IOP Conference Series: Earth and
Environmental Science

Analysis of stress-strain state changes in railway tracks during transition to European gauge

To cite this article: Szabolcs Fischer *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1348** 012029

Analysis of stress-strain state changes in railway tracks during transition to European gauge

Szabolcs Fischer[1], **Dmytro Kurhan**[2,3], **Mykola Kurhan**[2] **and Nelya Hmelevska**[2]

[1]Széchenyi István University, Egyetem tér 1, Győr, 9026, Hungary
[2]Ukrainian State University of Science and Technologies, Lazaryan St., 2, Dnipro, 49010, Ukraine

[3]Corresponding author: d.m.kurhan@ust.edu.ua

Abstract. The geographical location of Ukraine facilitates its integration into the transportation network connecting European countries. Various options exist for transitioning from the gauge of 1 520 mm to the European standard gauge of 1 435 mm. This paper aims to analyze the changes in the stress-strain state of railway track elements during the reconstruction of existing sections from the 1 520 mm gauge to the 1 435 mm European gauge or to a dual gauge of 1 435/1 520 mm. To perform these calculations, a spatial model of dynamic deformations in the railway track is employed, based on the principles of elasticity theory. The implementation of a combined railway track complicates the stress state of the ballast layer, leading to asymmetric stresses along the length of the sleepers, which vary depending on the track on which trains operate. There is also a redistribution of stresses acting on the ground structure, which has been in operation for many years. The research results identify changes in the stress-strain state of the railway track and can be used to justify measures for the appropriate reinforcement of the ballast layer and the ground structure.

1. Introduction

The geographical position of Ukraine enables its participation in the transportation network connecting European countries. During the transition to the European railway gauge, trains traveling to and from Ukraine experience significant time losses due to wheelset replacements, passenger transfers, and cargo transshipments at the borders with Hungary, Poland, Romania, and Slovakia. Adopting a unified European railway gauge of 1 435 mm would substantially economize time and foster an increase in train traffic between countries.

There are three possible approaches to implement the European gauge: laying a new track infrastructure; dividing existing double-track sections into two single-tracks, one with a gauge of 1 435 mm and the other with 1 520 mm; replacing the existing gauge with a dual gauge of 1 435/1 520 mm.

Each of these options carries its own set of advantages and drawbacks. It is evident that when considering a long-term perspective, priority should be given to the construction of a new track infrastructure. Such a track would be designed from the outset to accommodate high-speed operations in accordance with European standards, avoiding the technical challenges posed by existing railway networks. However, it is important to note that this option is unquestionably the most expensive.

Conversely, the other two options are more cost-effective as they do not require extensive land acquisition and utilize existing ground structure. Nevertheless, they come with significant drawbacks.

The division of a double track into two single-tracks would result in a substantial (approximately four to five-fold) reduction in the capacity of the section, necessitating the construction of additional segments for overtaking and train crossings. The dual gauge approach requires the application of specialized upper track structures, including complex engineering solutions for the intersection and weaving of railway tracks.

Certainly, the further implementation of European gauge railway tracks in Ukraine is likely to progress through a comprehensive combination of all possible options. As a result, ongoing scientific investigations are dedicated to the multifaceted exploration of these matters. Particular attention in these studies is directed towards dual gauge systems, recognized for their significant technical intricacies.

Dual gauge railways, which concurrently accommodate two different track gauges, have found application in several European countries. One prominent example is Spain, where two gauge standards coexist: the broad gauge (1 668 mm) and the standard gauge (1 435 mm). This historical and geographical divergence has led to what is now referred to as the "Iberian gauge" [1]. Another instance is Portugal, where dual gauges are also in operation. Furthermore, the international project "Rail Baltica," connecting the national borders of Lithuania and Poland to Kaunas, provides a notable case study. Along the Rail Baltica railway section, a new European standard gauge track of 1 435 mm width was laid alongside an upgraded existing rail line with a gauge of 1 520 mm [2, 3].

Presently, Ukraine has already established dual gauge railway tracks in certain regions. For instance, such sections are in operation at the border crossings with Poland (Dorohusk-Yelkova station), Slovakia (Uzhhorod station), and Hungary (Zahony station) [4]. In a previous study [5], a mathematical model was developed to analyze passenger movements utilizing trains on different tracks – the dual gauge track connecting two stations at the border with Poland (Nyzhankovychi–Starzhava) and the 1 520 mm gauge track (Sambir–Khryv).

