ACTA TECHNICA JAURINENSIS
Vol. 19, No. 3, pp. 229-241, 2026
10.14513/actatechjaur.00972

Research Article

Development of a method for experimental assessment of the degree of compaction of ground backfill of prefabricated metal corrugated structures of transport structures

Vitalii Kovalchuk[1,*], Artur Onyshchenko[2], Ihor Karnakov[2], Ivan Kravets[1], Roman Rybak[3]

[1]Department of Railway Transport, Lviv Polytechnic National University
Stepan Bandera St. 12, 79013, Lviv, Ukraine
[2]Department of Bridges and Tunnels and Hydrotechnical Structures, National Transport University
Mykhaila Omelianovycha-Pavlenka str., 1, 01010, Kyiv, Ukraine
[3]Department of Transport Technologies, Lviv Polytechnic National University
Stepan Bandera St. 12, 79013, Lviv, Ukraine
*e-mail: vitalii.v.kovalchuk@lpnu.ua

Submitted: 25/01/2026 Revised: 24/02/2026 Accepted: 02/03/2026 Published online: 26/08/2026

Abstract: The object of research is the degree of compaction of the ground backfill of transport structures made of prefabricated metal corrugated structures. An experimental method for estimating the degree of compaction of ground backfill of transport structures made of prefabricated metal corrugated structures has been developed. Based on the results of experimental studies, regularities of changes in the speed of propagation of sound waves of ground backfill of precast metal corrugated structures of transport structures depending on its density are obtained. It is established that with an increase in the degree of soil compaction, the speed of the sound wave of impact increases. Experimental studies of the speed of sound wave propagation were conducted in three series of experiments. When comparing compacted ground backfill with bulk density, in the first series of tests, the increase in wave speed was 31.09%, in the second series of tests, the increase in speed was 8.5%, and in the third series of experimental tests – 8.4 %. It is inserted that by increasing the speed of sound wave movement, it is possible to estimate the degree of compaction of ground backfill of transport structures made of prefabricated metal corrugated structures. This will ensure the standard degree of compaction of the ground backfill during its layer-by-layer filling and compaction, which has a direct impact on the load-bearing capacity and durability of transport structures made of metal corrugated structures.

Keywords: transport structures made of metal corrugated structures; ground backfill; degree of soil compaction; wave speed

I. INTRODUCTION

In the transport construction of railways and highways, progressive transport structures made of precast metal corrugated structures are used [1, 2]. Such structures work as the complex "metal shell – ground backfill". Transverse rigidity of precast metal corrugated structures (TRPMCS) is provided due to the thickness of the elements and their wavy corrugated shape. The strength and spatial rigidity of the metal shell is provided by the interaction of metal structures with the compacted backfill soil around the structure, in the thickness of which there is a transport structure made of PMCS. One of the most important indicators during the construction of transport structures with PMCS is to ensure the standard degree of compaction of the soil compacting backfill around metal corrugated structures. The process of installing ground backfill of a tunnel overpass with PMCS is shown in **Fig. 1**.

The device of soil backfill is performed by filling a layer of soil with a thickness of no more than 20-25 cm. At each stage, symmetrical compaction of the soil is performed on both sides of metal structures. This process of compaction of the ground backfill of metal structures of the structure occurs to the top (arches of the structure). At the same time, it is important to control the degree of soil compaction on each filled-out soil layer [3-7].

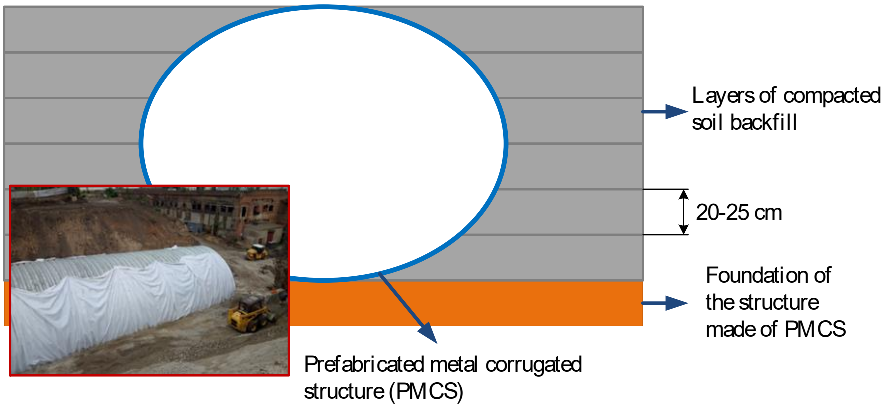


Figure 1. *Device of ground compacting backfill of a structure made of TRPMCS*

The vertical load acting on a transport structure made of prefabricated metal corrugated structures is transmitted through the side surfaces to the ground backfill of the structure located around the metal structures. If the physical and mechanical characteristics of the soil do not meet the regulatory requirements regarding the value of the compaction coefficient, the geometry of the metal structures of the structure may be violated. Also, this can lead to partial loss of stability and rigidity of the structure.

In this regard, ensuring the design coefficient of the degree of soil compaction qual to 0.98, at the construction stage of the structure, is an important task during the construction of transport structures made of precast metal corrugated structures [8-11]. Since, only with a standard degree of compaction, it is possible to ensure the load-bearing capacity and durability of transport structures made of PMCS [8].

II. Analysis of literature data and problem statement

In [9], it is indicated that during the construction of transport structures with PMCS, it is necessary to control the geometric position of structures. In the case of a small height of the ground backfill above the arch of structures, during the passage of construction equipment, significant deflections of structures can occur. Experimental studies have established that in the case of good compaction of soils around metal corrugated structures, trouble-free operation of structures in the area of butt joints is ensured.

Well – known methods of field control of the compaction coefficient of ground backfill of transport structures from prefabricated metal corrugated structures are the sand hole method, and when determining the elastic modulus of ground backfill– by static stamp Tests [3, 10-12].

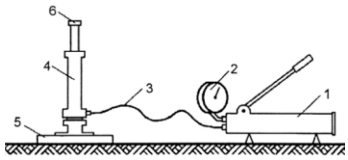
The sand hole method (**Fig. 2**) it is used to determine the compaction coefficients of soil mixtures containing engraved particles, crushed stone, frozen soil particles, as well as in the construction of embankments made of stone materials.

Figure 2. *Sampling of a compacted crushed stone-sand mixture by the well method*

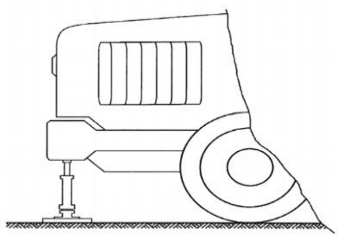
On the compacted layer of soil, level a small area, and dig a hole with a depth of 10-15 cm and a volume of 3-5 liters. the soil selected from the hole is selected and weighed. A double funnel with dry sand of a fraction of 0.5–1.0 mm, or 1-2 mm, is installed above the hole, which does not contain dusty and clay particles. Sand is filled with a hole with a complete filling of the selected volume of compacted soil. Knowing the mass of sand filling of the hole and the density of sand, determine the volume of the hole.

