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A LABORATORY STUDY OF PRESSURE DISTRIBUTION AND RESIDUAL SETTLEMENTS IN WIDE GRADING DOUBLE LAYER RAILWAY BALLAST UNDER LONG-TERM CYCLIC LOADING

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Ballast layer has weighty share in the lifecycle costs of railway track. The strict standards and maintenance rules of ballast grading significantly contribute to the ballast costs. One ways to the costs reduction is differential demands to ballast grading for the secondary and low loaded railway lines. Additional one is the different ballast grading over the ballast height. This study presents a full scale laboratory investigation of technical efficiency of such railway ballast under the long-term cyclic loading in comparison with the standard ballast layer. The double layer is presented with standard grading ballast upper layer and bottom sub ballast layer consists of ballast mixture. Pressure distribution under the ballast layer and permanent settlements of the layers are measured during the loading cycles. The reference measurements with standard grading ballast material are carried out. The study shows that initial settlement accumulation of the double layer railway ballast are lower to that of the standard ballast layer. However, the settlements accumulation intensity of the ballast is higher. The analysis of the pressure distribution measurements under the ballast layer and the settlements inside the ballast layer explain the causes of the different settlement accumulation.

Keywords: railway ballast, long-term behaviour, permanent settlements, ballast grading, pressure, pressure distribution

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1. INTRODUCTION

Railway ballast layer is functionally key part of track superstructure that transfers and distributes train dynamic loading from sleepers on the subgrade. The main functional advantage of ballasted track consists in the possibility of quick mechanized and cost-effective construction and correction of the necessary track geometry. Nevertheless, the cohesionless ballast material, from a technical point of view, is not the best material for perception of dynamical and vibrational loadings. This leads to the gradual accumulation of residual settlements of ballast layer under operational loadings. Inhomogeneous settlement accumulation results in geometrical irregularity and reduction of geometrical quality that demands track geometry correction with tamping works.

The average tamping cycle is about 40-70 million tons [1]. The tamping cycles for high-speed lines are even less and can occur 2-3 times a year [2]. The cycles are relative short compared the total life cycle of other elements of the track 500-1000 million tons. The frequent tamping works, in turn, cause ballast material destruction that demands cost-expensive cleaning works [3]. Thus, a share of maintenance costs related to ballast layer is higher than for other track elements. According to [2, 4, 5], the cost of ballast rehabilitation represents about 40 % of the track renewal and maintenance costs. There are different ways for reduction of ballast layer dependent life cycle costs (LCC). Many currently used methods are directed on the maintenance improvement due to early detection and prediction of sleeper support condition using monitoring means [6] and artificial intelligence methods [7]. The maintenance improvement includes both reduction of inspection and renewal costs [8, 9, 10] as well as ballast bed lifecycle prolongation.

Another way of LCC reduction is directed on improvement of track bed resiliency. There are many attempts to improve the mechanical properties of ballast layer and its material, like under-sleeper/ballast elastomers [11], ballast gluing [12], neoballast [13], etc. up to the full refusal from ballast layer in ballastless track [14-16, 17]. Despite the attempts there is no one technical best solution for all cases of track operation, especially for many railway lines of central Europe with low operational intercity, velocities and axle loadings. Therefore, there is a demand on low-cost technical solutions. One way for the solutions consists in the adjustment of ballast material grading and track-bed parameters. The relatively uniform grain size that is set by standards and maintenance rules of railway authorities, cause high production costs of ballast material [18, 19]. On the other hand, there is a number of studies that indicate the improvement ballast settlement and brakeage performance for wider ballast grading. The laboratory shear tests of TU Graz [20] have shown that the inclusion of 15 % of ballast material with grain size 15-30 mm to the standard ballast grading 30-60 mm, can increase the shear resistance from $\tan\varphi = 0.275$ to $\tan\varphi = 0.4$. However, the inclusion of 30 % of the same material causes the reduction of shear resistance to $\tan\varphi = 0.16$. The study [4] shows that well-graded range of grain sizes provides better support for the track. The TU Wollongong laboratory study of ballast particle breakage and ballast layer settlements in a ballast box [21, 22] have shown more than two times decrease of ballast layer settlements after 200.000 loading cycles for the wide graded ballast material with uniformity coefficient $D_{60}/D_{10} = 2.31$. Ballast breakage degradation for the wide graded ballast material was lower than for material with the standard ballast grading with uniformity coefficient $D_{60}/D_{10} = 1.52$. The full scale laboratory studies of TU Southhampton [18] demonstrate a significant improvement of ballast settlement performance due to changes in the ballast grading, reducing the ballast shoulder slope and two-layered ballast bed. The highest reduction of permanent ballast settlements about 28 % was reached with a widening the ballast grading using about 20 % of additional mixture 10/45 mm. The reducing the ballast shoulder slope from 1:1 to 1:2 produced the greatest reduction in permanent settlement about 36 % within 1-3 million loading cycles for the standard ballast grading. The testing of two layered trackbed with 250 mm layer of standard grade ballast overlain by a 50 mm layer of 10/20 aggregate show about 15 % reduction of permanent ballast settlements. Except of ballast settlements the measurements of longitudinal pressure, ballast breakage, attrition, and shoulder slope movement were carried out. Another study of improving the performance of railway track using the a two layered ballast system is demonstrated in [3, 23]. The idea consists in self filling the voids beneath the sleepers with small size crib ballast and thus maintaining the geometry quality without the use of tamping or stone-blowing. The small size crib ballast 3-20 mm was introduced by the two layered ballast system. The discussions to the proposed self maintenance method [24, 25] have shown the difficulties of its practical applying and the influence of other technical and maintenance factors. The other main factors are the ballast compaction quality, drainage, ballast tamping, particle brakeage behaviour under the operation and tamping loadings. The experimental measurement of ballast compaction after maintenance works and operation loading are presented in [26, 27]. The particle brakeage behaviour under the operation loading was investigated in the works [28-30]. The influence of the drainage properies of the subballast layers on the moisture content and freezing is presented in [31].