Several technical aspects of dual gauge application have been investigated in prior scientific research. For instance, in a study [6], the increase in stresses within the ballast layer of a three-rail dual gauge track was theoretically and experimentally demonstrated. Additionally, in another paper [7], the impact of gauge width variation on the stability of embankments with soft soil was explored, among other related works.

The purpose of this paper is to analyze changes in the stress-strain state of railway track elements during the reconstruction of existing sections from the 1520 mm gauge to the European standard gauge of 1 435 mm or to a dual gauge of 1 435/1 520 mm.

2. Methods

To investigate the stress-strain state, a plethora of mathematical models and methods are available today. The choice of tools primarily aligns with the specific problem at hand. Justification of a particular approach may itself be the subject of dedicated scientific inquiry. In the case of this study, authors employed a spatial model of dynamic deformations in railway tracks based on elasticity theory [8].

This mathematical model is founded on the formation of the geometry of elastic wave propagation in the three-dimensional space of the railway track structure under applied loading. The geometric outline of the elastic wave determines the propagation of stresses and deformations within the material layers comprising the railway track structure. Notably, in addition to the physical and mechanical properties, considerations encompass the geometric contours of structural elements, the pressure transmission planes between them, and the timing of stress initiation and duration. Stress calculations at spatial points at each time step are carried out by solving a system of differential equations describing pressure propagation in the material space, accounting for its dynamic deformation.

A detailed description of this mathematical model, its verification, and application examples in solving problems related to track-train interaction have been presented in a series of previous works by the authors. One of the recent contributions pertained to determining the deformation characteristics of railway ballast considering varying levels of contamination [8].

For this particular investigation, the movement of a passenger wagon on a railway track conforming to the I category of Ukrainian railways was considered. This corresponds to R65 rails, reinforced concrete sleepers, and 60 cm thick gravel ballast. The deformation modulus of the ballast was assumed to be 200 MPa, and that of soil was set at 35 MPa, reflecting the overall elasticity modulus of the railway track structure at a level of 50 MPa – a commonly adopted value for most typical railway strength calculations.

3. Results and discussion

3.1. Option to change the gauge width of a dual-track section from 1 520 to 1 435 mm

Altering the gauge width of a railway track entails the application of different rolling stock or modifications to existing wagon bogies that have been in operation. This inevitably introduces certain changes in the dynamics of rolling stock and its interaction with the railway track. However, these changes do not significantly impact the magnitudes or nature of the forces acting from the wheel to the rail. Consequently, stresses within the rails, rail fastening elements, and sleepers exhibit minimal dependency on gauge width. In the majority of stress calculation methods pertaining to track superstructure elements, the influence of the second rail gauge is altogether disregarded. Stresses in the ballast layer at depth will begin to experience the influence of the second rail gauge, but these alterations can also be considered inconsequential.

Undoubtedly, the transition to a different gauge width will necessitate technological implementation through the execution of reconstruction and technical upgrading of the respective track section. This form of maintenance will involve the replacement of the rail-sleeper lattice with a new one, coupled with the cleansing of the ballast layer. Consequently, the entire upper structure of the track will be renewed and maintained in operational condition.

The stresses that will propagate through the ballast layer to soil will not exceed permissible values, in accordance with the current regulatory documents governing the condition and operational requirements for rolling stock and railway tracks. However, unlike the track superstructure, soil remains essentially unchanged since its construction many years ago. It has undergone prolonged use and has inevitably experienced certain levels of consolidation and residual deformations in accordance with the historical load distribution profile. Altering this load distribution profile may induce additional deformations, even while remaining within acceptable stress limits. Figure 1 illustrates the percentage changes in stress distribution within the upper layer of soil resulting from a change in track gauge width.