The density of the soil selected from the well is determined by dividing the weight of the selected soil by the volume of the well. In addition, this method allows you to determine the soil moisture by drying and then weighing the selected and dried volume of soil. Static stamp testing method (**Fig. 3, a**) is used to determine the elastic modulus of ground backfill of transport structures made of prefabricated metal corrugated structures.

To do this, a rammer roller or excavator is installed on the compacted layer of ground backfill of structures made of PMCS (**Fig. 3, b**). Installation is carried out in such a way that the distance from its wheels to the stamp is not less than 1.7 m. the place of installation of the stamp is filled with sand and levelled with a thin layer 1-3 mm thick.



a)



b)

***Figure 3.** Scheme of static stamp testing of soils: a) elements of stamp equipment b) principle of use of stamp equipment: 1 – hydraulic pump; 2 – pressure gauge; 3-connecting hose; 4 - hydraulic cylinder; 5 - stamp; 6- rod.*

The device for performing static stamp testing of ground backfill consists of a hydraulic pump with a pressure gauge, which is connected to the hydraulic cylinder through a connecting hose, a die and loading equipment.

With the help of a hydraulic pump, a static load is carried out on the soil backfill layer. After the deformation fades, the strain count is recorded in the field measurement log. Then the pressure in the hydraulic pump is released, this leads to unloading of the ground backfill and damping of the reverse deformation, as a result, a new reading on the indicator is recorded again. These operations were repeated to the obtained values, which differ by no more than 10 %. After that, the average deflection value is taken as the value of elastic deflection. Determination of the elastic modulus is further carried out in accordance with DSTU B V. 2.3-42 [3]. In the works of the authors [13–22], it is indicated that such malfunctions of the rail track as subsidence of the roadbed and disorganization of the ballast of the railway track lead to an increase in the dynamic effect on rolling stock. Therefore, during the construction of transport structures made of prefabricated metal corrugated structures on railways, it is necessary to ensure the load-bearing capacity of such structures and prevent deformations of the vertical and horizontal dimensions of the structure. Since residual deformations of metal corrugated structures of the structure lead to subsidence of the railway track [23].

According to the results of the conducted studies, which are given in the works [24, 25, 26], it was established that the load-bearing capacity of a pipe made of metal corrugated structures depends on the degree of compaction of the ground backfill. In case of insufficient compaction of the ground backfill, the load-bearing capacity of the pipe decreases.

In [27], it is noted that when vibrations are excited in an elastic medium by a source located near the surface, two main types of waves are formed – bulk and surface. At the same time, studies [28] have established that the nature of wave propagation in the ground of the roadbed is influenced by its transverse profile and the types of soil masses involved in the compaction process.

In study [29], investigations of three-dimensional shell structures were carried out taking into account two different porosity distributions. The theoretical basis improved in this way provides a more accurate representation of the transverse shear stress distribution within the structure, considering the complexity of its behavior under loading conditions.

In paper [30], an experimental study of the relationship between cavitation acoustic waves and the erosion threshold is presented. The authors found that the relationship between the sound pressure level and the area of the eroded surface does not depend on the geometry and dimensions of the water tunnel.

This research paper [31] presents an efficient analytical method, namely the Sardar Sub-Equation Method (SSM), to construct new families of traveling solitary wave solutions of Fractional Partial Differential Equations (FPDEs), i.e., the Fractional Phi-Four Equation (FPFE) and the Fractional Generalized Duffing Equation (FGDE).

In study [32], repeated low-velocity impacts are numerically applied to investigate laminates using a layer-wise modeling strategy. The impact results are then directly used to predict the residual compressive strength of the laminates by performing compression-after-impact simulations.

In study [33], investigations of the behavior of ballasted railway tracks during settlement under dynamic loading were carried out, providing a comprehensive assessment of track deterioration models using extensive field data.

Studies [34–40] present investigations of the behavior of railway track ballast under loading. It was established that track deterioration depends on ballast compaction.

Study [41] established that the modulus of elasticity of the soil backfill of transport structures made of metal corrugated structures influences the stress–strain state of such structures.

In study [42], investigations of changes in the dynamic modulus of elasticity of asphalt mixtures with the addition of polymethyl methacrylate were carried out.

The above methods for assessing the degree of soil compaction of the roadbed have a number of disadvantages. The disadvantage of the sand hole method is that the value of the compaction coefficient shows how close the backfill soil density is to the maximum, but does not make it possible to quantify the load-bearing capacity of the backfill soil. When using the stamp test method, there is a need to use expensive measuring and loading equipment. Therefore, the development of effective experimental technologies for monitoring the degree of compaction of ground backfill of structures made of prefabricated metal corrugated structures is an urgent task of scientific research.

III. Materials and Methods of Studying the Degree of Compaction of Soil Backfill by Inertial Measurement Technologies

1. Inertial method for measuring the degree of compaction of ground backfill of structures made of prefabricated metal corrugated structures

An improved method for determining the degree of compaction of soil compaction backfill of structures made of PMCS consists in the use of inertial measurement technologies. The essence of the method is to determine the time and speed of sound wave propagation through the thickness of the soil backfill layer. In this case, the speed is determined depending on the thickness of the soil layer and the degree of compaction.

The general scheme of the device for conducting experimental measurements of the degree of compaction of ground backfill of structures with PMCS is shown in **Fig. 4**

