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EXPERIMENTAL AND THEORETICAL EVALUATION OF SIDE TAMPING METHOD FOR BALLASTED RAILWAY TRACK MAINTENANCE

Summary. Ballast layer is the most weak element of railway track that causes track geometry deterioration. At the same time, it is subjected to intensive particle breakage during the corrective tamping. This causes high maintenance costs of ballasted track. The present paper is devoted to the study of tamping methods. The present machine tamping methods are considered and compared. The possible influence of the tamping technology on the ballast-related maintenance costs is analyzed. The side tamping technology is studied in detail with theoretical and experimental methods. The process of material transport during the side tamping is studied using a scale model of ballast layer and photogrammetric measurements. A theoretical finite element model (FEM) is validated to the experimental results. The study shows that the side tamping is a promising method for the development of a universal, superstructure independent tamping technology.

1. INTRODUCTION

Railway track superstructure with ballast bed is the most widespread track superstructure worldwide. The superstructure has been optimized during the long history of railways. It has many advantages: quick and cost-effective mechanized construction and renewals, high operational stability in the difficult conditions, maintainability, etc. The investment costs of railway superstructure in the construction of new lines amount to only 5-7% of the general investment costs of railway infrastructure [1]. However, the cost share of the track maintenance in the overall maintenance costs is quite different to those of the investment costs. Almost 50% of the overall maintenance costs are used for track maintenance. The other 50% is spent for the signaling system, catenary devices, and engineering structures. The low maintenance costs of railway infrastructure lead to a reduction of railway transportation cost attractively compared with the other transportation systems. The modern transportation system of European countries offers a number of competitors to the rail transport both for passenger and for freight traffic. Therefore, the reduction of the track maintenance costs would be a promising way for the competitiveness of railway transportation.

The main reason of the high maintenance costs for railway track is first of all short lifecycles of track elements. This causes the frequent maintenance works and the cost-expensive replacement parts. The cause of lowest lifecycle in the track geometry is the inhomogeneous settlements of ballast layer.

This requires corrective tamping works, with the average tamping cycle of 40-70Mt [2]. The short ballast tamping cycles, compared with the overall lifecycle of track 700-1000Mt, lead to a significant share of the maintenance costs.

The technical cause of the short lifecycle of the ballast layer consists in its mechanical properties. As railway ballast is usually crushed stone, which is a cohesionless material, it badly perceives the dynamic load. During train travel over a track, enormous dynamic forces are generated, especially in zones of short geometrical irregularities, like rail joints, common crossings, and transition zones. The induced vibration causes a loss of friction between the stones of ballast layer, which leads to inhomogeneous settlements. The settlements over the long-term result in deterioration of the track geometry. This can lead to abnormalities, which means that the geometry of the track is no longer assured, and in these areas, it becomes necessary to impose temporary speed restrictions. To avoid a traffic operation limitation, tracks should be maintained at regular intervals – this includes levelling, lifting, lining, and tamping. This ensures that the geometry of the track is restored. The tamping works, however, are a cost-expensive process, which is performed with long-term traffic interruption. The correction of track geometry with the conventional tamping machines is accompanied by a significant destruction of ballast material. Therefore, the frequent tamping itself causes shortening ballast lifecycles and leads to ballast cleaning.

The present paper focuses on the study of ballast tamping process. A qualitative analysis of the tamping methods is carried out. The analysis shows the possible influence mechanism of tamping on the ballast cost reduction. The study deals with the detailed study of the side tamping technology providing the most advantages regarding the cost of railway track maintenance. The process of material motion during the side tamping process is studied using the scale tests and photogrammetric measurements. Theoretical finite element model of plastic flow is developed and validated with the experimental measurements.

2. LITERATURE REVIEW

Many recent studies are devoted to the study of railway ballast under the operational loading and during the tamping process. A systematization of the knowledge of ballast strength, deformation and degradation, particle attrition and breakage, track geometry deterioration, etc. is presented in the fundamental works of many authors [3-5]. A detailed experimental investigation of ballasted track geometry deterioration owing to ballast inhomogeneous settlements is presented in some other studies [6-9]. The authors study the process of rapid track quality decrease in the transition zones from ballasted track to ballasted one where high dynamic loading occur. A tool for analysis and prognosis of the track deterioration and maintenance planning is developed. An experimental investigation of track geometry deterioration in zones of high dynamic loadings – railway turnouts is presented in Salajka et al. [10]. The influence of under-sleeper pads on the geometrical quality of track and turnouts is studied in Plášek O. and Hruzikova M and Plášek O. et al. [11, 12] based on the long-term observations and measurements. The study has confirmed a significant positive influence of the elastic layers between sleeper and ballast on the quality deterioration for the ordinary track. The influence for the turnouts was estimated as statistically insignificant. The investigation of geogrid layers under railway ballast and their effect on the ballast layer stabilization is presented in Fischer S.Z. and Horvat F. [13]. The study results show a significant reduction in settlement in ballast layer, especially for rounded particles. Numerical simulations of track geometry deterioration owing to the differential settlements of the ballast layer in case of a track and a common crossing are presented in Nabochenko O et al. and Sysyn M. et al. [14, 15]. The model is validated with the results of on-board inertial measurements on operational trains. The study takes into account the complex process of short- and long-term settlement accumulation depending on the dynamic ballast pressure in relation to track stiffness variation in the settlement zones. The key finding of the studies [3-15] is the estimation of track geometry deterioration owing to ballast layer residual deformations with taking into account track structure properties. However, the findings are only applicable for the operation loading.

The process of ballast particle destruction under traffic loading is experimentally studied in other works [16, 17]. A new laboratory method for breakage test of railway ballast materials was developed in the studies. The test enables the laboratory breakage estimation with close to real loading conditions. A numerical simulation of ballast particle crushing under the vibration loading is presented in a number of papers [18-20]. The vibration characteristics of ballast stones with different aspect ratios under wheel-rail loading are analyzed as well as their influence on the contact loose between sleeper and ballast layer that leads to higher settlement of the ballast track. An evaluation of railway ballast attrition tests together with particle geometry measurement and petrography analysis is presented in the study by Bhanitiz A. [22]. The recommendations for efficient application and optimized test evaluation are proposed. Particle brakeage under traffic loading and tamping maintenance is studied in the study by Bhanitiz A. [22]. The laboratory study shows a significant influence of ballast tamping operation on the particle breakage and the following increase of ballast settlements owing to ballast destruction. Similar results were received in the studies by Soleimanmeigouni I et al. and Audley M. and Andrews J.D. [23, 24], where the track measurements were analyzed before and after tamping. It was concluded that degradation rate after tamping was increased. A paper [25] investigates the reasons for the deterioration rate increase in ballast after tamping with reference to triaxial tests on scaled ballast. The implication of the study is that the tamping is disruptive to ballast structure and resilience, and the tamping should be carried out as rarely as possible. The general shortcoming of the studies is that the ballast particle destruction process is usually considered separately from shape and compaction change processes.

