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Bearing capacity calculations of railway ballast

Les calculs de capacité portante du ballast ferroviaire

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ABSTRACT: Vehicle movement causes oscillations of railway track superstructure. The increase in loads and speeds of trains leads to a significant increase of dynamic vibration effects on substructure. This leads to accelerated ballast and subballast deterioration, which occurs due to soil strength decreasing.
The purpose of this study was to: 1. quantify the railway ballast stressed state in terms of heavy axle load operation, 2. apply test results to limit equilibrium theory and develop bearing capacity calculation method.
Field tests of railway ballast were performed at test site in terms of train operation with axle load up to 300 kN. The test results are operating stress values distribution in ballast layer. Paper describes case calculations of ballast and subballast bearing capacity.
RÉSUMÉ: Le mouvement des véhicules provoque des oscillations de la superstructure de la voie ferrée. L'augmentation des charges et de la vitesse des trains entraîne une augmentation significative des effets de vibration dynamique sur la sous-structure. Cela entraîne une détérioration accélérée du ballast et des sous-ballasts, due à la diminution de la résistance du sol.
Le but de cette étude était de: 1. quantifier l'état de contrainte du ballast ferroviaire en termes de charge à l'essieu lourd, 2. appliquer les résultats des essais pour limiter la théorie de l'équilibre et développer une méthode de calcul de la portance.
Des essais sur le terrain du ballast de chemin de fer ont été effectués sur le site d'essai en termes d'exploitation du train avec une charge à l'essieu jusqu'à 300 kN. Les résultats du test sont la distribution des valeurs de contrainte d'exploitation dans la couche de ballast. Le document décrit les calculs de cas de la capacité portante du ballast et du sous ballast.

Keywords: railway ballast; operating stress; limit stress; limit equilibrium theory

1 INTRODUCTION

Introduction of heavy freight trains on the railways of common use and the tendency to increase overhaul life leads to the additional activities to improve stability of the rail track. Stability of a superstructure depends on the strength and deformation properties of ballast and subgrade soils (Stoyanovich 2005, Pupatenko et al 2008).

Change of exploitation terms requires special measures for track preparation (Kolos, Konon 2016, Petriaev, Konon, Solovyov 2017). Increasing of speed and axle load causes rise of vibrational dynamic impact on railway track. World's exploitation experience shows that axle load increasing accelerates deformations of ballasted track. Ballast redistributes stress from rolling stock and track superstructure. Ballast performance makes great influence on track performance in total.

2 MATERIALS AND METHODS

Emperor Alexander I St. Petersburg State Transport University (PGUPS) scientists conducted in-situ tests of ballast layer stressed state. These tests were held at the Russian Railway Research Institute experimental track. On site rolling stock had axle loads of 230 to 300 kN at a speed of 70 km/h.

Track structure had the following parameters: 65 kg/m rails, concrete sleepers (2,000 items/km), tension clamp fastenings ARS-4, and thickness of granite ballast was 55 cm under the sleeper. Ballast consisted of 25−60 mm particles.

Vertical stress values in ballast layer were measured with soil pressure capsule set. Sensors were placed under the sleeper and in the depth of ballast layer. Sensors were set at the sleeper end, underrail section, and near centre line of the track and up to 55 cm under the sleeper (at the sleeper end). Sensor placement in ballast and subballast is presented in Figure 1.

3 TEST RESULTS

Test results show that axle load increasing causes the rise of stress values in ballast layer and subballast. Vertical stress distribution charts at levels of 10 and 55 cm under the sleeper are presented in Figures 2−3. Data analysis shows that car axle load primarily affects ballast and subballast stressed state. Vertical stress under the sleeper and in ballast grow intensively as a result of increasing axle load. Thus, at the underrail section (point "0.76 m" in Figures 2, 3) at the level of 10 cm under sleeper stress became 1.5 times as much and at the level of 55 cm under the sleeper they increased 1.9 times due to axle load change from 230 to 300 kN. This stressed state