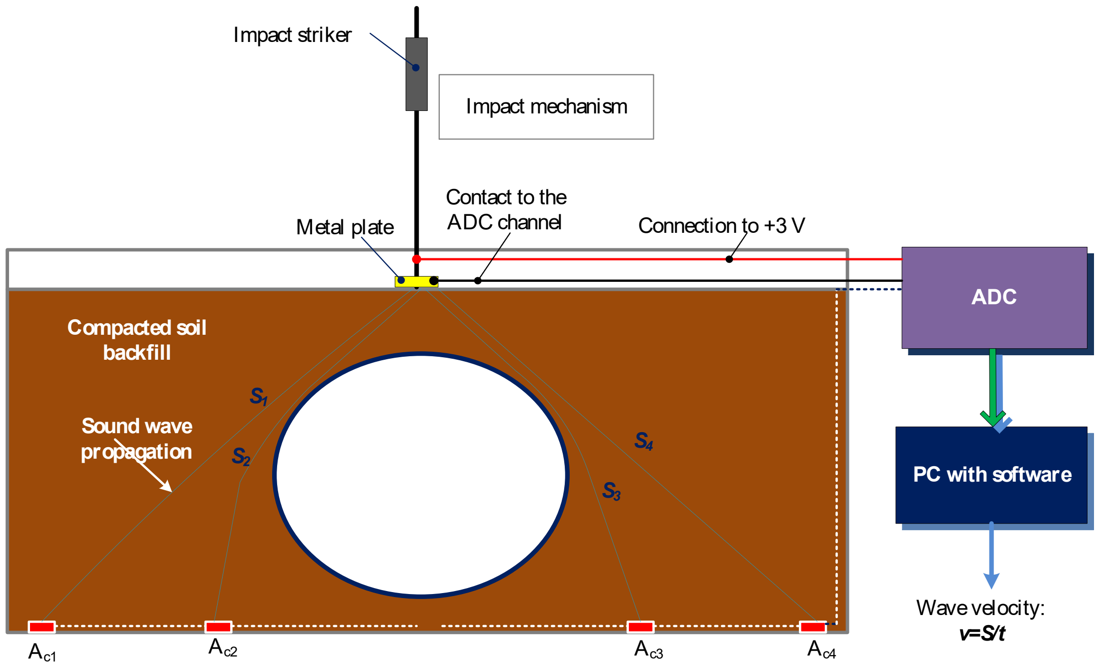


***Figure 4**. Diagram of a device for conducting experimental measurements of the degree of compaction of ground backfill of a structure made of prefabricated metal corrugated structures*

The installation consists of a corrugated pipe, which is located in the soil thickness of the embankment of the roadbed. Restrictions on the size of the ground backfill are the glass walls of the glass case. Four ADXL-335 analog high-frequency inertial acceleration sensors are embedded at the bottom of the case.

To set the sound wave of the impact that propagates through the thickness of the ground backfill, an impact mechanism is used. When the Impact striker falls from a certain height on a metal plate, an impact occurs, which causes sound waves propagating through the thickness of the ground backfill. To fix the beginning of sound wave propagation, the contact closure method is used. To do this, a 3.3 V contact goes from the shock striker to the analog-to – digital converter (ADC), and from the metal plate-a contact to the ADC channel. As a result, when the contacts are closed on the analog channel, a signal of 3.3 V occurs, which corresponds to the beginning of the pulse (shock) setting.

Sound waves propagate through the thickness of the soil backfill to inertial sensors that are located at the base of the soil prism. In our case, with four sensors, we assume the distance from the impactor to the accelerometer A_{c1} equal to S_1; to the accelerometer A_{c2} – S_2; to the accelerometer A_{c3} – S_3 and to the accelerometer A_{c4} equal to S_4.

In the study, it is assumed that the sound wave propagates along the shortest distance from the impulse source to the receiving sensor. The distances S_1, S_2, S_3, and S_4 are determined by geometric measurement along the shortest path of sound wave propagation. The wave will propagate over time. We denote the wave propagation time in accordance with the acceleration sensor numbers. We accept the wave propagation times t_{Ac1}, t_{Ac2}, t_{Ac3}, t_{Ac4} according to the acceleration sensor numbers.

All records of the propagation time of the sound wave of the impact are stored in the computer's memory.

2. Program of experimental tests for determining the time and speed of propagation of the sound wave of impact through the ground backfill of structures made of metal corrugated structures

A view of a full-scale experimental setup for determining the time and speed of propagation of sound waves of impact in the ground backfill of structures with TRPMCS is shown in **Fig. 5**.

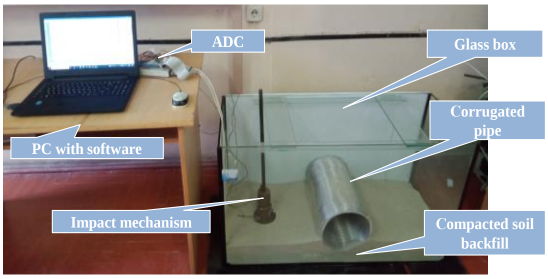
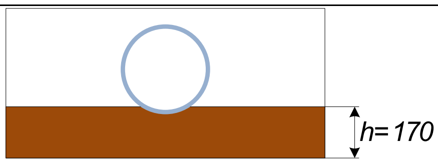
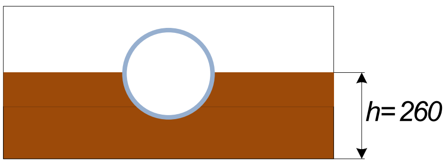
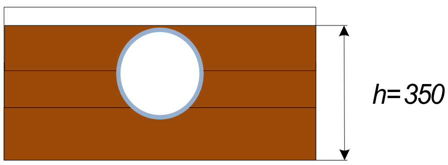


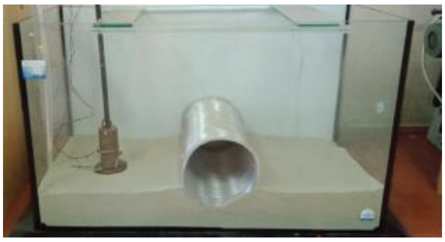
***Figure 5.** Installation for determining the speed of propagation of a sound wave of impact*

The program of experimental measurements provided for determining the speed of propagation of the impact wave depending on the degree of compaction of the soil backfill and the thickness of the soil layer. The research program is shown in **Table 1**.

A series of three tests was performed, with ten pulse beats set in each series. The drop height of the impact striker was assumed to be the same, equal to 38 cm above the surface of the metal plate. In each test series, the soil on the left side of the prism was compacted to the maximum possible degree of compaction by a manual rammer. At the same time, on the right side, the ballast prism was filled out without additional compaction, that is, there was a bulk density of soil. A view of the experimental setup for determining the degree of density of the soil compacting backfill of a structure with a metal corrugated pipe in three series of tests is shown in **Fig. 6**.

***Table 1.** Program of experimental studies to determine the time and speed of sound wave propagation in soil backfill*

No. of the experiment program	*Graphic view*	*Number of preset strokes, PCs.*	
		Left side	*Right side*
1		10	10
2		10	10
3		10	10



a)

b)

c)

Figure 6. *The process of experimental determination of the degree of compaction of soil backfill in three series of experimental tests:*
a) first series of tests b) second series of tests c) third series of tests

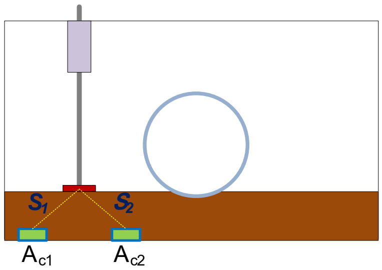
In the first series, the backfill height was 170 mm after compaction on the left side and 170 mm on the right, but without additional compaction. Similarly, in the second series of tests, the height of the soil compacting backfill was 260 mm on both sides of the corrugated pipe and in the third series – 350 mm.