Ballast compaction quality after tamping process and its influence on the following ballast resilience during operation was studied in papers by Sysyn M. et al. and Ilinykh A. et al. [26, 27]. A method for prediction of track quality deterioration is proposed, which takes into account maintenance works, subgrade stiffness superstructure, and operational properties. Laboratory and in-situ estimation of ballast compaction with non-destructive testing methods is presented in other studies [28-30]. The presented methods are based on the kinematic and dynamic interpretation of wave propagation in ballast layer. The studies by Sysyn M. et al. and Sysyn M. et al. [30, 31] allow to determine the differences in ballast compaction along the sleeper after vibration loading. Numerical simulation of ballast compaction and ballast porosity using discrete element method is shown in other papers [32-35]. Tamping operations, like sleeper lifting, tines insertion, vibrating and packing, their pulling, and sleeper settling were simulated in a realistic manner, which showed the decrease of inter-granular contacts number during the insertion of the vibrating tines and the packing process. The studies confirm that ballast compaction depends on the tamping technology, it is inhomogeneously distributed in the ballast bed, and it influences the ballast residual deformations.

Laboratory studies of stone blowing method of track geometry correction are presented in some other studies [36-39]. The studies indicate on the advantages of this method application for track maintenance. The mechanical performance of track settlement is estimated, namely, stiffness, energy dissipation, ballast degradation, etc. The studies show that stone-blowing process is more effective than conventional tamping owing to lower degradation of ballast and substructure.

3. ANALYSIS OF TECHNOLOGIES FOR TRACK GEOMETRY CORRECTION

There are a number of methods for machine track geometry correction. The main methods and their working principles are shown in Fig. 1. The most widespread tamping principle worldwide is using tamping tines that are penetrated in the ballast layer in zone near the rails (Fig.1a). The asynchronous squeezing with pressure of 115-125 bar and frequency of 35 Hz produces "liquefaction" of crushed stone and its movement in zone of void under the lifted sleeper. The stone blowing method for geometry correction is used by some railway companies in Great Britain. The method is based on air blowing of small particle mixture under the lifted sleeper (Fig.1b) so that the voids are unformal filled. Another principally different tamping method is - side tamping technology of machine type VPO that is often used in the former USSR countries. The crushed stone is transported under the lifted sleepers with a wedge-shaped vibrating plate that are continuously moved along the track (Fig.1c). The horizontal vibration and a complex form of wedges produce uniform distribution and compaction of crushed stone under the sleeper. Another vertical tamping principle that was used in a machine of firm Robel in 50th years is presented in Fig.1d. The transport of crushed stone under the sleeper is produces by vibration tines on the outside surface of ballast layer. However, this method of machine tamping has not found an application nowadays.

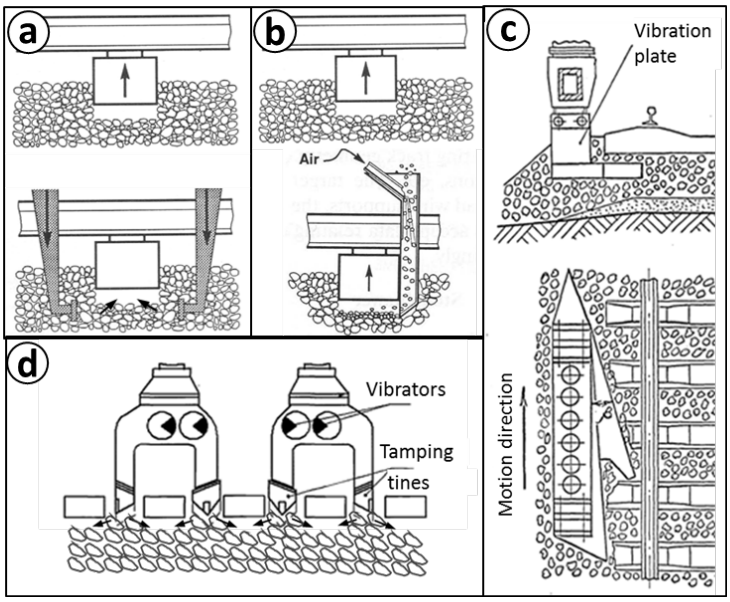

Fig. 1. Principal schemes of railway ballast machine tamping: a - conventional tamping technology of Plasser and Theurer [3]; b - stone blowing [3]; c - side tamping technology of machine type VPO [40]; and d - vertical tamping technology of Robel [40, 41]

Different tamping principles have their advantages and shortcomings. Plasser and Theurer development was perfected in many generations of tamping machines. The technology offers high geometrical quality and ballast compaction both for ordinary track and for switches and crossings (S&C). The further development of the tine tamping principle is presented in the studies by Lichtberger B. [42, 43]. The full-hydraulic tamping allows load-controlled tamping with better compaction quality as well as lower energy consumption and noise emission. However, the main shortcoming of the tine tamping is a high destruction of ballast material particles, which was indicated in many studies [22-25]. A high destruction and multiple tamping leads to a necessity of cost-expensive ballast cleaning. The cause of the high destruction is a high contact pressure on ballast stones by squeezing operation and the tines penetration. The high contact pressure causes also a rapid wear of expensive tamping tines. Additionally, for an efficient operation of the ballast tamping, a good quality of ballast material is necessary with contamination not more than 20%. The tamping principle unconsolidated ballast layer, and therefore after tamping, a dynamic stabilization is needed to produce a compaction. All new machines have lifting, tamping, and stabilizing units in one vehicle.

Stone blowing machines have an advantage to preserve ballast compaction under the sleeper that excludes quick initial settlements and the necessity of dynamic stabilization. Moreover, the machines can effectively operate on heavily contaminated ballast that allows to exclude or delay expensive ballast cleaning works. The main disadvantages are relative low productivity, low geometrical quality of correction, and low lateral stability of track owing to additional contamination with small particles. Different to the tine tamping, the stone blowing machines can correct only the short-wave fault in vertical profile.

The side tamping machines type VPO have advantages of high productivity and low ballast destruction. High track lifting and tamping up to 10 cm excludes a necessity of multiple layer tamping. Low destruction of ballast particles is caused with a high contact area of tamping units and correspondingly low contact pressure. The tamping can be potentially used for any sleepers and ballast material. However, the side tamping cannot be used for S&C. After the side tamping, a dynamic stabilization is necessary. The main shortcomings of the machine consist in its application only after ballast replacement or cleaning owing to the properties of tamping units. The machine is not used for corrective maintenance. A comparison of main parameters of the machine's operation is presented in Table 1 [2, 44].