This paper presents a comparative experimental investigation of double layer railway ballast under long-term cyclic loading. Different to other similar studies the upper layer is composed of the ballast grading 5/45 mm and the bottom sub ballast layer consists of ballast mixture 1/32 mm. The aim of the proposed double layer ballast is not an improvement of ballast performance but cost reduction due to ballast material saving and application of recycled ballast. Thereby, the performance the double layer ballast should remain acceptable for the loading conditions of the secondary lines. The performance is estimated with ballast layers permanent settlements and pressure distribution under the ballast layer.

2. METHODS AND MATERIALS

The aim of the laboratory measurements is investigation of settlement behavior, pressure distribution, stiffness and damping of ballast layers under the long-term cyclic loading. The laboratory model is presented with a full-scale ballast layer and a half sleeper B70 on a track bed layer. The track bed is width 600 mm is limited with fixed vertical walls (Fig.1) and stiff concrete floor underneath. The material of the track bed has free movement along the sleeper towards the free slopes 1:1.5.
Two types of track-bed layer structures are tested:
1. Wide graded double layer trackbed consisting of the following parts:
- geotextile;
- compacted to 50 MN/m2 200 mm subballast layer of grading 1/32 mm;
- compacted 150 mm ballast layer of grading 5/45 mm;
- half sleeper B70 with filled side ends of compacted ballast layer of grading 5/45 mm.
- rail pad Zw900 with stiffness c=40 kN/ mm.

2. The reference standard graded double layer trackbed:
- geotextile;
- compacted 350 mm ballast layer of grading 22,4/63 mm;
- half sleeper B70 with filled side ends of compacted ballast layer of grading 22,4/63 mm.
- rail pad Zw900 with stiffness c=40 kN/ mm.

The measurements of sleeper and ballast settlements as well as the pressure under the ballast were carried out during the loading cycles. The sleeper settlements were measured with four inductive transducers W1-4 in the zone of rail fastening. The sub ballast settlements were produced with the inductive transducers W5-6 that were decoupled from the upper ballast layer through pipes (Fig.1). The pressure measurements under the ballast layer were produced in two directions: along and across the sleeper longitudinal axis using the strain gauges sensors mounted in an u-profiles (Fig.2). The zones of the strain gauges sensors are separated with splits to avoid the influence of the longitudinal deformation distribution.