IV. Research Results

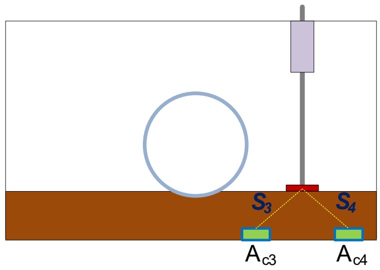
1. Results of recording the propagation of sound waves of impact in various series of experimental tests of ground backfill of structures

The time of movement of the impact wave from the moment of setting the pulse in the metal plate to the receiving sensor, in three series of tests, is determined by the diagrams shown in **Fig. 7**.

When setting the impact on the left side of the compacting soil backfill, the time is determined by the wave propagation to the accelerometers A_{c1} and A_{c2}. If the pulse is set from the right side of the ballast prism – to the accelerometers A_{c3} and A_{c4}. Similarly, the propagation time of sound waves of impacts in the second and third series of experimental tests is determined.



a)



b)

Figure 7*. Schemes for determining the propagation time of a sound wave from the moment of impact to inertial sensors: a) to sensors A_{c1} and A_{c2}; b) to sensors A_{c3} and A_{c4}*

The results of sound wave propagation of the impact in three series of tests are shown in **Fig. 8–10**.

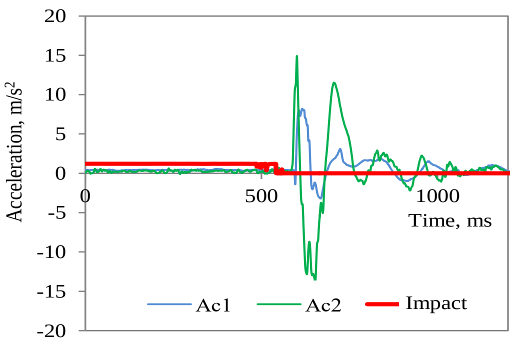
From the graphs of recordings of the propagation of sound waves of the impact, it can be seen that the sound wave arrives at the sensors with a certain delay. As a result, the time difference between the pulse setting and the time at which the pressure sound wave arrived at the sensor will be the time of propagation of the sound wave.

The formula for calculating the propagation time of a sound wave of an impact has the form:

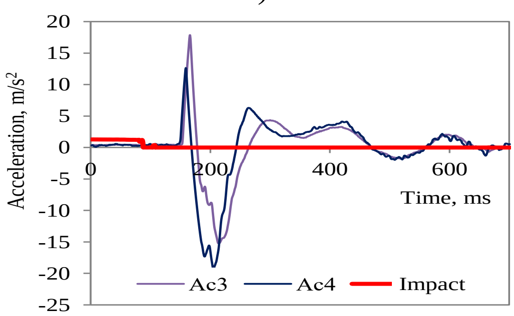
$$t_{Ac_n} = \frac{N_{Ac_n} - N_{Ac_{impact}}}{100000} \quad (1)$$

where: N_{Acn} is the moment when the pulse begins on the receiving acceleration sensor; $N_{Ac\ impact}$.- the moment when the impact setting starts, which leads to the propagation of the sound wave of the impact.

When dividing the difference in Signal points between the start of the impact setting and the arrival of the wave to the acceleration sensor by the sampling rate, when performing experimental tests, it was 100 kHz, we get the propagation time of the sound wave of the impact.

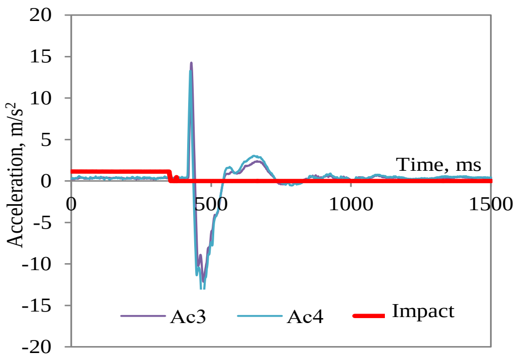


a)

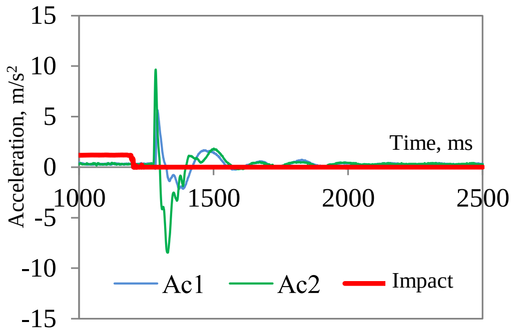


b)

Figure 8. *Wave propagation during the first series of tests: a) left side of the strike setting b) right side of the strike setting*

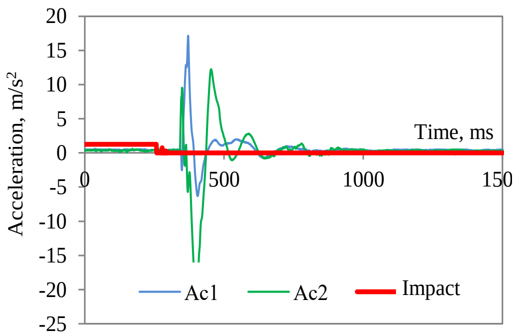


a)

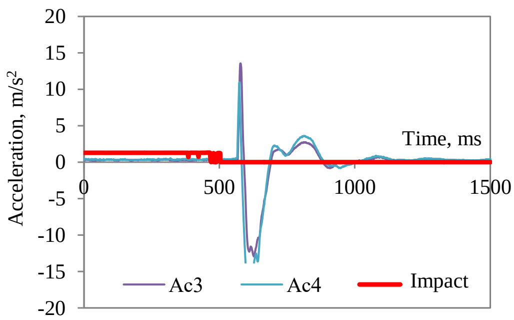


b)

Figure 9. *Wave propagation during the second series of tests: a) left side of the strike setting b) right side of the strike setting*



a)



b)

Figure 10*. Wave propagation during the third series of tests: a) left side of the strike setting b) right side of the strike setting*

From the results of experimental studies, it was found that in the case of compaction of the left side of the ground prism, the average time of sound wave propagation is less than the right uncompressed side of the prism. In the first series of experiments, the wave propagation time in the compacted state of the backfill was $t_{Ac1}=4.7\cdot10^{-4}$ s and $t_{Ac2}=4.87\cdot10^{-4}$ s, and in the bulk density of the soil – $t_{Ac3}=6.81\cdot10^{-4}$ s and $t_{Ac4}=6.89\cdot10^{-4}$ s.

In the second series of experimental studies, the propagation time of the impact wave on the left compacted side of the backfill was $t_{Ac1}=7.68\cdot10^{-4}$ s and $t_{Ac2}=7.667\cdot10^{-4}$ s, and on the right side, which has a bulk soil density, it was $t_{Ac3}=8.4\cdot10^{-4}$ s and $t_{Ac4}=8.4\cdot10^{-4}$ s.