Table 1

Parameters of tamping machines operation

Tamping machine	Tine tamping	Stone blowing	Side tamping
Vertical geometry precision, mm	±1	±3	±2
Maximal productivity, m/h	2000 (09-3x) 2400 (09-4x)	350	3000
Maximal lifting for one tamping, cm	5	5	10
S&C tamping	yes	no	no
Fine particles <25mm after tamping/blowing, kg/sleeper	1.6- 3.9	>5	0.6
Contact area of tamping unit, m2	0.01	-	0,35
Tamping pressure, MPa	11.5- 12.5	-	0.135

The tamping machines Dynamic Stopfexpress 09-4X and VPO-3000 in the process of tamping are shown on the Fig. 2 (left). The machine VPO-3000 (Fig. 2, right), except of tamping, produces also ballast layer surface formation.

Fig. 2. Machines for continuous tamping (left – Dynamic Stopfexpress 09-4X [45], right – VPO-3000)

Table 2 presents a comparison of the tamping methods relating to the potential of the ballast maintenance cost reduction. The cost of track tamping operation itself is not enough to estimate the overall cost effect. Additional advantages that are related to tamping technologies should be taken into account. There are in principle three main ways of tamping-related cost reduction. The main one was an application of high productive tamping machines. Advances in the improvement of machine productivity from the first to the last generations of Plasser and Theurer ballast tamping machines have increased the annual working length from 50 to 400 km/year [2]. This results in the corresponding decrease of tamping costs per running meter up to 90%. The further improvement of machine productivity would cause the cost reduction, but the potential of the reduction is insignificant.

Another tamping-related cost reduction factor is a lifecycle until the next tamping. The lifecycle prolongation has equivalent influence to the cost reduction as the improvement of the productivity. The lifecycle can be prolonged with 3 influence factors: low destructive tamping, initial track geometry quality, and compaction. The better the initial quality, the lower the dynamic loading and therefore lower inhomogeneous settlements of ballast layer, which leads to later next tamping. The Plasser and Theurer ballast tamping machines produce the best geometric and compaction quality, which results in up to 5-year lifecycle after the first tamping. However, the ballast destruction owing to the tamping works significantly reduces the further lifecycles.

Table 2

The potential of tamping methods relating to the ballast maintenance cost reduction

Continuous side tamping	Continuous-cyclic vertical tamping	Cyclic stone blowing
- Superstructure independent (wide sleepers and slab track) - Ballast condition tolerance - Particle low-destructive tamping - High productivity	- High track geometry quality - High productivity	- Ballast condition tolerance - Particle low-destructive tamping

Alternative cost reduction factor that depends on the tamping technology is related to applying another materials and structures in track. There are many examples of application of the wide, slab, frame, and other type of sleepers [46-48]. An observation of long-term behavior of wide sleepers proves almost 2.5 times lower settlement of ballast layer. Moreover, the ballast contamination from external sources is much lower that excludes the demand on ballast cleaning. However, the structures have not found an application owing to time and cost-expensive ballast tamping works. The conventional tamping machines cannon be used for the geometry correction on the wide sleeper superstructure. The side tamping technology is not dependent on superstructure and ballast type, and therefore, it would be a promising alternative to the conventional tamping technologies. An optimization of vibrating compactor of the VPO-3000 could enable its application for corrective maintenance [49]. The cost effect of the wide sleeper application together with side tamping consists not only in lifecycles prolongation, but also the lower dynamic pressure on the ballast layer would allow an application of low-cost ballast materials.

The aim of this article is an experimental and theoretical substantiation of the side tamping technology. The substantiation is performed using laboratory-scaled tests with photogrammetry measurements of particle flow. A theoretical FEM model is validated to the experimental results.

4. PHOTOGRAMMETRIC MEASUREMENT OF PARTICLE FLOW DURING SIDE TAMPING OF BALLAST

The scaled model of ballast layer is presented by a sample of sand with free slope between glass walls (Fig. 3, left). The sample is vertically and horizontally limited by stamps. The small particle sand was used instead of big particles of crushed stones for facilitating the photogrammetric measurements and the development of the photogrammetric method. Horizontal stamp corresponds to tamping plate and the vertical one, the action of the sleeper. Both stamps are equipped with loading cells for the estimation of ballast pressure.

The vertical stamp is moved horizontally with displacement control with the maximal force 1.4 kN that corresponds to the pressure 0.11 MPa. The top layer of the construction is loaded by the material weight of the horizontal steel stamp. This causes the movement of sand sample. The movement of sand particles in the plane of glass wall is recorded with high-resolution video camera. The aim of the photogrammetric measurements is to estimate the transportation of ballast material in zone under the sleeper stamp depending on the position of the vertical stamp. The ballast transportation is characterized with the particle velocity distribution in the vertical plane. The particle velocity is determined as an increment of particle vertical and horizontal position. Computer Vision Toolbox is used to determine the particle position for each video frame. The particles are detected as SURF (Speeded Up Robust Features) objects that are well suited and used for detection of image regions in which some properties are constant or approximately constant [50]. The properties of each object for the neighbour images are matched to find the same object and to determine the object motion. Figure 4 shows the full flow of particle motion in the vertical plane to the negative settlement in the vertical axis (under stamp). The pressure caused by horizontal loading clearly directs the particle motion to the upper part ballast. The direction of particle trajectories shows the different fields of motion. The field near the vertical stamp consists of two different groups: a bigger one is directed to the slope and a smaller one is in almost horizontal direction. The horizontal transport of ballast particles contributed to the useful tamping effect. The efficiency of tamping is estimated as the relation between the vertical motion under the sleeper and the horizontal motion of the tamping stamp.

