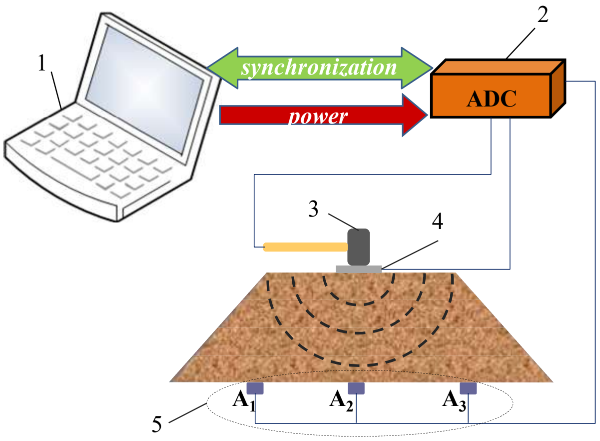


Fig. 2. Device for measuring the compaction of soils in the road subgrade: 1 – personal computer, 2 – analog-digital converter, 3 – hammer, 4 – stamp, 5 – analog acceleration sensors ADXL 335 (China)

The device includes personal computer 1, which acquires data and powers acceleration sensors, and an analog-digital converter. Analog-to-digital converter 2 transmits measured signals from the analog accelerator sensors ADXL 335 and the hammer to the personal computer for further use and processing. All data related to monitoring the subgrade state are acquired and stored in the computer's memory.

Hammer 3 and stamp 4 are used to generate pulses and a short circuit signal, the processing of which produces the wave passing time from the beginning of the impact to registering an oscillation by the analog accelerator sensors ADXL 335 (China). The analog information on the acceleration signals from the longitudinal and transverse waves from 3 accelerometers is digitized at a frequency of 30 kHz and stored on the personal computer.

The source of elastic waves is a hammer blow against a metal plate with a diameter of 13 cm, which is placed on the subgrade after each degree of compaction. Impacts occur alternately; the onset of the pulse is registered using separate digital channels on the analog-digital converter.

To dynamically interpret the subgrade density signals, we recorded the wave propagation oscillations from the moment of impact by using the acceleration sensors ADXL 335 (A1 to A3).

After each measurement, the results of the acceleration measurements were recorded in a file tagged with the recording date and the time of device operation.

A bench to study the degree of subgrade compaction was a glass box filled with soil with dimensions of 1.0×0.5×0.7 m (Fig. 3). The box was filled with the soil in the form of an embankment of the subgrade without compaction.

The bottom of the box consists of n-shaped profiles, which host signal cables and the power cables to the acceleration sensors. The accelerometers are placed in separate parts of a metal profile with the dimensions of width and length of 40 mm and a height of 20 mm. These elements are separated from the adjacent sensors and the base by noise-protective material in order to partially eliminate side noise. The total number of individual profiles with sensors is three pcs. The accelerometers in Fig. 3 are denoted A_1–A_3.

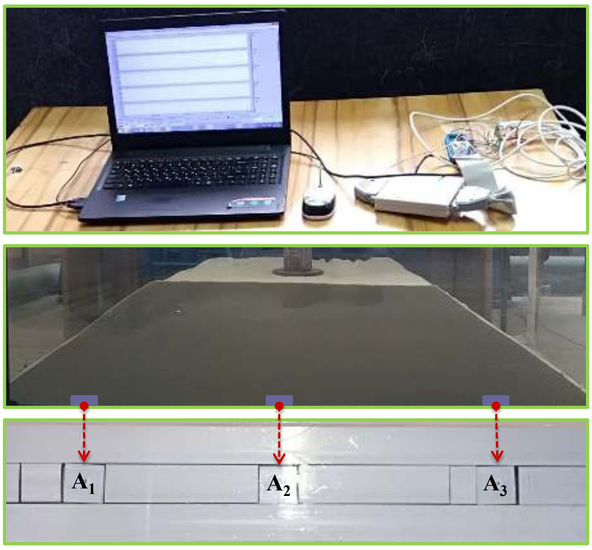


Fig. 3. Experimental study of the subgrade soil compaction (bottom: location of sensors (accelerometers) under the subgrade, top: measuring devices, middle: view from the subgrade model in a box with glass walls)

5. Results of determining the propagation rate of elastic waves in subgrade depending on the degree of soil compaction

We analyze the time and propagation rate of the impact's waves for three states of the subgrade soil density and for two different environments. Thus, by measuring the propagation rate of elastic waves after generating a pulse from the hammer, we can conclude about the degree of soil compaction. Rate is determined from a known formula:

$$V = \frac{S}{t}, \tag{1}$$

where S is the path of wave propagation from the hammer to the accelerometer; t is the time of passing the impact's waves from the hammer to the pulse receiver (accelerometer).