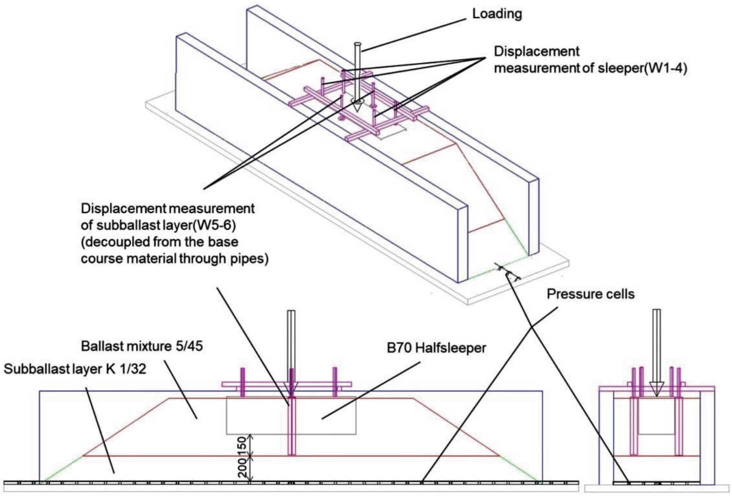


Fig. 1. Schematic view of the test set-up

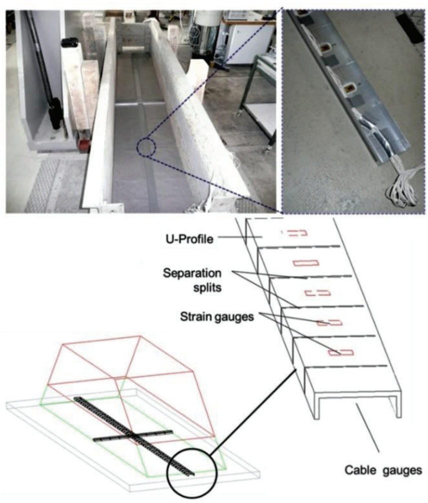


Fig. 2. Pressure measurement sensors setup and sensor location

The program of the experiment consisted of loading cycles and measurement cycles for five different accumulated cycles' moments. During the moment 0, 200, 500, 800 and 1200 thousand cycles, the permanent settlements and pressure distribution were measured. Additionally, the dynamic and static stiffness were tested. The measurement devices and the track bed set-up for the standard grading and the double layer wide grading ballast are demonstrated in the Fig. 3.

Fig. 3. Photographs of the laboratory tests (top: double layer ballast, bottom: standard ballast layer)

The long-term loading cycles are composed of the sleeper elastic loading similar line with maximal loading 60 kN and the minimal pre-loading 5 kN (Fig. 4).The frequency 6 Hz for 0-200 thousand cycles and 18 Hz for the last 200-1200 thousand cycles.

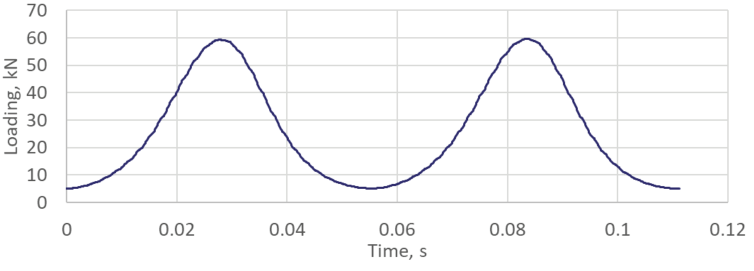


Fig. 4. Loading line of the sleeper for the 200-1200 thousand cycles

3. ANALYSIS OF LONG-TERM RESIDUAL SETTLEMENTS OF BALLAST LAYERS

The present study aims to estimate the differences between the standard grading trackbed and the double layer one with wide grading during 1200 thousand cycles. Additionally, the influence of the track bed structure for much more cycles should be assessed. A calculation model fitting to the experimental data is used for the analysis. There are used a lot of ballast settlement models at present studies [1, 32-36]. The most used finite element and discrete element models provide the detailed simulation of the complex processes in the ballast layer. However, the models have a disadvantage of the difficult multi-parameter fitting and interpretation for the long-term behaviour. The present study uses a phenomenological approach that is the most appropriate for the available experimental data [37]. The behaviour of the permanent settlement is described as the sum of the plastic part s_{pl} and the viscous part s_{vis} :

(1) $$s = s_{pl} + s_{vis}$$

The short-time plastic part of the settlement s_{pl} occurs suddenly, and mainly, in the initial period of track stabilization. The component its maximum value after about 1-3 million tons of train passage. The nonlinear asymptotic dependence of the ballast settlements is used to describe the influence of loading cycles [38]:

(2) $$s_{pl} = s_{pl\,max} \frac{N}{a+bN}$$

where:

N – number of repetitive loads, a, b – coefficients that depend on the stress state and the physical properties of the crushed stone, $s_{pl\,max}$ -the maximal plastic settlement that depends on the ballast loading and material properties.