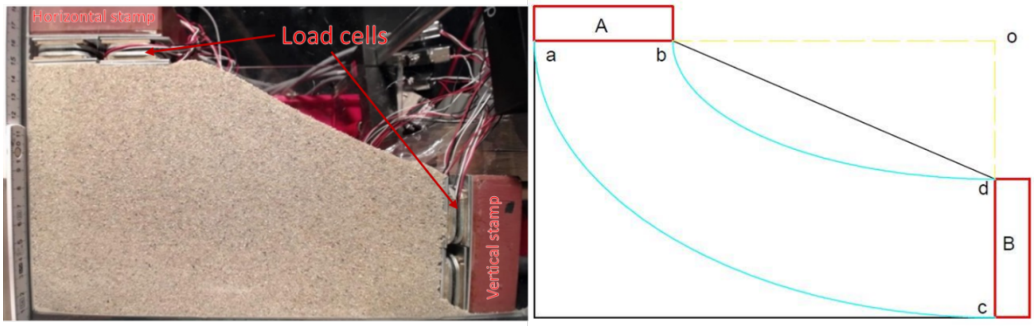

Fig. 3. The model of ballast side tamping in scale of approximately 1:4, height – 140mm, width – 240mm (left) and a calculation scheme of ballast transport (right)

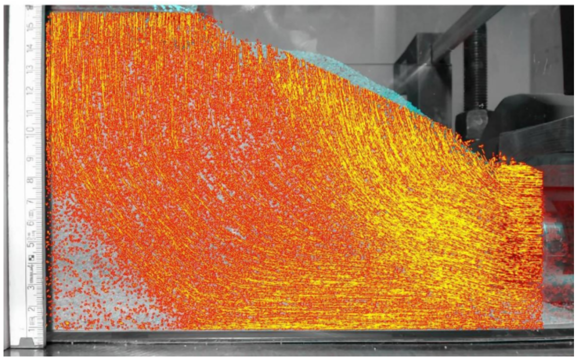

Fig. 4. The scaled model of ballast side tamping

Figure 4 shows the particles' trajectories over all the motions of tamping stamp. However, for one moment of time, which corresponds to two images, there are too little matched objects and too much noise. To increase the reliability of particle vector estimation for each position of the stamp, the particles' vectors are averaged for a rectangle mesh of nodes that corresponds to the flow area. The particle vectors in the nodes of the mesh for two cases of stamp position are shown in Fig. 5. The velocity vectors with an angle more than 45° are marked with blue color.

Fig. 5 shows that the most material transport is performed to the slope with circle trajectories. The ratio between the vertical particle motion under the sleeper stamp and that of the tamping one is about 0.26. Quite different velocity field is observed for the position of tamping stamp in case 2. In the case, the vector field is much more homogenously distributed. The ratio between the useful material transportation and the stamp displacement is about 0.6.

5. SIMULATION OF THE PARTICLE PLASTIC FLOW WITH FEM MODEL

Aim of the FEM modelling is a development of a numerical model that could be used for an optimization of tamping process, namely, the size and position of tamping stamp, its value, and the direction of motion. The numerical model of plastic flow is developed using software Matlab and is based on Mohr–Coulomb failure criterion with a viscoplasticity approach for generation of body loads [51, 52]. In principal stress space, the Mohr–Coulomb criterion takes the form of an irregular hexagonal cone, as shown in Fig. 6. In this approach, the temporarily resistance of the material to the stresses outside the failure criterion is allowed. Overshooting the failure criterion, as signified by F > 0, is an integral part of the method and is used to drive the algorithm.

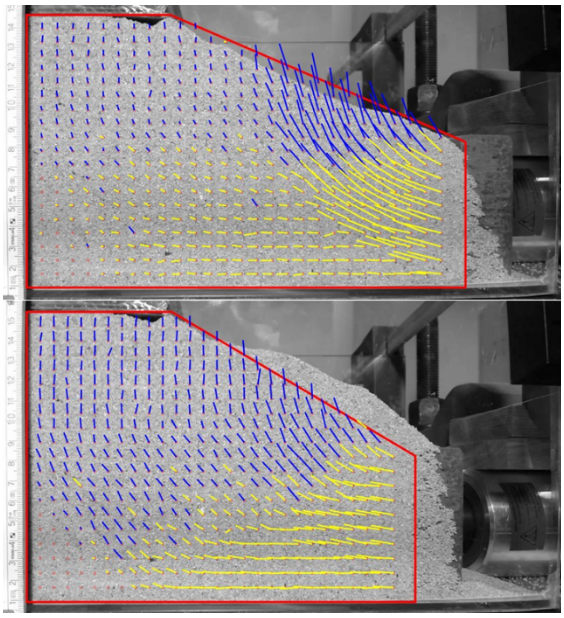

Fig. 5. The mesh of particle motion for beginning of tamping (case1, top) and after 25 mm displacement (case 2, bottom)

$$F_{mc} = \frac{\sigma_1+\sigma_3}{2} sin(\theta) - \frac{\sigma_1-\sigma_3}{2} - c \cdot cos(\varphi) \quad (1)$$

By substituting σ_1 and σ_3 we receive the following:

$$F_{mc} = \sigma_m \, sin(\varphi) + \bar{\sigma}(\frac{cos(\theta)}{\sqrt{3}} - \frac{sin(\theta)\, cos(\varphi)}{3}) - c \cdot cos(\varphi) \quad (2)$$

where F_{mc} – Mohr-Coulomb failure criterion, σ_m, $\bar{\sigma}$ and θ – three stress invariants, [Pa], φ - friction angle, and c- cohesion [Pa].

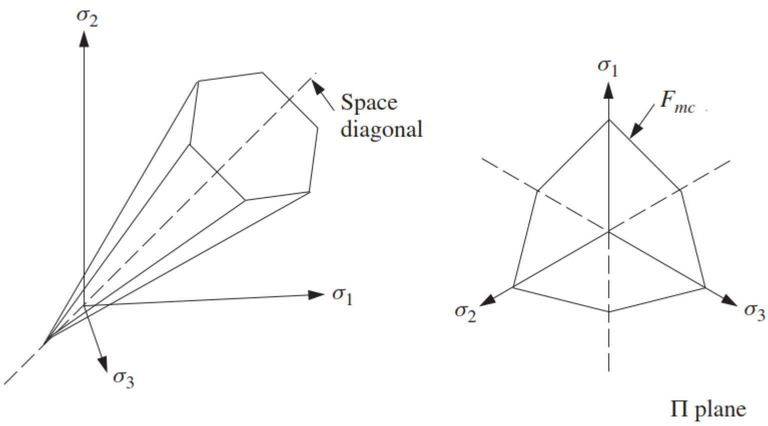

Fig. 6. Mohr-Coulomb failure criterion [51]

The model failure is induced by increasing the body loads, with the material properties remaining constant. The gravity loads generated by material properties are taken into account. A repeated elastic solution of the nonlinear plastic problem is used within the constant stiffness method to reach the convergence by iteratively varying the body loads on the following system:

$$[Km]\{U\}i = \{Fa\} + \{Fb\}i \tag{3}$$

where $\{U\}i$ - global displacement increments, $[Km]$ - global stiffness matrix, $\{Fa\}$ – global external load, and $\{Fb\}i$ – body loads vector.