The distance S is determined depending on the thickness of the subgrade soil layer after each compaction cycle.

The scheme to determine the propagation distance of the impact's elastic wave from the hammer to the accelerometer is shown in Fig. 4. The shortest way for the wave to propagate is to the accelerometer A_2, so the time of the wave propagation should be the smallest.

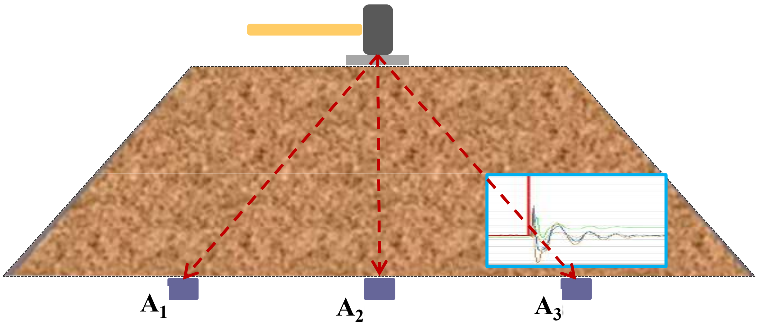


Fig. 4. Measuring the subgrade soil compaction

Next, we analyze the results of the effect of subgrade soil compaction on the time and rate of wave propagation for the case when the hammer is in the center of the soil model of the subgrade.

The results of the propagation time of the impact's waves from the hammer to accelerometers A_1, A_2, A_3 at different cycles of compaction of the homogeneous subgrade are shown in Fig. 5; for heterogeneous – in Fig. 6.

The propagation time of the impact's elastic wave in a homogeneous subgrade ranges from 60 ms to 100 ms in the loose state. With intermediate subgrade compaction, from 50 ms to 78 ms; at the maximally compacted subgrade, from 40 ms to 58 ms.

When the subgrade is heterogeneous, the propagation time of an elastic wave at the loose subgrade ranges from 45 ms to 68 ms. At the intermediate subgrade compaction, from 40 ms to 65 ms; at the maximally compacted subgrade, from 30 ms to 53 ms.

For sensor A2, which is closest to the pulse source, at the loose state of the homogeneous subgrade, the wave passing time is 59 ms. At the intermediate compaction, 51 ms; at the maximally compacted subgrade, the wave propagation time is 40 ms.

The propagation time of the impact's elastic wave through a heterogeneous subgrade in a loose state is 44 ms; at the intermediate compaction, 40 ms; at the maximally compacted one, 31 ms.

Fig. 7 shows the records of the acceleration of longitudinal waves by the A2 accelerometer from the hammer after three compaction cycles in a homogeneous subgrade; Fig. 8 – at the heterogeneous subgrade. In addition, these diagrams demonstrate the moment when the pulse is generated.

The average propagation time of an impact's elastic wave after three cycles of the homogeneous subgrade experiment is, respectively, 59 ms, 51 ms, and 40 ms. In the heterogeneous subgrade – 44 ms, 40 ms, and 31 ms.

In a given case, according to the recordings of the wave passing time by the accelerometer at a frequency of 30 kHz, at the greatest compaction, the wave passing time is 25 points of the digitized signal. An increase in the accuracy could be achieved by increasing the frequency of the acceleration signal digitization.

Based on the known values of the propagation time of an impact's elastic waves and the distance from the hammer to the receiving sensor, we calculate the wave propagation rate in the homogeneous subgrade (Fig. 9) and in the heterogeneous subgrade (Fig. 10).