The viscous behaviour of the permanent settlement linearly depends on the cycle number number. The intercity of the viscous settlement accumulation $b(\sigma_i, U)$ depends on the on the stress in the ballast layer σ_i under the sleeper and the elastic modulus of the subgrade U_s and other parameters:

(3) $$s_{vis} = b(\sigma_i, U)N$$

The ballast maximal pressure in the present experimental tests is constant over the loading cycle. The subgrade stiffness is considered the highest for the experimental condition.

The results of permanent settlements measurements and the model fitting for the standard and wide grading ballast are shown in the Fig. 5. The ballast layer with the standard grading is subjected to high initial settlements despite the initial tamping before the test. The most quick initial settlements occur until 200-300 thousand cycles where the permanent settlement of the sleeper reaches 3.5 mm. The ballast layer initial settlement 150 mm under the sleeper reaches about 0.7 mm. Therefore the most plastic settlements occur in the upper 150 mm ballast layer. The intercity of viscous ballast settlements of the sleeper is 0.15 mm/Mt and the subballast layer – 0.011 mm/Mt.

The test of the double layer ballast track bed with wide ballast grading demonstrate quite different results as that of the standard grading. The initial plastic settlements are the most intensive in the same cycles time as for the standard grading, but their value is about 1.4 mm. Thus, the maximal initial settlements for the double layer ballast are more than twice less that for the standard ballast layer. However, the viscous settlement intercity of the double layer ballast is 0.38 mm/Mt and thus much higher than for the reference track bed. Remarkable is the settlement of the subballast 200m layer of 1-32 mm grading. Its intensity is 0.14 mm/Mt that is 37 % of the overall slepper settlement intercity. The intensity ration is much higher than for the standard ballast with 7.3 % share of sub-ballast settlement intensity.

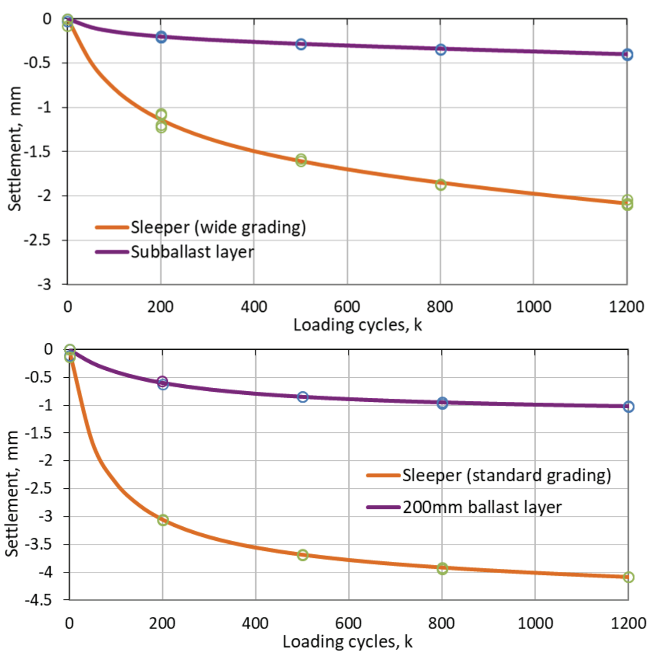


Fig. 5. The points of settlements measurements and the phenomenological model fitting for the reference ballast layer (top) and the double layer ballast

The model based estimation of the ballast settlements for the longer loading cycles is shown on the Fig. 6. The approximated settlements for both track bed variants are presented in megatons assumed that the axle loading is 25 t that corresponds to the sleeper maximal loading in the experiment. The lower initial settlements of the double ballast layer summed together with much intensive settlement accumulation, reach the same value as the standard grading track bed at about 140 Mt.

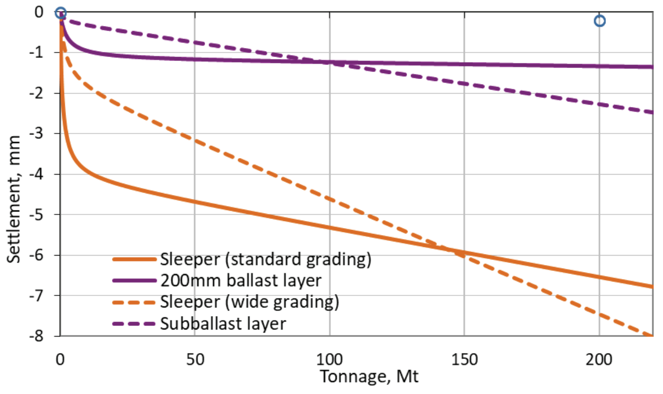


Fig. 6. Model assessment of long-term behaviour

The subballast settlements show a somewhat different result – the same settlement is reached at about 100Mt. That indicated that the bottom layer in the double layer ballast is a cause of high intensive settlements. If only upper layers are considered for the settlements comparison (Fig. 7) then the equal settlement could be reached at about 210 Mt.