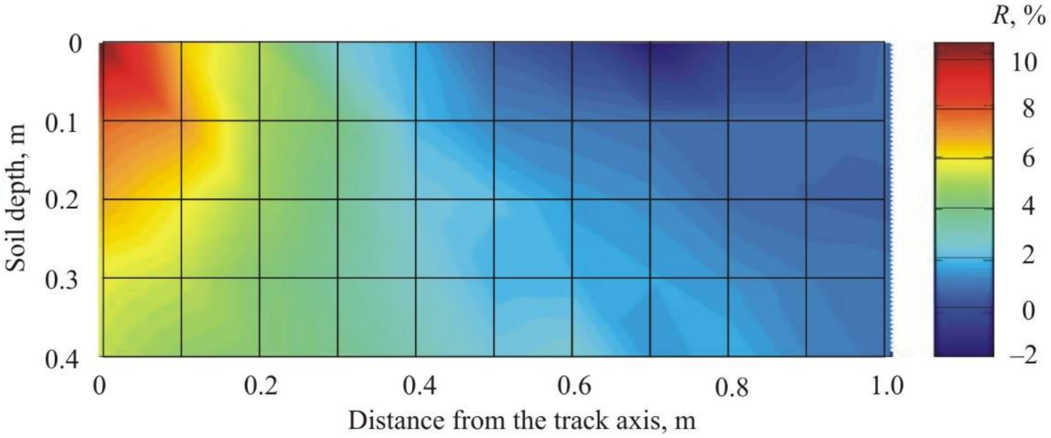


Figure 1. Changes in the stress state of the soil during transition from 1 520 mm to 1 435 mm gauge width.

The stress in the soil was obtained using the mathematical model described above. The passage of a passenger car at a speed of 160 km/h on a track with a gauge width of 1 520 mm was simulated, followed by a track with a gauge width of 1 435 mm. From the stress array formed during the passage of the wheels over the specified cross-section of the track, the maximum stresses were selected for further comparison. The parameter (R) presented in figure 1 shows the change in stresses in the soil as a percentage when changing the track gauge width:

$$R = \frac{100(\sigma_{1435} - \sigma_{1520})}{\sigma_{1520}}, \tag{1}$$

where σ_{1520}, σ_{1435} are the stresses in the soil generated during the passage of the passenger car on the track with widths of 1 520 mm and 1 435 mm, respectively, kPa.

On the horizontal axis, the change in stresses is shown relative to the track axis, and on the vertical axis, relative to the depth below the ground surface. As seen in figure 1, an increase in stresses of up to 10% occurs in the upper layers of the soil along the track axis. This increase can be explained by a slightly higher concentration of stresses when the load base narrows onto the railway track. In areas away from the track axis, a small (a few percent) decrease in stresses can be observed. Overall, it can be argued that there are no significant changes in the stress-strain state of the soil in this case.

3.2. Option of applying the dual gauge track 1 435/1 520 mm

The dual gauge railway track of 1 435/1 520 mm consists of four rails placed on a single concrete sleeper. The three-rail construction variant, which is commonly used worldwide in other combinations of track gauges, is not feasible in this case due to the small difference between their values. The sleeper required to accommodate four rails has an increased length. Therefore, replacing the track-and-sleeper grid with a gauge width of 1 520 mm with a dual gauge track may pose additional challenges related to ensuring clearance distances. Figure 2 illustrates the reconstruction scheme of a double-track section with the replacement of one track with the dual gauge structure.

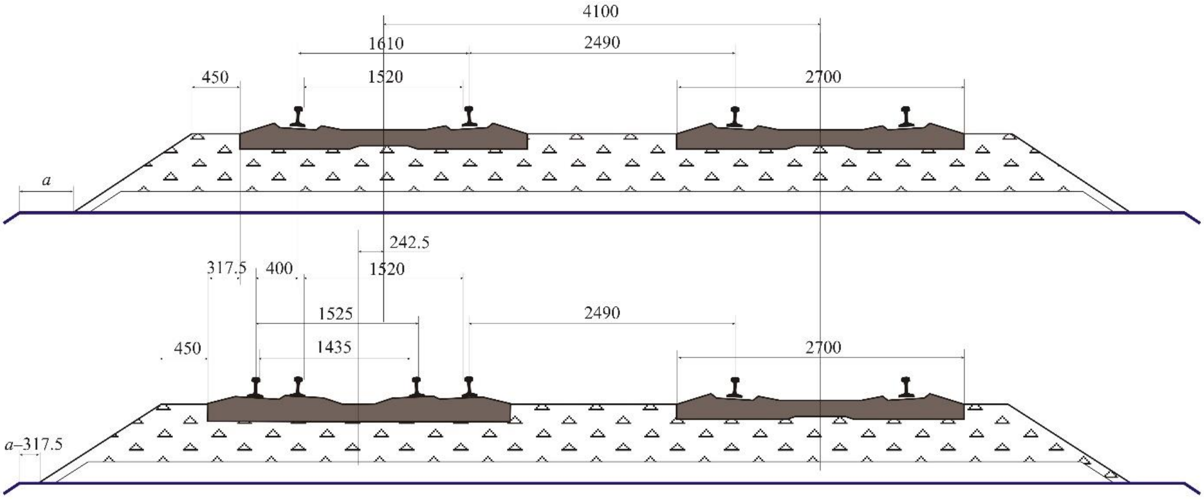


Figure 2. Changes in the cross-sectional profile of the railway track superstructure when installing dual gauge track on a double-track section.