In the third series of experimental studies, the propagation time of the impact wave on the left compacted side of the backfill was $t_{Ac1}=10.07\cdot10^{-4}$ s and $t_{Ac2}=9.92\cdot10^{-4}$ s and on the right side, which has a bulk density of soil – $t_{Ac3}=11.01\cdot10^{-4}$ s and $t_{Ac4}=10.86\cdot10^{-4}$ s.

2. Results of determination of the speed of propagation of the sound wave of impact in the ground backfill

The analysis of the speed of propagation of the shock wave in three cycles of the experiment was carried out by the formula:

$$V_{Ac} = \frac{S_n}{t_{Ac}} \qquad (2)$$

where: S_n is the distance from the impact setting to the receiving accelerometer along the shortest rectilinear trajectory of the wave; t_{Ac} is the determined time of wave movement from the beginning of the impact setting to the corresponding receiving accelerometer.

Based on the results of the propagation time of the sound wave of the impact, the speed of the wave movement was studied. The results of the wave velocity during the first series of experiments are shown in **Fig. 11**, in the second series of tests – in **Fig. 12** and the third series of tests are shown in **Fig. 13**.

In **Fig. 11** it can be seen that the speed of propagation of the sound wave of impact on the left side of the backfill is higher than on the right. At the same time, the values of the wave velocity to the sensors A_{c1} and A_{c2}, respectively, are v_{Ac1}=363.44 m/s and v_{Ac2}=354.28 m/s. at the bulk density of the soil (the right side of the soil backfill), the wave velocity to the sensors A_{c3} and A_{c4}, respectively, is v_{Ac3}=250.42 m/s and v_{Ac4}=248.44 m/s.

In **Fig. 12** shows that the average value of the wave velocity on the compacted left side of the backfill to the A_{c1} and A_{c2} sensors, respectively, is v_{Ac1}=339.21 m/s and v_{Ac2}=340.55 m/s.

With the bulk density of the soil on the right side of the backfill, the wave velocity to the sensors A_{c3} and A_{c4}, respectively, is v_{Ac3}=310.41 m/s and v_{Ac4}=310.39 m/s.

In **Fig. 13** it can be seen that the average value of the wave velocity on the compacted left side of the soil backfill to the sensors A_{c1} and A_{c2}, respectively, is v_{Ac1}=347.79 m/s and v_{Ac2}=353.39 m/s. with the bulk density of the soil on the right side of the soil backfill, the value of the wave velocity to the sensors A_{c3} and A_{c4}, respectively, is v_{Ac3}=318.56 m/s and v_{Ac4}=323.36 m/s.

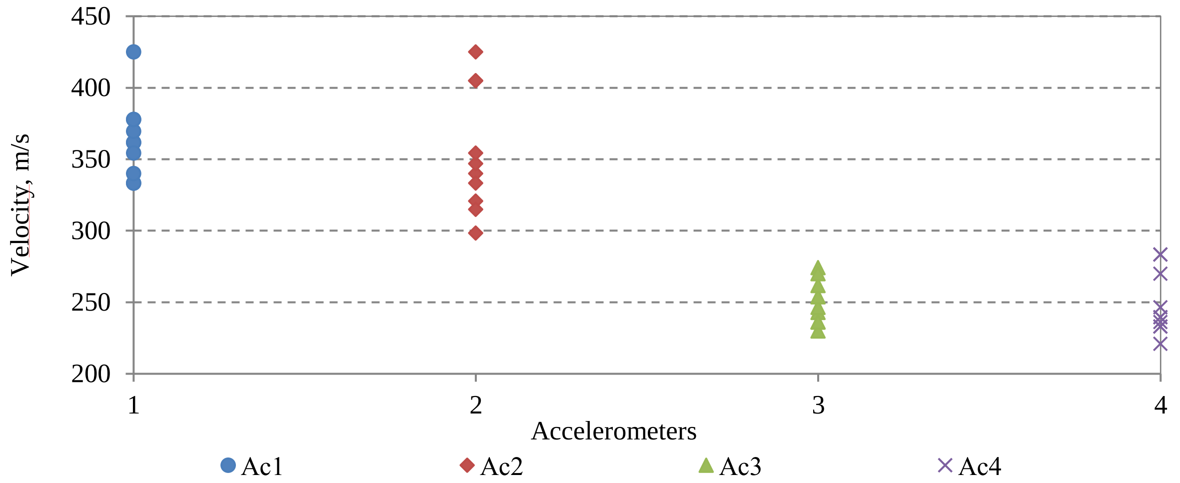


Figure 11. *Speed of impact wave propagation in the first series of experimental studies*

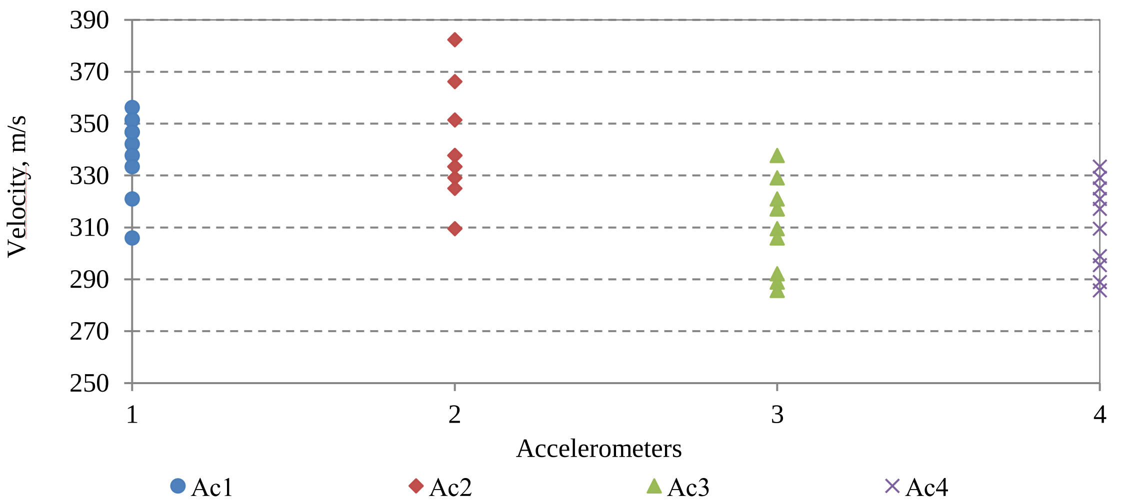


Figure 12. *Speed of impact wave propagation in the second series of experimental studies*