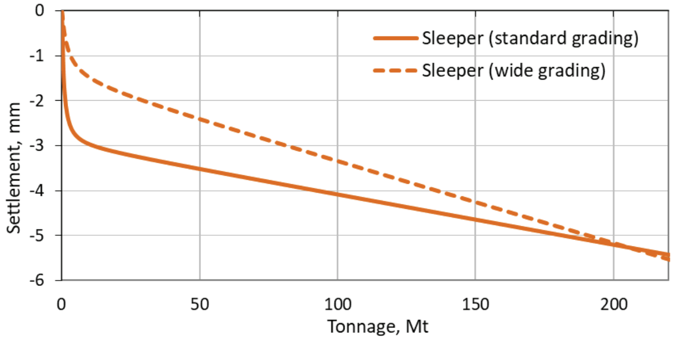


Fig. 7. Comparison of long-term settlement behaviour for upper layer of wide graded ballast and that of standard ballast

4. PRESSURE DISTRIBUTION AND STIFFNESS ANALYSIS

The settlement analysis shows the increased permanent settlement behaviour for the double layer wide grading track bed. The pressure distribution analysis is carried out to find out the causes of the behaviour. There is a number of studies to investigation of the pressure distribution angle.

The authors in the studies [39, 40] present a method for the estimation the pressure distribution angle. The angle is determined according to two the height of the ballast prism and the horizontal distance from the edge of the sleeper to the boundaries between 5 % and 95 % quantiles of measured pressure distribution stress distribution. The studies have shown the influence of ballast material, under-sleeper pads and the ballast layer contamination on the pressure distribution angle. It was determined the pressure distribution angle 11-20° for the contaminated ballast and 17-22° for the clean one. Another study [41] has used the same approach to investigate the influence of ballast compaction on the pressure distribution angle. It was determined the increase of pressure distribution from 8.1° to 20.7° while the ballast compaction. However, the actual method for calculating the pressure distribution angle has a significant disadvantage – the 5 % and 95 % quantiles are really the subjective not theoretically substantiated values. Thus, in the present study, alternative simple approach is proposed to improve the shortcoming. Figure 8 shows the measured pressure distribution and its idealization as the geometrical model of linear pressure distribution. According to the model, the loading of the sleeper of the is uniformly distributed of the subgrade under the sleeper F_{sl} and outside of it with loadings F_1 and F_2:

(4) $$\sum \sigma_{meas}\, \Delta l = F_1 + F_{sl} + F_2,$$

where:

σ_{meas} – measured in experiment ballast pressure, $F_{sl} = \sum \sigma_{meas}^{sl}\, \Delta l$ – mean loading under the sleeper, $F_1 = \sum \sigma_{meas}^{1}\, \Delta l$, $F_2 = \sum \sigma_{meas}^{2}\, \Delta l$ – mean loadings corresponding on the left and right sides out of the sleeper.

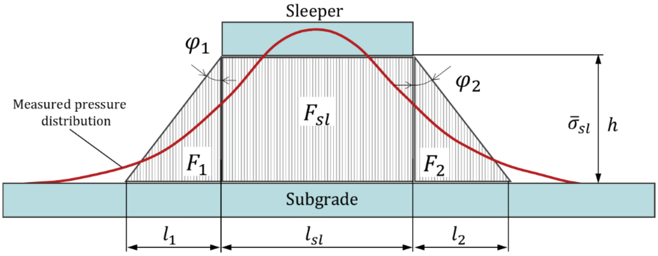


Fig. 8. The scheme for calculation of pressure distribution angle

The mean pressure under the sleeper is determined taking into account the sleeper length l_{sl} :

(5) $$\bar{\sigma}_{sl} = F_{sl}/l_{sl}$$

The widths l_1 and l_2 of side pressure triangles is determined using the loadings and the triangle height $\bar{\sigma}_{sl}$ from the formulae:

(6) $$S_1 = \frac{1}{2}\bar{\sigma}_{sl} \cdot l_1 \, , S_2 = \frac{1}{2}\bar{\sigma}_{sl} \cdot l_2$$

The pressure distribution angles are determined with the ballast layer height h:

(7) $$\varphi_1 = \mathrm{arctg}(l_1/h), \varphi_2 = \mathrm{arctg}(l_2/h),$$

The measured tension distribution in the pressure cells during the loading cycles for the standard and the double layer wide grading track beds are shown on the Fig. 9. The initial tension is high in one local point for the standard grading. However, the average tensions and the maximal ones after 200 thousand cycles are higher for the double layer wide grading track bed. The average sleeper width l_{sl} for the angle φ_1 and φ_2 calculation is 190 mm.

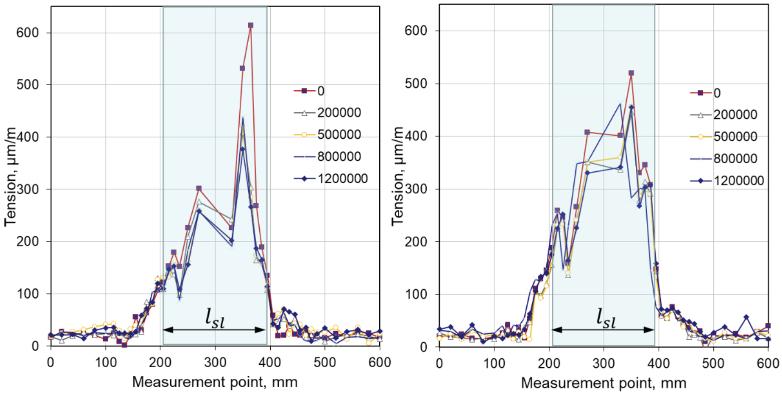


Fig. 9. Measured tension across the sleeper in pressure sensors sensors (left – standard grading, right – wide grading)

The results of the pressure distribution angles calculation are shown in the Table 1 and the Fig. 10. The results demonstrate a significant growth of the pressure angles from about 11° to 18° for the standard grading track bed. The initial pressure distribution angles for the double layer track bed with wide grading are about 12.7° that is higher than for the standard grading trackbed. However, the increase of the distribution angles 2° until the 1200 thousand cycles is relative low.

Table 1. Calculated pressure distribution angles depending on the loading cycle

Loading cycles, k		0	200	500	800	1200
Standard grading	ϕ_1, deg	11.3	15.7	17.9	17.0	18.1
	ϕ_2, deg	10.5	14.3	16.1	14.9	18.2
Wide grading	ϕ_1, deg	13.0	13.1	13.0	15.3	14.7
	ϕ_2, deg	12.4	12.8	13.6	14.5	15.3

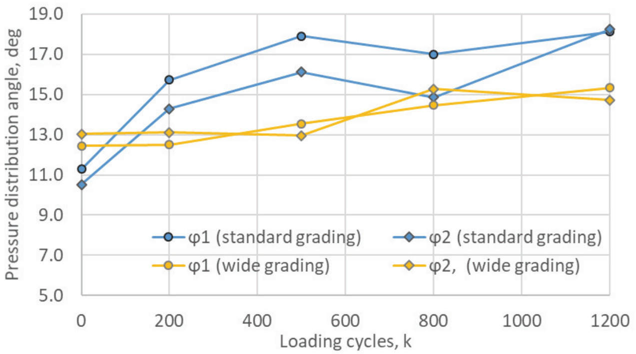


Fig. 10. Pressure distribution angles depending on the loading cycle

The measurements static and dynamic stiffness of the track bed variants provide additional information about the processes in the ballast layer during the long-term loading cycles. Many studies [1, 42, 43] point out the relation between the stiffness and the bearing capacity of structural layers of ballast layer and the subgrade.

The static tests are carried out in 2 cycles within 11 loading steps from 0 to 60kN loading on the sleeper (Fig.11). The relation of loading to settlement of the sleeper is analysed.