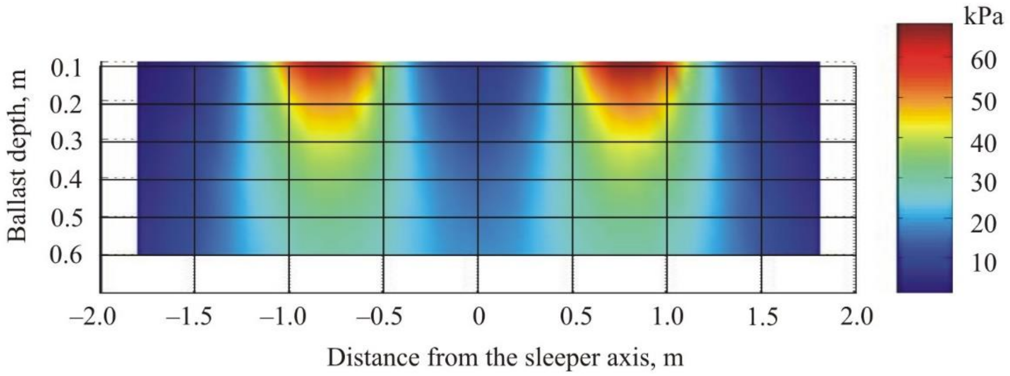
The figure illustrates the key geometric dimensions primarily related to minimum clearance distances. In the dual gauge construction, Ukrainian pre-stressed concrete sleepers are employed. The dual gauge sleeper is positioned to maintain the track centerline for the 1 520 mm variant, ensuring minimal changes in clearance distances. In this arrangement, the sleeper axis is shifted outward by 24 cm, the outer rail for the 1 435 mm gauge by 40 cm, while maintaining a 45 cm ballast prism shoulder. Consequently, the width of ground structure embankment will decrease by 32 cm.

The considerations regarding the stress state of rails, rail fastenings, and sleepers can be considered identical to those mentioned for the previous variant. The stress-strain state of the ballast in such a construction will be more complex. Assuming proper condition of rolling stock and track, and adherence to operational conditions, there is no expected excess of permissible stresses in the ballast. However, the stress profile during the passage of rolling stock on tracks of different gauges will significantly differ.

It should be noted that, during the passage of rolling stock, the ballast layer primarily responds to vertical elastic deformations. The intensity of residual deformation accumulation, among other factors, depends on the quality of ballast consolidation. Therefore, in addition to compaction by tamping and regulating machines, which occurs during the laying of the rail and sleeper grid in the design position, a special track machine, a track stabilizer, is used. Typically, it operates after all other repair work is completed and imparts vibration action on the track that mimics the passage of a certain number of trains. This allows the ballast to "adapt" (compact) to the specific load profile imposed by the trains in subsequent operation. For dual gauge track, this profile will vary depending on whether the train runs on the 1 435 mm or 1 520 mm gauge, as shown in figure 3. To create the image in figure 3b, stresses observed during the passage of trains on rails with gauges of 1 435 mm and 1 520 mm are simultaneously displayed:

$$\{\sigma\} = \{\sigma_{1520}\} \cup \{\sigma_{1435}\}. \tag{2}$$

a)



b)

