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Experimental estimation of the degree of compaction of the roadbed by the propagation time of elastic shock waves

Abstract: The study is a model of a roadbed with a heterogeneous structure. The method of laboratory experimental studies for determining the accelerations of elastic waves in the model of an inhomogeneous roadbed at different degrees of density is presented. Experimental studies were conducted using the developed laboratory setup, and it was found that with increasing density, The Wave travel time decreases since, in a dense medium, the wave propagation speed is higher. It is determined that the shortest Wave travel time is obtained to the A3 sensor, and it is 0.0016 ms in the case of non–compacted state, in the case of intermediate compaction – 0.0015 ms and at the maximum compaction – 0.0012 ms. The travel time of the wave to the sensors A2 and A4, which are located at the same distance from the drummer, is almost the same and is 0.0022 Ms. and 0.002 ms in case of non–compacted state, in case of intermediate compaction-0.0019 ms and at the maximum compaction – 0.001 ms and 0.0009 ms. Experimental studies will help determine the degree of compaction of the soil of the roadbed based on the time and speed of propagation of elastic waves. It is worth noting that the laboratory installation allowed studying the propagation of elastic waves for a roadbed model, which can be designed from different types of soils. In addition, it makes it possible to consider various inhomogeneities that may occur during the operation of the roadbed of a railway track.

Keywords: roadbed, acceleration sensor, elastic wave, degree of compaction, inhomogeneous medium.



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Експериментальна оцінка ступеня ущільнення земляного полотна за часом поширенням пружних хвиль удару

Анотація: Об'єктом досліджень є модель земляного полотна з неоднорідною структурою. Наведено методику лабораторних експериментальних досліджень для визначення прискорень пружних хвиль у моделі неоднорідного земляного полотна при різних ступенях щільності. Проведено експериментальні дослідження за допомогою розробленої лабораторної установки та встановлено, що при збільшенні щільності час проходження хвилі зменшується, оскільки у щільному середовищі швидкість поширення хвилі є вищою. Визначено, що найменший час проходження хвилі отримано до датчика АЗ і він становить 0,0016 мс. при неущільненому стані, при проміжному ущільненні – 0,0015 мс. та при максимальному ущільненні – 0,0012 мс.. Час проходження хвилі до датчиків А2 та А4, які розташовані на однаковій відстані від ударника, практично однаковий і становить 0,0022 мс. та 0,002 мс. при неупцільненому стані, при проміжному ущільненні – 0,0018 мс. та 0,0019 мс. та при максимальному ущільненні – 0,001 мс. та 0,0009 мс. Експериментальні дослідження допоможуть визначити ступінь ущільнення грунтів земляного полотна на основі часу та швидкості поширення пружних хвиль. Варто зазначити, що створена лабораторна установка дозволяє проводити дослідження поширення пружних хвиль для моделі земляного полотна, яке може бути спроектоване з різних типів ґрунтів. Крім того, вона дає можливість враховувати різні неоднорідності, які можуть виникати під час експлуатації земляного полотна залізничної колії.

Ключові слова: земляне полотно, датчик прискорень, пружна хвиля, ступінь ущільнення, неоднорідне середовище.

(S S D)

Introduction

Ukraine's railway transport is significant in ensuring the state's defence capability. The functioning of many branches of the national economy depends on its state. Increasing the capacity and speed of trains is an important task.

The roadbed is one of the main elements of the railway track structure (*Danilenko, 2010*). Under operating conditions, the roadbed, under the influence of increasing loads and natural factors, undergoes deformations and inhomogeneities, leading to loss of load-bearing capacity and stability. Especially dangerous are deformations of clay soils, which lead to the formation of weakened zones, hidden cracks, loss of soil density and, as a result, the development of splashes (*Kravets, 2021*), as shown in the appendix (*Figure 1*) and other defects (*Dyachenko et al., 2001*). This requires developing design solutions to increase its load-bearing capacity and durability (*Dubinchik et al., 2023; Kravets, 2021*).