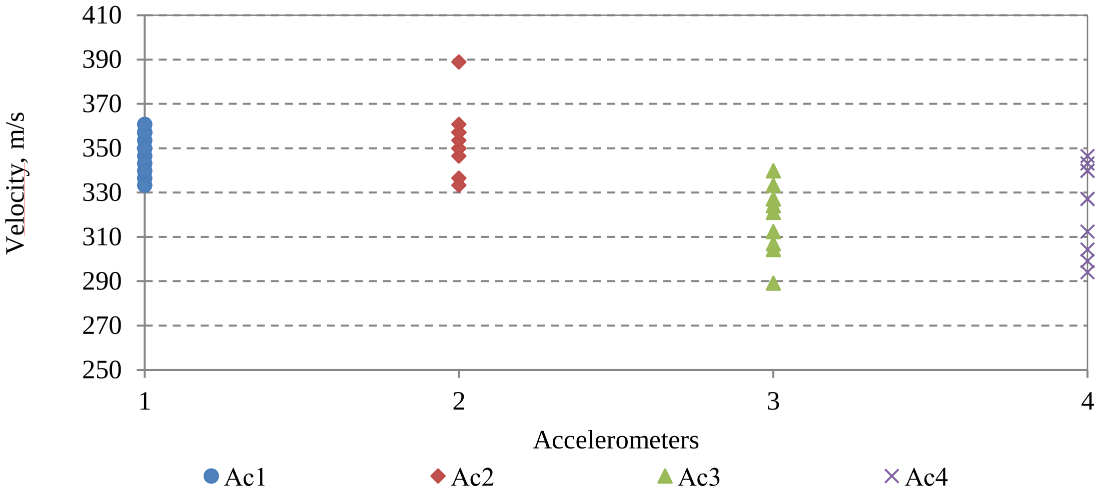


Figure 13. *Speed of impact wave propagation in the third series of experimental studies*

V. The results of the discussion

From the results of experimental studies, it was found that in each series of tests, the propagation time of the shock wave to the A_{c1} and A_{c2} sensors is shorter than that of the A_{c3} and A_{c4} sensors. This is due to the greater compaction of the left side of the ground backfill of the metal corrugated pipe compared to the right side, which has the bulk density of the ground backfill.

Analysis of the propagation time of sound waves of impact shows that an increase in the degree of compaction of the ground backfill of structures with PMCS leads to a decrease in the time of wave movement through the backfill thickness to the receiving sensor in comparison with the bulk density of the soil.

It should be noted that the difference in the reduction of the wave propagation time in the three series of experimental tests is explained by the higher degree of soil compaction on the left side of the corrugated pipe compared to the right. In addition, in each series of tests, during the filling of the soil, the soil itself was compacted on the right side of the corrugated pipe. This also affected an increase in the degree of soil compaction on the right side of the ballast Prism, which is explained by a smaller difference in the propagation time of the sound wave of the impact in the second and third series of tests.

From three series of experimental tests of soil backfill with different thickness and degree of compaction, it was found that the speed of the impact wave increases with increasing degree of density of the soil backfill. When comparing the compacted left side of the soil prism with the bulk density of the right side of the soil backfill, in the first series of tests, the increase in wave speed is 31.09%, in the second series, the increase in speed is 8.5%, and in the third series of experimental tests, the increase in speed is 8.4 %.

So, by increasing the speed of movement of the sound wave of impact, it is possible to judge the degree of compaction of the ground backfill of transport structures made of prefabricated metal corrugated structures.

One of the disadvantages of the research is the failure to take into account changes in the speed of propagation of the sound wave of impact during different humidity of the soil backfill. Such studies will be conducted in the following research papers.

VI. Conclusions

1. With an increased degree of compaction of the ground backfill of transport structures made of prefabricated metal corrugated structures, the time of movement of the sound wave decreases. When performing three series of tests, it was found that in the first series of experiments on the left compacted side of the soil backfill, the wave propagation time is tAc1=4.7·10-4 s and tAc2=4.87·10-4 s, and on the right side of the soil backfill with a bulk density – tAc3=6.81·10-4 s and tAc4=6.89·10-4 s. Accordingly, in the second series of experimental studies, the propagation time of the impact wave is tAc1=7.68·10-4 s, t tAc2=7.667·10-4 s, tAc3=8.4·10-4 s, tAc4=8.4·10-4 s. in the third series of experimental studies, the propagation time of the impact wave is tAc1=10.07·10-4 s, tAc2=9.92·10-4 s, tAc3=11.01·10-4 s, tAc4=10.86·10-4 s.

2. When comparing the propagation time of the sound wave of impact on the compacted side to the uncompressed side, the reduction in the wave movement time in the first series of ground backfill tests was by 28.6%, in the second series it was by 8.6% and in the third series it was by 8.5 %.

3. From three series of experimental tests, it was found that the speed of the impact wave increases with an increase in the degree of density of ground backfill of structures made of prefabricated metal corrugated structures. In the first series of experimental tests, on the compacted left side of the backfill, the average wave velocity was v_{Ac1}=363.44 m/s and v_{Ac2}=354.28 m/s, and on the right side, which has a bulk soil density, the wave velocity was v_{Ac3}=250.42 m/s and v_{Ac4}=248.44 m/s.

In the second series of tests, the average wave velocity on the compacted left side of the backfill was v_{Ac1}=339.21 m/s and v_{Ac2}=340.55 m/s. with the bulk soil density on the right side of the backfill, the average wave velocity was v_{Ac3}=310.41 m/s and v_{Ac4}=310.39 m/s.

In the third series of tests, the average wave velocity on the compacted left side of the backfill was v_{Ac1}=347.79 m/s and v_{Ac2}=353.39 m/s, and on the right side of the backfill at bulk soil density was v_{Ac3}=318.56 m/s and v_{Ac4}=323.36 m/s.

4. When comparing the compacted left side of the backfill with the bulk density of the right side, in the first series of tests, the increase in wave speed was 31.09%, in the second series of tests, the increase in speed was 8.5% and in the third series of experimental tests was 8.4 %. Therefore, by increasing the speed of movement of the sound wave of impact, it is possible to make an assessment of the degree of compaction of the ground backfill of transport structures made of prefabricated metal corrugated structures.

Acknowledgement

We express our sincere gratitude to the research laboratory of risks and safety in railway transport for the opportunity to conduct experimental studies of the degree of compaction of the ground backfill of metal corrugated pipe.