The system is solved for the global displacement increments {U}i within the i- iterations. {Fa} is the actual applied external load increment, and {Fb}i is the body loads vector that varies from one iteration to the next, and [Km] is the global stiffness matrix. The {Fb}i vector must be self-equilibrating so that the net loading on the system is not affected by it.

The body loads are determined using the viscoplasticity approach assuming that the viscoplastic strain rate is related to the yield function of the plastic potential function Q:

$$\{\dot{\varepsilon}^{\upsilon\rho}\} = F\left\{\frac{\partial Q}{\partial \sigma}\right\} \tag{4}$$

where F – yield function and Q – plastic potential function.

At each time step, the body loads {Fb}i are accumulated by summing the stress integrals for all elements with positive criterion (F>0) in each Gauss point:

$$\{Fb\}^{i} = \{Fb\}^{i-1} + \sum_{elements}^{all} \int\int [B]^{T}[D^{e}]\{\delta\varepsilon^{\upsilon\rho}\}^{i}dxdy \tag{5}$$

here, $\{\delta\varepsilon^{\upsilon\rho}\}^{i}$ - is an increment of viscoplastic strain which is accumulated from one time step or iteration to the next and it is determined with multiplication of the viscoplastic strain rate by a pseudo-time step Δt.

$$\{\delta\varepsilon^{\upsilon\rho}\}^{i} = \Delta t\{\dot{\varepsilon}^{\upsilon\rho}\}^{i} \tag{6}$$

where $\{\delta\varepsilon^{\upsilon\rho}\}^{i}$ - increment of viscoplastic strain, Δt - pseudo-time step, and $\{\dot{\varepsilon}^{\upsilon\rho}\}^{i}$- viscoplastic strain rate.

This process is repeated at each time step until no integrating point stresses violate the failure criterion within a certain tolerance.

The geometrical model of ballast layer in the experiment (Fig. 3) is presented in Fig. 7. The model parameters are 560 elements, 1815 nodes, and friction angle 36.5°. The experimental measurements have been used to calibrate the FEM model. The material properties, such as Young modulus, Poisson ratio, and friction angle, were fitted with the experimental modelling.

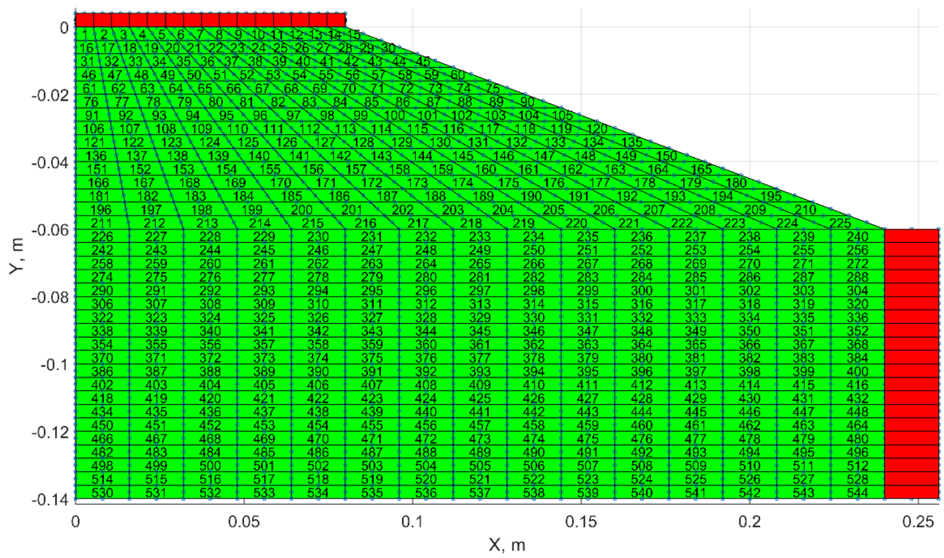

Fig. 7. The geometrical model of ballast layer sleeper stamp and a tamping stamp

One of the determiners we have been using to assess the stability of the embankment was Mohr-Coulomb criterion. After reaching the elastic approach results, we can easily see on the picture below two unstable zones with factors higher than 0, which means the deformation under the load was too big and it required the plastic calculation. After the plastic calculation, the zones are significantly smaller, and the values, which are still > 0, are near equal to 0 and can be omitted. Figure 8 shows the distribution of Mohr-Coulomb criterion through the elements.

As a final result, we received the deformation and vector map plot. Two different methods of measure, experimental and theoretical, of embankment stabilization are considered to be successful. Comparison of displacement vectors shows the similarity in sand flow under horizontal and gravity loads. Furthermore, the ratio of horizontal and vertical displacement (marked by blue circles in the left picture) are relatively equal with results we received in photogrammetry method.