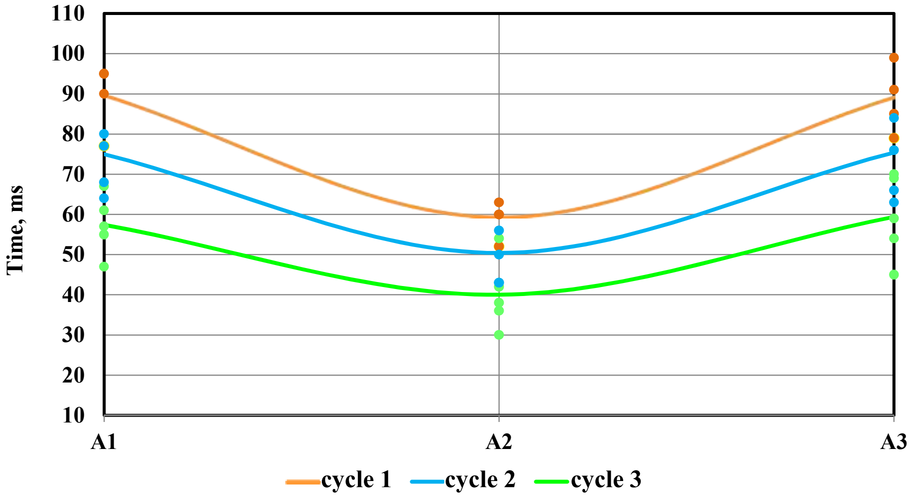


Fig. 5. Propagation time of the impact's elastic wave in a homogeneous subgrade

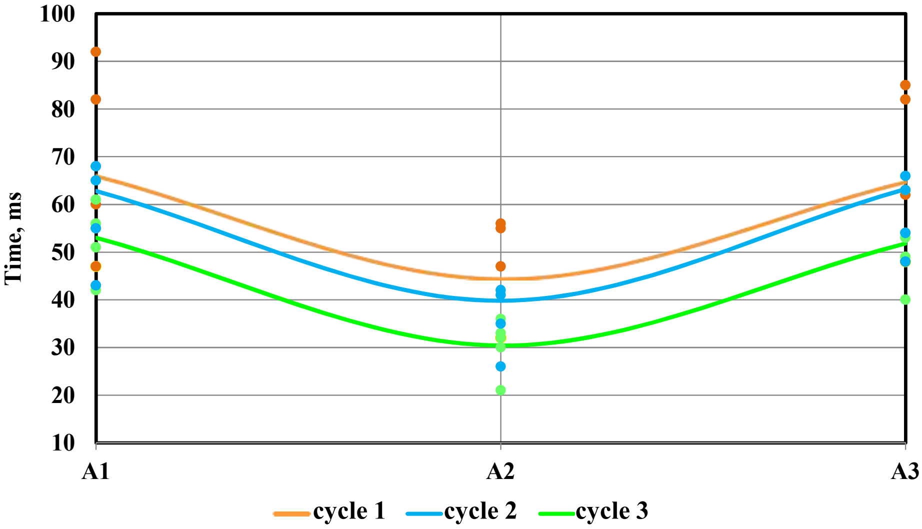


Fig. 6. Propagation time of the impact's elastic wave in a heterogeneous subgrade

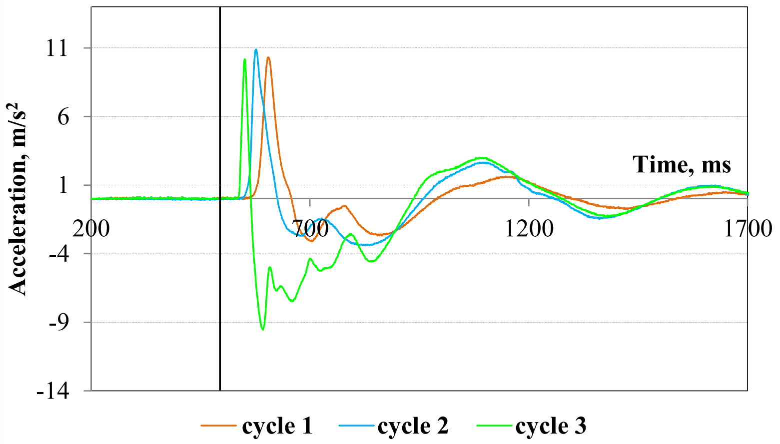


Fig. 7. Recording the propagation of an impact's waves in a homogeneous subgrade

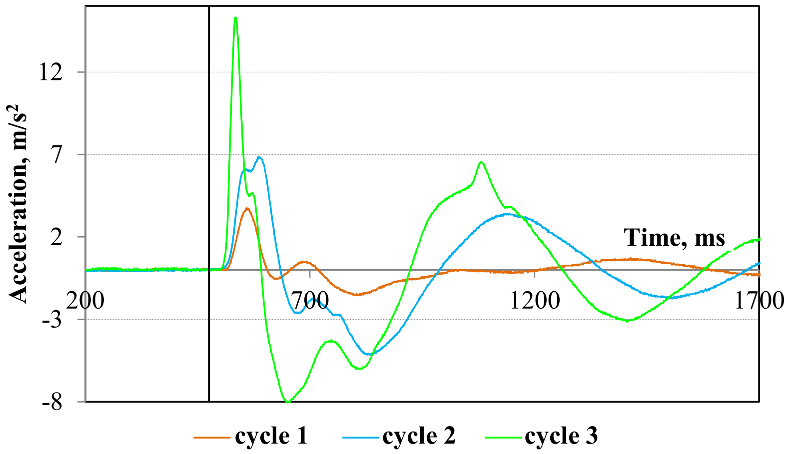


Fig. 8. Recording the propagation of an impact's waves in a heterogeneous subgrade