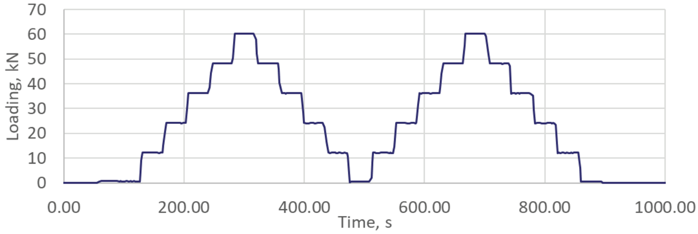


Fig. 11. Loading cycle for the ballast stiffness estimation test

Fig. 12 shows the results of the static tests for 2 variants of the track bed that are compared at the 200 thousand cycles and after the long-term cyclic loading 1200 thousand cycles. The comparison of 200 thousand cycles is selected instead of the first ones due to high permanent initial settlement and the difficulty of comparison. Fig. 12 demonstrates a significant changes in the static stiffness during the loading cycles for the double layer track bed with wide grading ballast. The changes occur both in the ballast and in the subballast layer. The most conspicuous change is about 15 % growth of the stiffness. The standard ballast layer has about two times lower increase of the static stiffness for the ballast layer and almost no change for the subballast one. Another noticeable difference between the track bed variants is the distinct higher nonlinear behaviour of the double layer track bed with wide grading ballast. Thereby, its stiffness is lower than for the standard grading for the loading range 0-20 kN and higher for the upper 20 kN range. The subballast layer of the double layer track bed has noticeable 3-5 times higher stiffness than the same position ballast layer of the standard grading track bed.

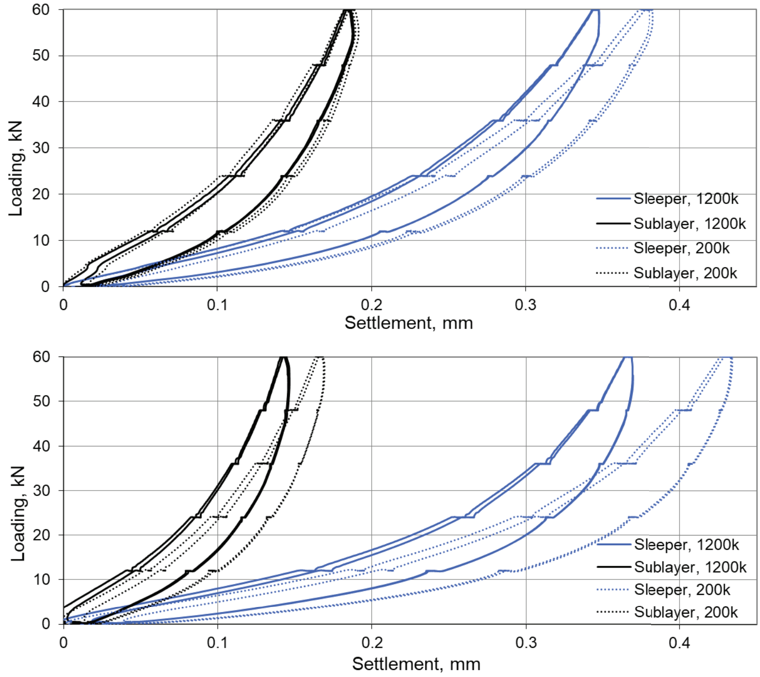
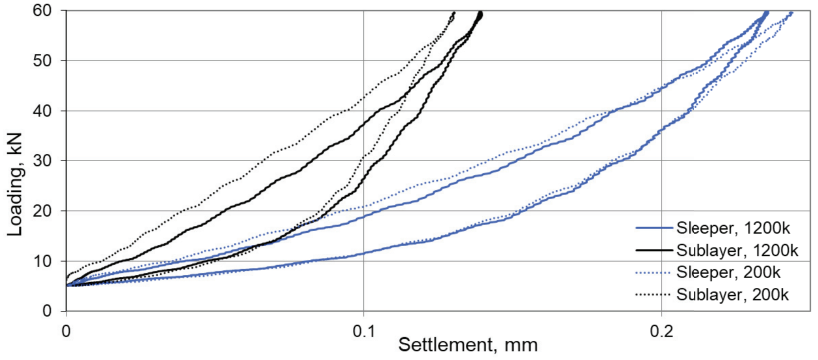


Fig. 12. Static stiffness of the whole ballast layer and the sublayer at the beginning and after 1,2 mio loading cycles (top – standard grading, bottom – wide grading)

The results of the dynamic stiffness tests for the same loading cycles is shown in the Fig. 13. The dynamic loading is performed in 2 cycles according to the Fig. 4. Different to the static tests the preloading 5 kN is applied. The dynamic stiffness for the both variants is higher than the static one. The comparison of the overall stiffness for the standard grading and the wide one shown approximately the same results. However, the subballast dynamic stiffness for the wide grading ballast is as high as for the static tests. A high nonlinear behaviour of the wide grading ballast is noticeable for the dynamic stiffness test. Such behaviour could point out to the increase of the loadings concentration in the ballast layer and therefore the lower bearing capacity.