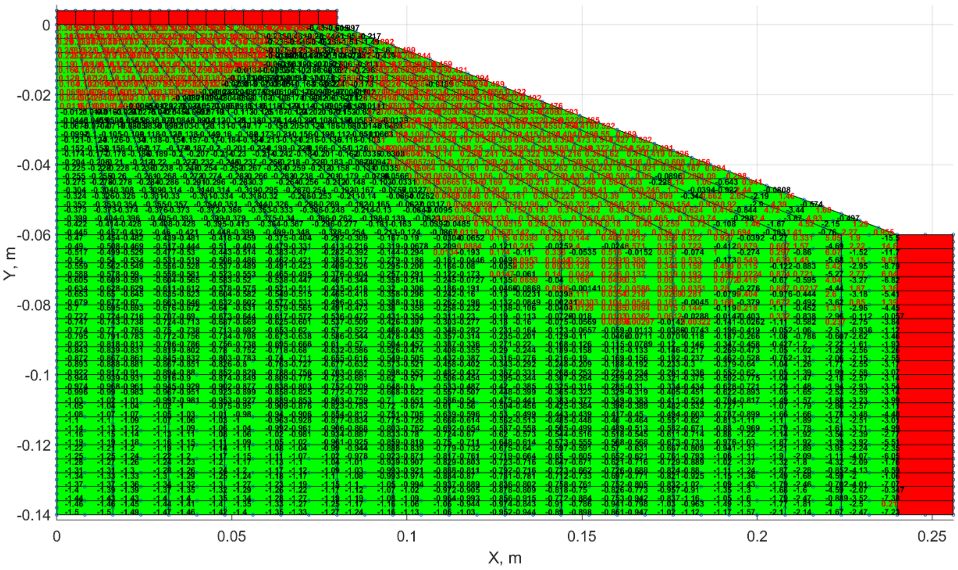

Fig. 8. Distribution of Mohr-Coulomb criterion

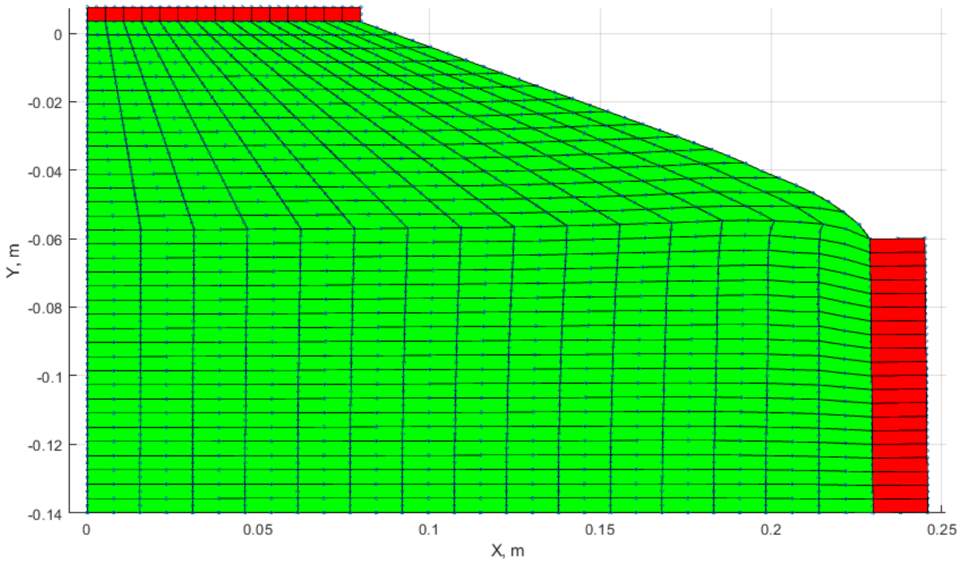

Fig. 9. Deformation of ballast

Ratio of horizontal and vertical displacement in:

– photogrammetry method

$$\frac{x}{y} = \frac{1{,}23}{0{,}44} = 2{,}795 \ ,$$

– Finite Element Method.

As we can see in the plot below, along with increasing the horizontal load, the difference between displacements are stabilizing and are relatively equal to the photogrammetry ratio.

Table 2

Settlement stabilisation

F,kN	0,3	0,35	0,4	0,5	0,6	0,7
X/Y	-18,76	-4,97	-3,74	-3,13	-2,96	-2,95

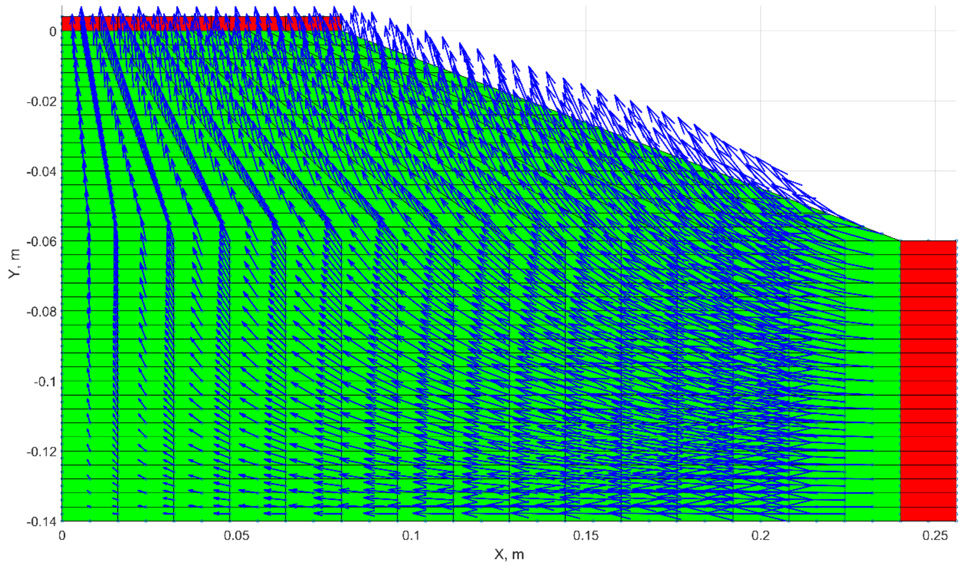

Fig. 10. Vector map of ballast deformation

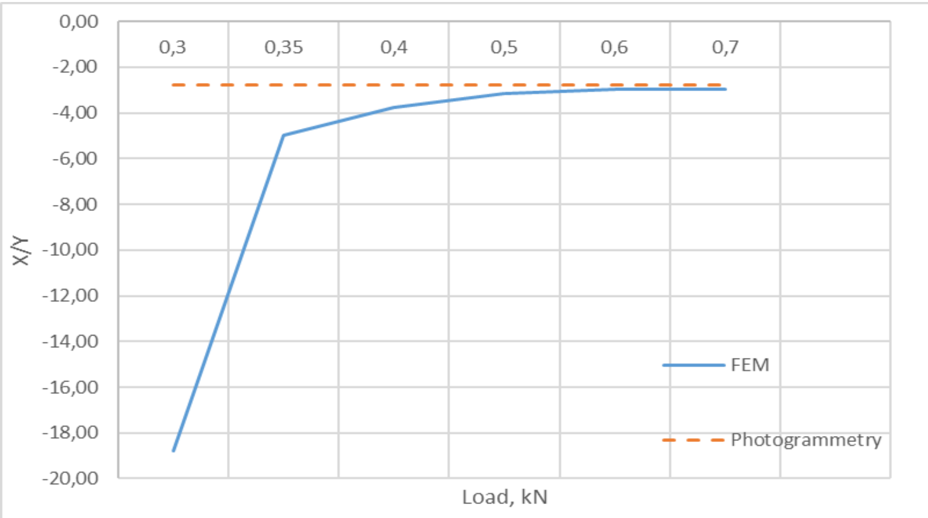

Fig. 11. Ratio of horizontal and vertical displacement

6. CONCLUSION AND SUBSEQUENT STUDIES

The current paper presents a study of the tamping efficiency of side tamping geometry correction method. The analysis of track tamping principles and corresponding machines showed that the current tamping methods using tamping tines and high dynamic pressure on the ballast have a significant disadvantage. The main one is high ballast particle breakage that shortens ballast tamping lifecycles and demands cost-expensive ballast cleaning. The side tamping method is the most promising for the achievement of the highest productivity and preserving the ballast particle destruction. The highest cost effect from the method would be expected from its suitability to correct the superstructure geometry independently of sleeper types. However, the present side tamping machines are not suitable for low lifting correction owing to the properties of tamping plates.