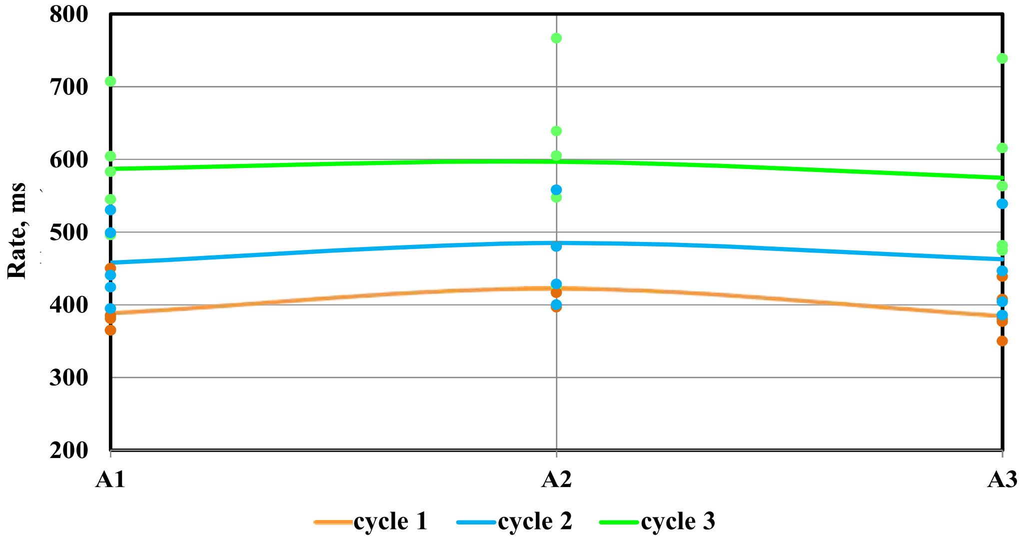


Fig. 9. The propagation rate of an impact's elastic wave in a homogeneous subgrade

The rate of propagation of an impact's elastic wave in the loose homogeneous subgrade to the A2 accelerometer is 422 m/s; at the intermediate compaction – 485 m/s; at the maximum layer-wise subgrade compaction– 597 m/s. The rate of wave propagation to the extreme accelerometers A1 and A3 is 390 m/s and 386 m/s in the loose state of the homogeneous subgrade. At the intermediate compaction, 458 m/s and 463 m/s, respectively; at the maximally compacted state – 588 m/s and 575 m/s, respectively.

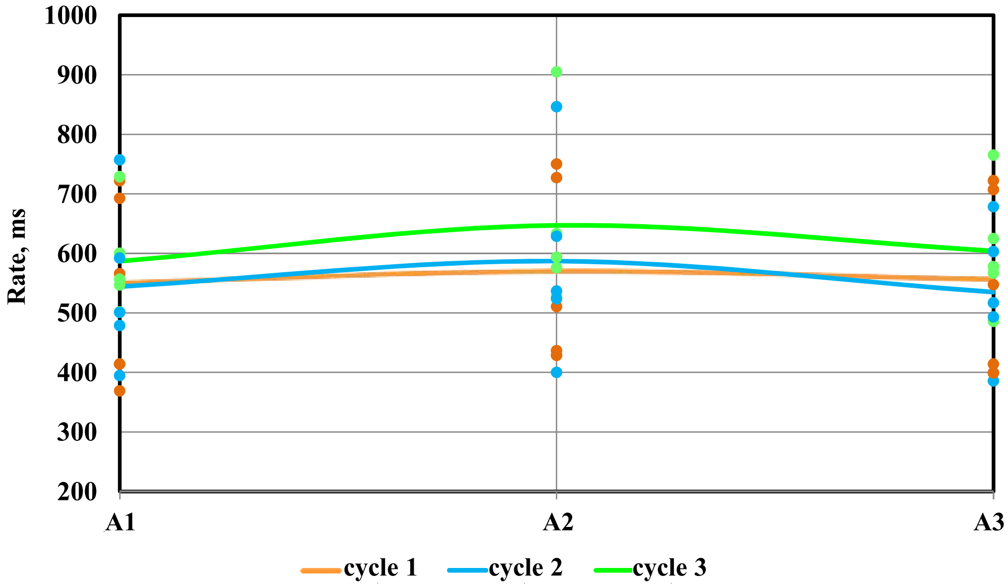


Fig. 10. The propagation rate of an impact's elastic wave in a heterogeneous subgrade

When the subgrade is heterogeneous, the propagation rate of an elastic wave to the A2 accelerometer in a loose state is 570 m/s; at the intermediate compaction, 588 m/s; at the maximally compacted – 648 m/s. The rate of wave propagation to the extreme accelerometers A1 and A3 is 553 m/s and 558 m/s at the loose state of the subgrade. At the intermediate compaction, 544 m/s and 534 m/s, respectively; at the maximally compacted state – 587 m/s and 605 m/s, respectively.