AUTHOR CONTRIBUTIONS

V. Kovalchuk: Conceptualization,Experiments, Theoretical analysis, Writing, Review and Editing.

A. Onyshchenko: Conceptualization,Experiments, Theoretical analysis, Writing, Review and Editing.

I. Karnakov: Conceptualization,Experiments, Theoretical analysis, Writing, Review and Editing.

I. Kravets: Experiments, Theoretical Analysis, Review and editing.

R. Rybak: Experiments, Theoretical Analysis, Review and editing.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

V. Kovalchuk https://orcid.org/0000-0003-4350-1756

A. Onyshchenko https://orcid.org/0000-0002-1040-4530

I. Karnakov https://orcid.org/0000-0002-8751-9934

I. Kravets https://orcid.org/0000-0002-2239-849X

R. Rybak https://orcid.org/0000-0002-0745-6620

References

[1] V. Kovalchuk, I. Karnakov, A. Onyshchenko, O. Petrenko, R. Boikiv: Assessing the stresses and magnitude of plastic hinge in a tunnel conduit made of precast metal corrugated structures taking into account the soil backfill parameters. Eastern-European Journal of Enterprise Technologies. Kharkov, Vol. 4/7 (124), 2023, pp. 43–53. https://doi.org/10.15587/1729-4061.2023.285893

[2] V. Kovalchuk, M. Sysyn, M. Movahedi Rad, S. Fischer: Investigation of the Bearing Capacity of Transport Constructions Made of Corrugated Metal Structures Reinforced with Transversal Stiffening Ribs. Infrastructures 2023, 8 (9), 131. https://doi.org/10.3390/infrastructures8090131 - 01 Sep 2023

[3] DSTU B V.2.3-42:2016. Automobile roads. Methods for determining the deformation characteristics of the subgrade and pavement. https://online.budstandart.com/ua/catalog/doc-page?id_doc=65397

[4] Y. Y. Chaplya, B. V. Gera, V. V. Kovalchuk: A Heat-Conduction Problem for a Composite Body with Elements of Different Dimensions. J Math Sci Vol. 294, 2025, pp. 293-308. https://doi.org/10.1007/s10958-025-08102-7

[5] A. M. Onyshchenko, I. A.Karnakov, D. Yu. Husiev, D. I. Mykytiuk, L. L. Yanchuk, V. V. Kovalchuk: Models and Methods for Assessing the Technical Condition of Transport Structures under Special Conditions. Theory and Practice (Monograph). Kyiv: Liudmyla Publishing House, 2023. ISBN 978-617-555-087-8, in Ukrainian.

[6] A. M. Onyshchenko, V. V. Kovalchuk, O. V. Fedorenko, Yu. Ye. Kovalchuk: Stress-strain state of metal corrugated structures of transport facilities. Industrial Construction and Engineering Structures, (1), 2021, pp. 24–31, in Ukrainian.

[7] V. Kovalchuk, M. Sysyn, Y. Hnativ, A.Onyshchenko, M. Koval, O.Tiutkin, M. Parneta: Restoration of the bearing capacity of damaged transport constructions made of corrugated metal structures. The Baltic Journal of Road and Bridge Engineering, 16 (2), 2021, pp. 90–109. https://bjrbe-journals.rtu.lv/bjrbe/article/view/bjrbe.2021-16.529

[8] Guide to VBN V.2.3-218-198:2007. Transport structures. Design and construction of structures made of metal corrugated constructions on public highways. Kyiv, 2007, 122 p., in Ukrainian.

[9] Handbook of steel drainage and highway construction products. Published by Corrugated Steel Pipe Institute, American Iron and Steel Institute, 2002, 470 p.

[10] Y. Y. Luchko, V. V. Kovalchuk, I. B. Kravets: Bridges and culverts made of corrugated metal structures and monitoring of soil foundations of roads and structures: Monograph. Lviv: Svit, 2020, 272 p.

[11] A. M. Onyshchenko, V. V. Kovalchuk, M. P. Koval, I. A. Karnakov, I. B. Kravets, A. S. Torkhov: Transport structures made of metal corrugated constructions: design, construction, testing (Monograph). Kyiv: Liudmyla Publishing House, 2024. ISBN 978-617-555-208-7, in Ukrainian.

[12] A. M. Onyshchenko, V. V. Kovalchuk, M. V. Harkusha, M. N. Tsyvin, I. A. Karnakov, R. V. Moshkivskyi: Ensuring the Reliability and Durability of Hydraulic Structures in Transport Construction Using Road Culverts under Operating Conditions (Monograph). Kyiv, 2023. Liudmyla Publishing House. ISBN 978-617-555-206-3, in Ukrainian.

[13] D. Kurhan, S. Fischer: Modeling of the Dynamic Rail Deflection using Elastic Wave Propagation. Journal of Applied and Computational Mechanics, Vol. 8 (1), 2022, pp. 379–387. https://doi.org/10.22055/JACM.2021.38826.3290

[14] B. Eller, M. Majid and S. Fischer: Laboratory Tests and FE Modeling of the Concrete Canvas, for Infrastructure Applications. Acta Polytechnica Hungaricathis, Vol. 19 (3), 2022, pp. 9–20. https://doi.org/10.12700/APH.19.3.2022.3.2

[15] S. Fischer: Investigation of the Horizontal Track Geometry regarding Geogrid Reinforcement under Ballast. Acta Polytechnica Hungarica, Vol. 19 (3), 2022, pp. 89–101. https://doi.org/10.12700/APH.19.3.2022.3.8

[16] S. Fischer: Investigation of effect of water content on railway granular supplementary layers. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, Vol. 2021 (3), 2021, pp. 64–68. https://doi.org/10.33271/nvngu/2021-3/064

[17] L. Ézsiás, R. Tompa, S. Fischer: Investigation of the Possible Correlations between Specific Characteristics of Crushed Stone Aggregates. Spectrum of Mechanical Engineering and Operational Research 2024, Vol. 1 No. 1. https://doi.org/10.31181/smeor1120242

[18] O. Nabochenko, M. Sysyn, V. Kovalchuk, Yu. Kovalchuk, A. Pentsak, S. Braichenko: Studying the railroad track geometry deterioration as a result of an uneven subsidence of the ballast layer. Eastern-European Journal of Enterprise Technologies, Kharkov, Vol. 1/7 (97), 2019, pp. 50–59. https://doi.org/10.15587/1729-4061.2019.154864

[19] M. Sysyn, O. Nabochenko, V. Kovalchuk and U. Gerber: Evaluation of railway ballast layer consolidation after maintenance works. Acta Polytechnica. Journal of Advanced Engineering. Czech Technical University in Prague, Vol. 59, No 1, 2019, pp. 77–87. http://orcid.org/0000-0001-6893-0018

[20] L. Ezsias, A. Brautigam, S. Kocsis Szurke, S. Szalai, S. Fischer: Sustainability in Railways – A Review. Chemical engineering transactions 2023, 107. https://doi.org/10.3303/CET23107002

[21] M. Sysyn, U. Gerber, V. Kovalchuk and O. Nabochenko: The complex phenomenological model for prediction of inhomogeneous deformations of railway ballast layer after tamping works. Archives of Transport. Poland, Vol. 46 (3), 2018, pp. 91–107. https://doi.org/10.5604/01.3001.0012.6512

[22] A.Németh, S.K.Ibrahim, M.Movahedi Rad, S.Szalai, Z.Major, S. Kocsis Szürke, V. Jóvér, M. Sysyn, D. Kurhan, D. Harrach et al: Laboratory and Numerical Investigation of Pre-Tensioned Reinforced Concrete Railway Sleepers Combined with Plastic Fiber Reinforcement. Polymers 2024, 16, 1498. https://doi.org/10.3390/polym16111498