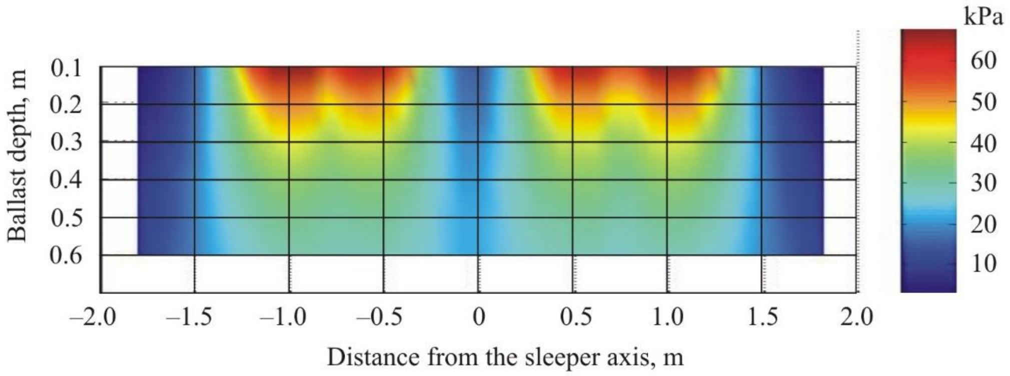


Figure 3. Stresses in the ballast layer: a) for a railway track with a gauge of 1 520 mm; b) for a dual gauge railway track with a gauge of 1 435/1 520 mm.

In many scientific papers, the performance of the ballast layer is regarded as one of the most complex among the various components of a railway track. Gravel ballast accumulates contaminants and requires regular maintenance work for cleaning and restoration [9]. Additionally, the ballast layer serves the purpose of water drainage (precipitation), making its physical and mechanical properties dependent on weather conditions [10]. Such a significant alteration in the load distribution within the ballast, observed when trains travel on different rails supported by the same sleeper, as well as the asymmetry of this distribution along the sleeper's length (figure 3), is an additional factor that can lead to a substantial increase in the accumulation of residual deformations.

The complex stress-strain state of the ballast layer undoubtedly has an impact on the behavior of the soil. Figure 4 illustrates changes in soil stresses when transitioning from a 1 520 mm gauge track to a dual gauge track with 1 435/1 520 mm. The zero horizontal mark corresponds to the centerline of the dual gauge sleeper (figure 2). The change indicator (*R*) is determined by the equation:

$$\begin{cases} R = \dfrac{100\left(\sigma_{\text{dg}} - \sigma_{1520}\right)}{\sigma_{1520}}; \\ \left\{\sigma_{\text{dg}}\right\} = \left\{\sigma_{\text{dg}\,1435}\right\} \cup \left\{\sigma_{\text{dg}\,1520}\right\} \end{cases}, \quad (3)$$

where $\left\{\sigma_{\text{dg}\,1435}\right\}$ and $\left\{\sigma_{\text{dg}\,1520}\right\}$ are the stress distributions in the soil generated as a passenger wagon passes over the dual gauge track with gauges of 1 435 mm and 1 520 mm, respectively; σ_{dg} – a combination of these stress arrays, kPa.

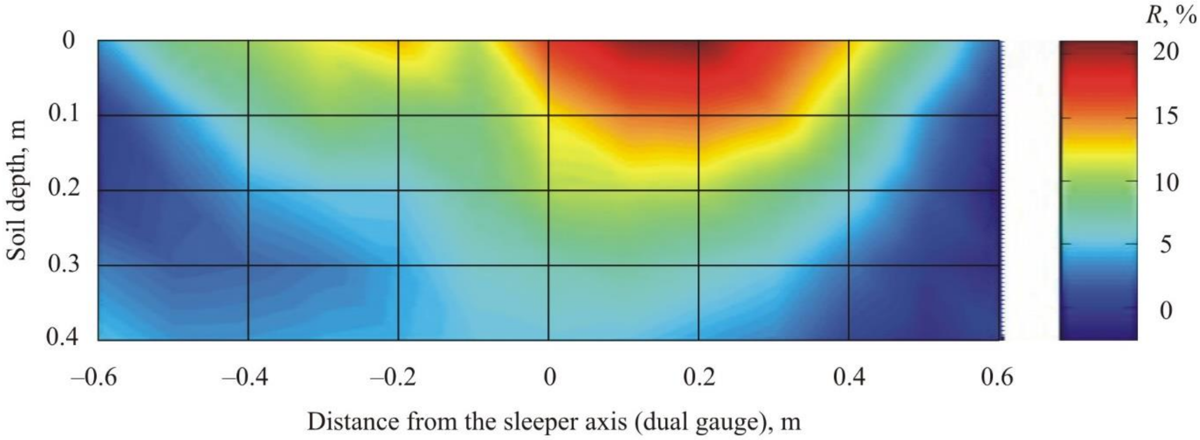


Figure 4. Changes in the stress state of the soil during the reconstruction of a track into a dual gauge 1 435/1 520 mm track.