One of the most significant indicators of reliable roadbed operation is ensuring the soil density's design degree (*Danilenko, 2010*). Therefore, the assessment and control of the soil density of the roadbed, both in the conditions of construction and operation, is relevant. Increasing soil density reduces deformations and increases the stability of the roadbed. One of the methods that can be used to estimate the soil density of the roadbed is the method of

measuring the speed of propagation of sound waves of impact (*Karnakov et al., 2023; Kovalchuk et al., 2023a; Kovalchuk et al., 2023b*). To date, there are many studies on the use of inertial methods to assess the degree of density of the ballast layer and soils of the railway roadbed, which are given in the works (*Kovalchuk et al., 2021; Przybylonicz et al., 2020; Sysyn et al., 2020; Sysyn et al., 2019*). In addition, inertial technologies are used to assess the degree of compaction of ground backfill of transport structures made of metal corrugated structures (*Onishchenko et al., 2024*).

In the paper (Przybylowicz et al., 2020), a homogeneous crushed stone layer was studied by inertial measurements to assess the quality of lining the ballast layer of a railway track. The study of the degree of compaction of the crushed stone layer by ballast compaction machines by complex dynamic and kinematic interpretation of the pulse response is given in the paper (Sysyn et al., 2019). The paper (Sysyn et al., 2020) presents the results of laboratory experiments on the propagation of elastic waves in a crushed stone layer depending on the degree of its compaction. In the paper (Kovalchuk et al., 2021), it is noted that the propagation of elastic waves through a granular medium depends on the mineralogical and granulometric composition of grains, as well as on the density of the soil layer, i.e., the number of contacts between grains. By measuring the speed of waves after each soil compaction, you can determine the degree of compaction. As the density increases, many contacts and friction between the grains increases, and the porosity decreases. However, the wave velocity does not directly depend on the shear strength. It serves as a qualitative indicator of changes in strength, especially in heterogeneous soils. In coarsegrained soils, shear strength and transverse wave velocity depend on grain density (Dashwood et al., 2020). The propagation of waves is also affected by the humidity of the medium; such studies were conducted in the paper (Seoungmin et al., 2023).

The analysis of scientific papers (*Kovalchuk et al., 2021*; *Przybylowicz et al., 2020*; *Sysyn et al., 2020*; *Sysyn et al., 2019*) found that the primary studies of the degree of compaction of the roadbed were conducted on models with a uniform structure. However, there are no experimental studies on the propagation of waves and their accelerations in an inhomogeneous soil environment. Therefore, conducting laboratory experimental studies on wave propagation in heterogeneous soils is an urgent task of scientific research. This will allow us to establish the dependence of the acceleration value on the degree of compaction of soil with inhomogeneities.

Materials and methods

The study object is a roadbed model made of heterogeneous soil in a glass box with dimensions of $1.0 \times 0.5 \times 0.7$ m. The accelerations of elastic waves are determined on the roadbed model given in the appendix (*Figure 2*). The study was performed at different degrees of compaction of the roadbed's heterogeneous soil.

Experimental laboratory studies consisted of a sequence of soil compaction cycles of the roadbed model and recording the accelerations of the passage of elastic shock waves. The drummer set the impact on a round die located in the centre of the model, as shown in the appendix (*Figure 3*). The experiment was performed for three states of the model: non-compacted state, intermediate compaction, and maximum compaction.

After each compaction cycle, wave propagation was recorded in the medium of a model of an inhomogeneous roadbed using an inertial instrument (*Kovalchuk et al., 2021; Kravets, 2021*). To determine the optimal value of the wave propagation time for each state (non-compacted,

intermediate compaction, maximum compaction) of the inhomogeneous roadbed model, impacts (pulses) were set five times.

Results

The results of recording the wave propagation time in the roadbed model with noncompacted, intermediate compaction, and maximum soil compaction are shown in the appendix (*Figure 4*). According to the results of the recordings (*Figure 4a*), in the non-compacted state, the wave travel time from the beginning of the pulse setting to analogue acceleration sensors is up to sensor A1 – 0.0004 ms, sensor A2 – 0.0022 ms, sensor A3 – 0.0015 ms, sensor A4 – 0.002 ms and sensor A5 – 0.0026 ms.