Deriving reliable values of the rate of propagation of an impact's elastic waves in the subgrade, depending on its compaction, requires the use of modern statistical methods of data treatment. The application of modern micro computing systems would enable the automated accumulation of data on a change in the propagation rate of an impact's elastic waves depending on the degree of subgrade compaction.

6. Discussion of results of assessing the degree of compaction of the railroad track subgrade

The quality of the exploited subgrade, unlike other elements of the track, is ensured during a repair. The subgrade is understood to be the greatest degree of its compaction, which corresponds to its greatest bearing capacity and resistance to a shape change, which leads to the subsequent emergence of defects and deformations. Knowing the subgrade density is important since this indicator makes it possible to assess the quality of the railroad track subgrade. A well-compacted subgrade makes it possible to extend the inter-repair period of the upper structure of the track by more than 30 %.

The devised and applied method of determining the compaction of the heterogeneous subgrade underneath a railroad track has shown a significant change in the propagation time and rate in the course of our experimental research. The results from determining the propagation time of an impact's elastic waves (Fig. 5, 6) demonstrate that the ratio of the time of passing the elastic wave of an impact through a homogeneous subgrade in a loose state to the time at the maximally compacted subgrade is 1.49 times; and at the heterogeneous subgrade – 1.41. This is due to an increase in the soil density and, accordingly, a decrease in the wave passing time. Therefore, based on the propagation time of an impact's wave from the pulse source to the receiving sensor, it is possible to estimate the degree of soil compaction in the embankment for a railroad track.

Our experiments show a significant increase in the time of passing a wave to the side acceleration sensors. This phenomenon is explained by some loosening of the subgrade on the side faces of the prism.

The rate of wave propagation in the soil varies depending on its density; the greater the density, the higher the rate. That is, low propagation speeds indicate the presence of a weakened layer with the possible occurrence of heterogeneities.

The peculiarity of the nature of the distribution of the propagation of an impact's elastic waves, as opposed to the distribution of time, is almost the same rate in the initial state. At the same time, it is necessary to note the high scattering of measured speeds, which increases together with the average speed value.

In the course of our research into the propagation of elastic sound waves across the subgrade, it was established that the measurement of speed values should vary depending on its compaction within significant limits relative to the initial compaction.

The methods that analyze wave propagation are inseparable from mathematical methods of information processing, signal analysis, and statistics. The use of machine learning methods makes it possible not only to automate the treatment and interpretation of data but also significantly improve the degree of information utilization and the accuracy of measurements. For greater clarity, we applied the cluster and discriminant analysis methods to identify the characteristic signs of subgrade compaction.

Further advancement of the current research is the use of algorithms of computer statistics and machine learning to establish the relationship between the compaction of the subgrade made from various filling materials and the characteristics of pulse response. The employment of modern microcontroller technologies could enable the development of autonomous systems for monitoring the technical condition of the subgrade on those sections of the track that are prone to flooding and deformation.

7. Conclusions

1. Qualitative assessment of the measurements of elastic waves in subgrade requires spatial measurements. To this end, the spatial resolution of measuring the density of the subgrade should not be less than half the thickness of the prism of the subgrade, that is, measurements must be carried out simultaneously by a dense network of sensors. The proposed approach to assessing the degree of compaction of the subgrade could significantly improve the accuracy of determining the spatial compaction during its operation, especially in problem areas.

2. With an increase in the subgrade compaction, the propagation rate of an elastic sound wave increases. Our results of measuring the rate of wave propagation show a significant concentration of the local increase in the passing rate of longitudinal waves in the homogeneous and heterogeneous subgrade in the central zone. This is due to a greater degree of the compaction of the central part of the prism of the subgrade, unlike its lateral areas. The results of numerous measurements of the subgrade compaction have established that the signal significantly loses its power in an insufficiently compacted subgrade. This can be seen from the time of passing the elastic wave to the extreme sensors that are closest to the free end of the prism.

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