Observations from figure 4 reveal alterations in the stress state of the upper soil layers over a length of 1.0-1.2 meters, with changes reaching up to 20%. While the stresses within the soil remain within permissible limits in absolute terms, these alterations, compared to the previous long-term operational conditions, could have detrimental effects. Therefore, the reconstruction of the railway section, which involves such modifications in its stress-strain state, should include appropriate measures to reinforce the ground structure.

4. Conclusions

In the paper, the alteration of the stress-strain state of the Ukrainian 1 520 mm gauge railway after reconstruction to accommodate the European 1 435 mm gauge or a dual gauge 1 435/1 520 mm track is investigated. A spatial model of dynamic deformations in the railway track, based on elasticity theory, was used for calculations. Stress in the railway track elements was determined based on the passage of a passenger train. The railway track construction complied with the requirements of the I category of Ukrainian railways.

During the reconstruction of one track of a double-track railway section from 1 520 mm gauge to the European 1 435 mm gauge, a complete replacement of the upper track structure elements with cleaning and renewal of the ballast layer will take place. There is no expectation of exceeding permissible stresses in these track elements. However, the ground structure remains existing and has a long operational period. The stress distribution in soil will undergo changes, with concentration along the track axis increasing up to 10 %.

In the reconstruction of the existing 1 520 mm gauge railway section for dual gauge 1 435/1 520 mm track, special reinforced concrete sleepers capable of accommodating four rails simultaneously will be used. When employing this design, special attention should be given to the quality of compaction and reinforcement of the ballast layer. Stresses occurring within its space will be asymmetric along the length of the ballast and will vary depending on which track the trains are using. Consequently, the stress distribution transmitted to soil will also significantly change compared to previous years of operation, resulting in zones of stress concentration up to 20 %. Reconstruction of the railway section, accompanied by such changes in its stress-strain state, should include appropriate measures for reinforcing the ground structure.

Acknowledgments

This research was funded by The National Research Foundation of Ukraine under the project "Scientific Justification of the Introduction of the European Track on the Territory of Ukraine in the Post-War Period" (project registration number 2022.01/0021), which was obtained through the "Science for the Recovery of Ukraine in the War and Post-War Periods" competition. Authors express gratitude to the employees of the Ukrainian State University of Science and Technologies, and the members of the "SZE-RAIL" research team at Széchenyi István University.

References

[1] Almech A, Roanes-Lozano E, Solano-Macías C and Hernando A 2019 A new approach to shortest route finding in a railway network with two track gauges and gauge changeovers *Mathematical Problems in Engineering* **2019**

[2] Maskeliūnaitė L 2021 Railways in Lithuania: from Tsarist Russia to Rail Baltica *Transport* **36** (4) 364–375

[3] Vaičiūnas G and Steišūnas S 2017 Investigation of priority directions of Rail Baltica extension from Warsaw *Procedia Engineering* **187** 40–45

[4] Kurhan M, Fischer S and Kurhan D 2023 The prospect of using the dual gauge line for the Ukraine–Hungary railway connection *Periodica Polytechnica Transportation Engineering*, **51** (1) 70–78

[5] Gera B, Hermaniuk Y and Matviiv V 2023 Organization of passenger rail transportation on the section with the combined track Nyzhankovychi-Starzhava *Transport technologies* **4** (1) 29–37

[6] Villalba S I, Franco R I, Fernández P M and Zuriaga P S 2021 Experimental and numerical investigations of dual gauge railway track behavior *Construction and Building Materials* **299** (3) 123943

[7] Mwanza A D, Hao P, Muya M and Haiwei Z 2016 Impact of dual gauge railway tracks on traffic load induced permanent deformation of low embankments *Procedia Engineering* **143** 880–887

[8] Kurhan D, Kurhan M, Horváth B and Fischer S 2023 Determining the deformation characteristics of railway ballast by mathematical modeling of elastic wave propagation *Appl. Mech.* **4** (2) 803–815

[9] Andrieiev V, Tiutkin O, Hubar O, Markul R and Mukhina N 2022 Methods of assessment of ballast contamination on railways of Ukraine *Int. Scientific Conf. Transport Means* 2022 842–849

[10] Liu J, Liu Z, Wang P, Kou L and Sysyn M 2022 Dynamic characteristics of the railway ballast bed under water-rich and low-temperature environments *Engineering Structures* **252** 113605