During intermediate compaction of the roadbed model's ground (*Figure 4b*), the wave travel time from the start of pulse setting to analogue acceleration sensors is up to sensor A1 - 0.0002 ms, sensor A2 - 0.0018 ms, sensor A3 - 0.0016 ms, sensor A4 - 0.0019 ms and sensor A5 - 0.0021 ms.

At the maximum compaction of the roadbed model's ground (*Figure 4c*), the wave travel time from the start of pulse setting to analogue acceleration sensors is up to sensor A1 - 0.0001 ms, sensor A2 - 0.001 ms, sensor A3 - 0.0012 ms, sensor A4 - 0.0009 ms and sensor A5 - 0.0012 ms.

For better clarity of the results, the experimental data obtained are given in the appendix (*Table 1*), which is given in the appendix. As we can see from the results of experimental studies, the propagation time of the sound wave of impact decreases with an increased degree of soil compaction. This suggests that wave propagation speed in a dense medium is higher.

Discussion

Conducting laboratory experimental wave propagation studies in heterogeneous soils is a significant scientific study task. Such experimental studies will make it possible to determine the degree of compaction of the soil of the roadbed by the time and speed of propagation of elastic shock waves. It is worth noting that the developed laboratory installation, given in the appendix (*Figure 2*; *Figure 3*), allows you to perform studies of the propagation of elastic waves for the roadbed model, which can be designed from various types of soils. In addition, it allows you to set various inhomogeneities that may occur during the operation of the roadbed of a railway track.

The results of experimental studies of the roadbed model at different degrees of soil compaction showed that as the density increases, the wave travel time decreases (*Figure 4*). According to the diagram (*Figure 3*), we can see that the sensor A3 located is located at the smallest distance to the impactor, so the time (*Table 1*) of wave passage is the smallest. Sensors A2 and A4 are located at the same distance from the impactor, respectively, and the wave travel time is almost the same with a slight deviation. This is due to the presence of heterogeneous inclusions in the form of clay. It is also worth noting that the wave's travel time to sensor A1 is the shortest because it is located where there is no inhomogeneity of the roadbed, i.e., the wave speed in such a medium is the highest.

Conclusion

A laboratory installation has been developed for conducting experimental studies of wave propagation in soils with different densities and inhomogeneities. This will allow determining the degree of compaction of the roadbed's soil at the time of elastic shock wave propagation.

Based on the obtained values of the travel time of impact waves in the roadbed model, it was found that with increasing density, the wave's travel time decreases since, in a dense medium, the wave propagation speed is higher. Accordingly, the shortest wave travel time is obtained by the sensor A3. It is 0.0016 ms in the non-compacted state, in the case of intermediate compaction -0.0015 ms and at the maximum compaction -0.0012 ms. The travel time of the wave to the sensors A2 and A4, which are located at the same distance from the drummer, is almost the same and is 0.0022 ms and 0.002 ms in case of non-compacted state, in the case of intermediate compaction compaction -0.0018 Ms. and 0.0019 Ms. and at the maximum compaction -0.001 ms and 0.002 ms.

Conflict of interest

The authors declare that there is no conflict of interest.



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Figure 1. Defective places of the roadbed (a) a section of railway track with spills, (b) loss of stability of the slope of the roadbed due to soil compaction



Figure 2. Model of a roadbed with non – uniform inclusion: A1, A2, A3, A4, A5-analogue acceleration sensors



Figure 3. Diagram of a laboratory installation for performing measurements: (1) laptop, (2) analogue-to-digital converter, (3) drummer, (4) stamp, (5) acceleration sensors



Figure 4. Wave propagation records in the roadbed model (A1, A2, A3, A4, A5 are analogue sensors; vertical line impacts moment (start of pulse setting)): (a) in the non-compacted State; (b) intermediate seal; (c) maximum seal

Analog acceleration					
sensors, ms	A1	A2	A3	A4	A5
Degree of compaction					
not compaction	0.0004	0.0022	0.0016	0.002	0.0026
intermediate compaction	0.0002	0.0018	0.0015	0.0019	0.0021
maximum compaction	0.0001	0.001	0.0012	0.0009	0.0012

Table 1. Results of wave travel time in the roadbed model at different degrees of soil compaction