The paper describes the laboratory-scaled experiments of sand side tamping as well as the numerical FEM simulations. The developed method for the photogrammetric measurement of ballast particles flow showed the complex relations of useful ballast transportation and the tamping stamp motion. The numerical FEM model was validated to the experimental results. The model can be used for optimizing the tamping process by changing the geometry of the ballast as well as loading type or adoption of new kinds of materials. The paper shows an opportunity to future develop on side tamping technology, which also allows to use wide sleeper. The ballast flow process can be controlled with additional tamping units, which could increase the received transportation ratio 0.6 and thus improve the tamping effectiveness.

The consequent studies are directed to the laboratory testing of big particle ballast material under the vibration loading. Simultaneous measurement of ballast compaction during the ballast compaction using nondestructive methods would give the additional information about the quality of compaction.

References

1. Fendrich, L. & Fengler, W. *Handbuch Eisenbahninfrastruktur*. Berlin Heidelberg: Springer-Verlag. 2013. 1105 p. DOI: 10.1007/978-3-642-30021-9. [In German: *Handbook of railway infrastructure*].
2. Lichtberger, B. *Track compendium: formation, permanent way, maintenance, economics*. Hamburg: Eurailpress. 2005. 634 p.
3. Selig, E.T. & Waters, J.M. *Track Geotechnology and Substructure Management*. London: Thomas Telford. 1994. 39-61 p.
4. Indraratna, B. & Salim, W. & Rujikiatkamjorn, C. *Advanced rail geotechnology - Ballasted track.* Taylor and Francis Group. 2011. 410 p.
5. Li, D. & Hyslip, J. & Sussmann, T. & Chrismer, S. *Railway Geotechnics*. CRC Press. 2015. P. 90-95. DOI: 10.1201/b18982-4.
6. Ižvolt, L. & Šestáková, J. & Šmalo, M. Tendencies in the development of operational quality of ballasted and ballastless track superstructure and transition areas. *IOP Conference Series: Materials Science and Engineering*. 2017. Vol. 236(1). No. 012038. P. 1-8. DOI: 10.1088/1757-899X/236/1/012038.
7. Ižvolt, L. & Šestáková, J. & Šmalo, M. The railway superstructure monitoring in bratislava tunnel no. 1 - Section of ballastless track and its transition areas. *MATEC Web of Conferences.* 2017. Vol. 117. No. 00063. P. 1-8. DOI: 10.1051/matecconf/201711700063.
8. Ižvolt, L. & Šmalo, M. & Malchová, J. The quality evaluation of the ballastless track construction in the area of Bratislava tunnel no. 1. *MATEC Web of Conferences*. 2016. Vol. 86. No. 05001. P. 1-7. DOI: 10.1051/matecconf/20168605001.
9. Ižvolt, L. & Šestáková, J. & Šmalo, M. Impact of operation on the geometric parameters of the track in ballastless track transition area. *MATEC Web of Conferences*. 2017. Vol. 107. No. 00019. P. 1-8. DOI: 10.1051/matecconf/201710700019.
10. Salajka, V. & Kala, J. & Plášek O. Dynamical response of railway switches and crossings. *MATEC Web of Conferences*. 2017. Vol. 107. No. 00018. P. 1-6. DOI: 10.1051/matecconf/201710700018.
11. Plášek, O. & Hruzikova, M. Under sleeper pads in switches & crossings. *IOP Conference Series: Materials Science and Engineering*. 2017. Vol. 236(1). No. 012045. P. 1-8.
12. Plášek, O. & Hruzíková, M. & Svoboda, R. & Vendel, J. Influence of under sleeper pads on track quality. *Akustika*. 2015. Vol. 23(1) P. 28-33.
13. Fischer, S.Z. & Horvat, F. Investigations of the reinforcement and stabilisation effect of geogrid layers under railway ballast. *Slovak Journal of Civil Engineering.* 2011. Vol. 19(3). P. 22-30.
14. Nabochenko, O. & Sysyn, M. & Kovalchuk, V. & Kovalchuk, Y. & Pentsak, A. & Braichenko, S. Study railroad track geometry deterioration as a result of an uneven subsidence of the ballast layer.

Eastern-European Journal of Enterprise Technologies. 2019. Vol. 1. No. 7(97). P. 50-59. DOI: 10.15587/1729-4061.2019.154864.
15. Sysyn, M. & Gerber, U. & Gruen, D. & Nabochenko, O. & Kovalchuk, V. Modelling and vehicle based measurements of ballast settlements under the common crossing. *European Transport - Trasporti Europei*. 2019. Vol. 71. No. 5. P. 1-25.
16. Fischer, S. & Juhasz, E. Railroad ballast particle breakage with unique laboratory test method. *Acta Technica Jaurinensis.* 2019. Vol. 12. No. 1. P. 26-54.
17. Fischer, S. Breakage test of railway ballast materials with new laboratory method. *Periodica Polytechnica Civil Engineering*. 2017. Vol. 61(4). P. 794-802. DOI: 10.3311/PPci.8549.
18. Wang, B. & Martin, U. A random form generator for ballast stones. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.* 2018. Vol. 232. No. 6. P. 1660-1670. DOI: 10.1177/0954409717743604.
19. Wang, B. & Martin, U. & Rapp, S. Discrete element modeling of the single-particle crushing test for ballast stones. *Computers and Geotechnics*. 2017. Vol. 88. P. 61-73. DOI: 10.1016/j.compgeo.2017.03.007.
20. Wang, B. & Martin, U. & Rapp, S. Vibration Characteristic Analysis of Ballast with Different Aspect Ratios by Means of the Discrete Element Method. *Geotechnical Special Publication*. 2016. January (268 GSP). P. 16-23. DOI: 10.1061/9780784480113.003.
21. Bach, H. *Evaluation of attrition tests for railway ballast.* PhD thesis. Graz University of Technology. 2013.
22. Bhanitiz, A. *A laboratory study of railway ballast behaviour under traffic loading and tamping maintenance.* PhD thesis. University of Nottingham. 2007.
23. Soleimanmeigouni, I & Ahmadi, A. & Khouy, I.A. & Letot, C. Evaluation of the effect of tamping on the track geometry condition. *A case study, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. 2016. Vol. 232. No. 2. P. 408-420. DOI: 10.1177/0954409716671548.
24. Audley, M. & Andrews, J. D. The effects of tamping on railway track geometry degradation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. 2013. Vol. 227. No. 4. P. 376-391. DOI: 10.1177/0954409713480439.
25. Aingaran, S. & Le Pen, L. & Zervos, A. & Powrie, W. Modelling the effects of trafficking and tamping on scaled railway ballast in triaxial tests. *Transportation Geotechnics*. 2018. Vol. 15. P. 84-90. DOI: 10.1016/j.trgeo.2018.04.004.
26. Sysyn, M. & Gerber, U. & Kovalchuk, V. & Nabochenko, O. The complex phenomenological model for prediction of inhomogeneous deformations of railway ballast layer after tamping works. *Archives of Transport*. 2018. Vol. 46. No. 3. P. 91-107. DOI: 10.5604/01.3001.0012.6512.
27. Ilinykh, A. & Manakov, A. & Abramov, A. & Kolarzh, S. Quality assurance and control system for railway track tamping. *MATEC Web of Conferences*. 2018. Vol. 216. No. 03004. DOI: 10.1051/matecconf/201821603004.
28. Bold, R.D. *Non-destructive evaluation of railway tracked ballast.* PhD thesis. Institute for Infrastructure and Environment, School of Engineering, University of Edinburgh. 2011.
29. Sysyn, M. & Nabochenko, O. & Gerber, U. & Kovalchuk, V. Evaluation of railway ballast layer consolidation after maintenance works. *Acta Polytechnica.* 2019. Vol. 59. No. 1. P. 77-87. DOI: 10.14311/AP.2019.59.0077.
30. Sysyn, M. & Kovalchuk, V. & Gerber, U. & Nabochenko, O. & Parneta, B. Laboratory evaluation of railway ballast consolidation by the non-destructive testing. *Communications - Scientific Letters of the University of Zilina*. 2019. Vol. 21. No. 2. P. 1-12.
31. Sysyn, M. & Kovalchuk, V. & Gerber, U. & Nabochenko, O. & Pentsak, A. Experimental study of railway ballast consolidation inhomogeneity under vibration loading. *Pollack Periodica*. 2020. Vol. 15. No. 1, P. 27-36. DOI: 10.1556/606.2020.15.1.3
32. Kim, D.S. & Hwang, S.H. & Kono, A. & Matsushima, T. Evaluation of ballast compactness during the tamping process by using an image-based 3D discrete element method. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. 2018. Vol. 232. No. 7. P. 1951-1964. DOI: 10.1177/0954409718754927.