[23] V. Kovalchuk, Y. Kovalchuk, M. Sysyn, V. Stankevych, O. Petrenko: Estimation of carrying capacity of metallic corrugated structures of the type multiplate mp 150 During interaction with backfill soil / // Eastern-European Journal of Enterprise Technologies. Kharkov. 1/1 (91), 2018. – pp. 18–26.

https://doi.org/10.15587/1729-4061.2018.123002

[24] D. Beben: Experimental Testing of Soil-Steel Railway Bridge Under Normal Train Loads. Experimental Vibration Analysis for Civil Structures, Lecture Notes in Civil Engineering 5, 2018, pp. 805–815. https://doi.org/10.1007/978-3-319-67443-8_71

[25] V. Kovalchuk, J. Luchko, I. Bondarenko, R. Markul, B. Parneta: Research and analysis of the stressed-strained state of metal corrugated structures of railroad tracks. Eastern-European Journal of Enterprise Technologies. – Kharkov 6/7 (84), 2016, pp. 4–10. http://dx.doi.org/10.15587/1729-4061.2016.84236

[26] V. Kovalchuk, R. Markul, A. Pentsak, B. Parneta, O. Gajda, S. Braichenko: Study of the stressstrain state in defective railway reinforcedconcrete pipes restored with corrugated metal structures. Eastern-European Journal of Enterprise Technologies. Kharkov. 5/1 (89), 2017, pp. 37–44. https://doi.org/10.15587/1729-4061.2017.109611

[27] V. V. Antipov, V.G. Ofrikhter: Modern nondestructive method of researching of geological-engineering section. PNRPU Bulletin Construction and architecture, 7 (2), 2016, pp. 37–49. https://www.researchgate.net/publication/305270448_Modern_nondestructive_method_of_researching_of_geological-engineering_section

[28] L. Izvolt, J. Sestakova, M. Smalo: Analysis of results of monitoring and prediction of quality development of ballasted and ballastless track superstructure and its transition areas. COMMUNICATIONS Scientific Letters of the University of Zilina, 2016, 18(4):1929. https://www.researchgate.net/publication/317756116_Analysis_of_results_of_monitoring_and_prediction_of_quality_development_of_ballasted_and_ballastless_track_superstructure_and_its_transition_areas

[29] H. Mallek, H. Mellouli, L. B. Said, M. Wali, F. Dammak, M. Alhadri. Porosity effect on nonlinear static performances of functionally graded shells considering thickness stretching. Facta Universitatis. Series: Mechanical Engineering. 23, 4, 2025, pp. 827–860. https://doi.org/10.22190/FUME240920015M

[30] A. Nasseroleslami, A. Sarreshtehdari, M. S. Seif, A. A. Ebrahimi Valmoozi. Experimental Investigation of the Relationship Between Cavitation Acoustic Waves and Erosion Threshold with a Novel Piezoelectric Configuration. Journal of Applied and Computational Mechanics, 2025, 11(4), pp. 1009-1021. https://doi.org/10.22055/jacm.2024.47786.4793

[31] A. Said, A.Bakkar, H. Khan, C. Cattani, F. Tchier. Construction of Mechanically Preserved Optical Travelling Wave Solution for Fractional Generalized Reaction Duffing Model. Journal of Applied and Computational Mechanics, 2025, 11 (4), pp. 1139-1148. https://doi.org/10.22055/jacm.2025.48049.4941

[32] K. Anam, M. Todt, H. E. Pettermann. Numerical Investigation of Double Low-Velocity Impact and Post-Impact Compression Behavior in Laminated Composites. Journal of Applied and Computational Mechanics, 2026, 12 (1), pp. 21-30. https://doi.org/10.22055/jacm.2025.48157.5019

[33] S. Fischer. Investigation of the Settlement Behavior of Ballasted Railway Tracks Due to Dynamic Loading. Spectrum of Mechanical Engineering and Operational Research, 2025, 2 (1), pp. 24-46. https://doi.org/10.31181/smeor21202528

[34] S. Fischer, D. Harangozó, D. Németh, B. Kocsis, M. Sysyn, D. Kurhan, A. Brautigam. Investigation of heat-affected zones of thermite rail weldings. Facta Universitatis, Series: Mechanical Engineering, 2023, 22 (4), pp. 689-710. https://doi.org/10.22190/FUME221217008F

[35] L. Ižvolt, P. Dobeš, M. Holešová, D. Navikas. Assesment of the possibility of foam glass application in the sub-ballast layers. Journal of Civil Engineering and Management, 2023, 29 (3), pp. 253-267. https://doi.org/10.3846/jcem.2023.18429

[36] S. Fischer. Geogrid reinforcement of ballasted railway superstructure for stabilization of the railway track geometry–A case study. Geotextiles and Geomembranes, 2022, 50 (5), pp. 1036-1051. https://doi.org/10.1016/j.geotexmem.2022.05.005

[37] S. Fischer. Investigation of the horizontal track geometry regarding geogrid reinforcement under ballast. Acta Polytechnica Hungarica, 2022, 19 (3), pp. 89-101. https://doi.org/10.12700/APH.19.3.2022.3.8

[38] N. Kumar, B. Suhr, S. Marschnig, P. Dietmaier, C. Marte, K. Six. Micro-mechanical investigation of railway ballast behavior under cyclic loading in a box test using dem: effects of elastic layers and ballast types. Granular Matter, 2019, 21 (4):106. https://doi.org/10.1007/s10035-019-0956-9

[39] Z. Xu, C. Zhao, W. Zhai, C. Shi, Y. Feng. Investigation of track settlement and ballast degradation in the high-speed railway using a full-scale laboratory test. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2018, 233 (8), pp. 869-881. https://doi.org/10.1177/0954409718812231

[40] S. Fischer. Evaluation of inner shear resistance of layers from mineral granular materials. Facta Universitatis, Series: Mechanical Engineering. 2023. https://doi.org/10.22190/FUME230914041F

[41] V. Kovalchuk, I. Karnakov, A. Onyshenko, M. Sysyn, O. Bal, S. Hrevtsov, M. Babyak. Mathematical model for evaluating the stress-strain state of transport structures made of prefabricated corrugated metal constructions depending on the modulus of elasticity of the foundation soil. Cognitive Sustainability, 2025, 4 (3). https://doi.org/10.55343/CogSust.20522

[42] F. Kaya, S. Aslan, M. Fahad, K. Madarász, S. Rosta, R. Nagy, S. Fischer. Performance of PMMA and SBS Modified Asphalt Mixtures in Railway Supplementary Layers and Road Pavements,4 Periodica Polytechnica Transportation Engineering, 2025, 53 (3), pp. 334–346. https://doi.org/10.3311/PPtr.39763