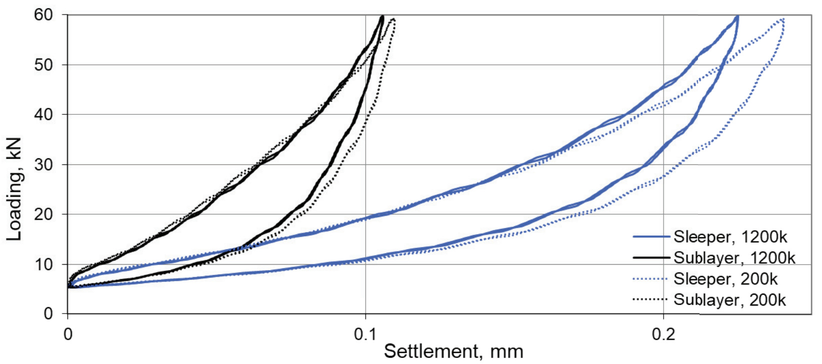


Fig. 13. Dynamic stiffness of the whole ballast layer and the sublayer at the beginning and after 1,2 mio loading cycles (top – standard grading, bottom – wide grading)

5. DISCUSSION AND CONSEQUENT STUDIES

The paper has presented an experimental investigation of long-term behaviour of low-cost ballast track bed under the cyclic loading. The track bed can potentially reduce the ballast material costs up to 4 times than the standard grading ballast due to high recycling effectivity and therefore significantly contribute to clean and resource saving production. However, the tests demonstrate a significant increase of permanent settlements intensity for the track bed with wide ballast grading. Thereby, the tests show a quite different behaviour of the track bed during the loading cycles.

The initial settlements of the track bed with wide ballast grading are almost two times lower than for the standard grading track bed. However, this advantage is compensated with more rapid settlements accumulation after the initial stabilisation. The same permanent settlement for the both track beds is estimated in about 140 Mt of freight traffic. The sub ballast layer of the wide grading ballast track bed is subjected to relative rapid settlements. The application of one layer wide grading of the upper layer would potentially reduce the settlement intensity that would delay appearing the same settlements as the wide grading to about 210 Mt. The estimated 140-210 Mt period up to 3 times longer than the usual ballast tamping works. However, the conclusion about the plausibility of applying the wide grading track bed in some secondary lines should be decided taking into account many other influencing factors. The most important factors are the efficiency of conventional tamping techniques for the wide grading ballast, drainage properties, vibration loading, lateral sleeper stability etc.

The similar to the present results were presented in other studies. The definitely positive influence of the wide grading of the settlement and brackage behaviour was confirmed in the studies [21]. The decrease of settlement intensity for the wide grading ballast, different to the present study, could be explained with the ballast box tests without free slopes.

The additional measurements of pressure distribution properties as well as the static/dynamic stiffness, explain the causes of the increased settlements intensity. The study demonstrates high growth of pressure distribution angles due to the ballast compaction during the long-term loading cycles. The similar results of the pressure distribution angles were experimentally determined in other studies [39, 40].

The present study shows a wide field for the subsequent studies of the wide grading ballast layer. Except of the additional factors investigation and LCC research, the studies of the internal processes of ballast compaction distribution and the settlement relation to the static/dynamic nonlinearity would be a promising aim of the further research.

6. CONCLUSIONS

The present study delivers the following main conclusions:

- The track bed of double layer wide ballast grading has more than two times lower initial permanent settlements but also 2.5 times higher intensity of long term settlement accumulation than the standard grading track bed;
- The equal to the reference track bed permanent settlements of the double layer one are assessed to be about 140 Mt and 210 Mt for the one layer wide grading ballast;
- The pressure angles distribution of the double layer wide ballast grading track bed growth from on average from 12.7° to 15° during the loading cycles 0-1200 thousand cycles, while the growth for the standard grading is about 11° to 18°.
- The dynamic and static stiffness of the double layer track bed is subjected to higher variation during the loading cycles as for the standard grading
- The linear elastic stiffness of both standard and wide grading ballast track beds in loading range 0-60 kN is approximately the same, but the nonlinear part in the upper 20 kN range is 3-5 times higher.

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LIST OF FIGURES AND TABLES:

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