33. Zhou, T.Y. & Hu, B &, Zhao, X.Y. & Yan, B. Numerical study porosity of railway ballast during tamping process. *Advanced Materials Research*. 2014. Vols. 919-921. P. 1124-1127. DOI: 10.4028/www.scientific.net/AMR.919-921.1124.
34. Zhou, T. & Hu, B. & Sun J. Study of railway ballast compactness under tamping operation. *Journal of Applied Sciences*. 2013. Vol. 13. No. 11. P. 2072-2076. DOI: 10.3923/jas.2013.2072.2076.
35. Perales, R & Saussine, G. & Radjai, F. Optimizing the tamping process to reduce track settlement. *7th EUROMECH Solid Mechanics Conference (ESMC2009).* Sep 2009, Lisbonne, Portugal.
36. Zaytsev, A.A. & Abrashitov, A.A. & Sydrakov, A.A. 1g physical modelling of the stoneblowing technique for the improvement of railway track maintenance. *Physical Modelling in Geotechnics*. 2018. Vol. 1. P. 203-206.
37. Abrashitov, A. & Semak A. Experimental Study of Stoneblowing Track Surfacing Technique. *Procedia Engineering*. 2017. Vol. 189. P. 75-79. DOI: 10.1016/j.proeng.2017.05.013.
38. Sol-Sánchez, M. & Moreno-Navarro, F. & Rubio-Gámez, M.C. Analysis of ballast tamping and stone-blowing processes on railway track behaviour: The influence of using USPs. *Geotechnique*. 2016. Vol. 66. No. 6. P. 481-489. DOI: 10.1680/jgeot.15.P.129.
39. Kaplin, V.N. & Abrashitov, A.A. & Grin,' E.N. Technology and determination of the applicability of stone blowing at the current track maintenance. Vestnik of the Railway Research Institute. 2020. Vol. 79. No. 2. P. 74-79. DOI: https://doi.org/10.21780/2223-9731-2020-79-2-74-79.
40. Atamanyuk, A. *Technology of ballast layer compaction by machines of type VPO in the process of deep ballast cleaning.* PhD thesis. St. Petersburg State Transport University, St.-Petersburg. 2010.
41. *Tamping technology of Robel.* Available at: http://www.bdf007.privat.t-online.de/_stopfmaschinen-ohne-plasser/strobel-supermat/strobel-supermat.htm.
42. Lichtberger, B. Der neu entwickelte Universal Tamper 4.0. *EI-Eisenbahningenieur*. 2018. No. 8. P. 2-8. [In German: New developed Universal Tamper 4.0].
43. Lichtberger, B. Vollhydraulisch Stopfen - eine neue Technologie für effiziente Instandhaltung, *EI-Eisenbahningenieur*. 2015. No. 7. P. 18-22. [In German: Full-hydraulic tamping – a new technology for effective tamping].
44. Pfaff, N. *Vergleich von räumlicher und lokaler Stopftechnologie.* Master Thesis. Technische Universität Dresden. 2018. [In German: Comparison of spatial and local tamping technologies].
45. *Tamping technology of Plasser & Theurer.* Available at: https://www.plassertheurer.com/de/maschinen-systeme/stopfung.html.
46. Unbehaun, O. Breitschwellengleis – erste Testergebnisse. *EI-Eisenbahningenieur*. 2000. Vol. 51. No. 9. P. 106-113. [In German: Wide sleepers – first test results].
47. *Rail.One, Wide sleeper track.* Available at: https://www.railone.com.
48. Rießberger, K. Festere Fahrbahn auf Schotter. *ETR Eisenbahntechnische Rundschau*. 2002. Vol. 51. No. 4. P. 183-193. [In German: Stable railway on gravel].
49. Lee, S. & Akhmetov, M. & Ibraimov, A. & Taran, M. Upgrading of vibrating compactor of the railway track ballast of VPO-3000 machine. *Transport Problems*. 2012. Vol. 7. No. 4. P. 95-105.
50. Bay, H. & Ess, A. & Tuytelaars, T. & Van Gool L. SURF: Speeded Up Robust Features. *Computer Vision and Image Understanding (CVIU).* 2008. Vol. 110. No. 3. P. 346-359.
51. Smith, I.M. & Griffiths, D.V. & Margetts, L. *Programming the Finite Element Method. Fifth Edition*. Wiley. 2014.
52. Zienkiewicz, O.C. & Taylor, R.L. *The Finite Element Method. Fifth Edition.* Butterworth-Heinemann. 2000.

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