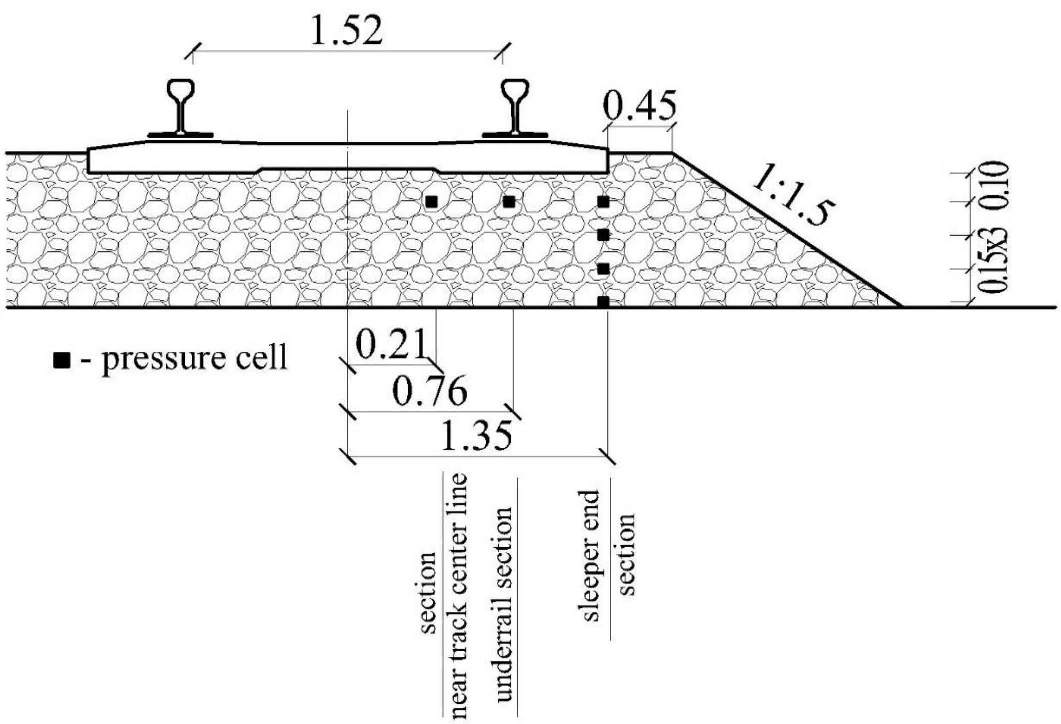

Figure 1. Sensor placement in ballast and subballast

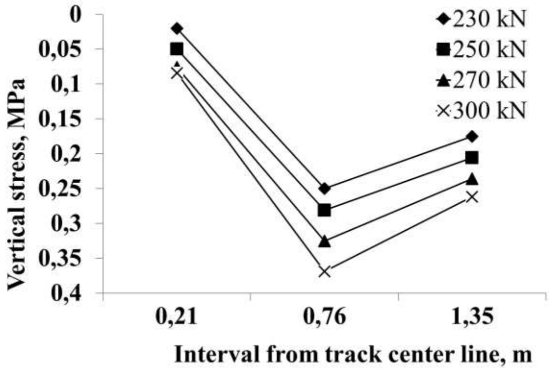

Figure 2. Vertical stress distribution at the level of 10 cm under sleeper

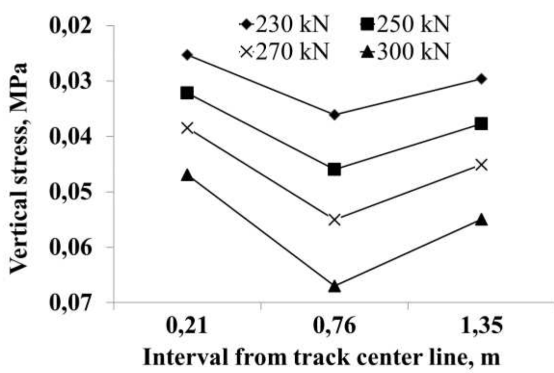

Figure 3. Vertical stress distribution at the level of 55 cm under sleeper

change should be taken into account while designing ballast layer and subballast structure from the point of bearing capacity. Derived stress values are used as operating stress values in ballast and subballast strength inequality (or condition) (equation (1)):

$$\sigma_z \leq \frac{[\sigma_z]}{\gamma_n} \quad (1)$$

where σ_z is operating stress (MPa); $[\sigma_z]$ is limit stress value (MPa) according to ballast bearing capacity calculation; γ_n is reliability factor.

4 CALCULATION RESULTS OF BALLAST AND SUBBALLAST BEARING CAPACITY

Limit vertical stress values at the ballast surface under sleeper pad are determined using calculation method, which is based on limit equilibrium theory considering vibrodynamic impact of rolling stock (Petriaev, Morozova 2013).

Russian design standards prescribe railway subgrade design with subballast for operation with axle loads up to 300 kN. Subballast and subgrade are constructed from medium and coarse sands and gravels. For the case calculation medium sand was taken as the subgrade material with properties shown in Table 1.

Table 1. Properties of medium sand for subgrade

Property	Value
USCS type	SW
Density	18 kN/m
Angle of internal friction	38°

Strength properties of ballast materials were determined according to multiple tests. Specimens with various quality and contamination were taken from quarries and railway tracks (Kolos & Konon, Chistyakov 2017).

Comparison between operating and limit stress showed combinations of ballast friction angle, vehicle axle load, for which bearing capacity is not ensured.

Calculation results and comparisons are shown in Tables 2 and 3.

Bearing capacity calculations showed that in terms of operation with 250 kN axle load bearing capacity of traditional track substructure without subballast is not ensured. This fact meets the world experience of heavy haul operation (Mishra, Qian, Huang, Tutumluer 2014). As worlds studies show, rails and sleeper have enough safety against failure in terms of

Table 2. Limit stress values under the sleeper pad at the underrail section due to various ballast strength properties, MPa.

Axle load, kN	Ballast friction angle, degree						
	38°	39°	40°	41°	42°	43°	44°
230	*0.35*	0.43	0.46	0.50	0.52	0.56	0.59
250	**0.31**	*0.39*	0.41	0.42	0.45	0.47	0.48
270	**0.29**	**0.36**	*0.38*	*0.40*	*0.42*	*0.44*	*0.44*
300	**0.28**	**0.35**	**0.37**	**0.39**	*0.40*	*0.42*	*0.44*

Note. Type designation means: regular – bearing capacity is ensured (inequality 1 holds), *italic* - bearing capacity is ensured with no margin of safety ($\frac{[\sigma_z]}{\gamma_n} < \sigma_z \leq [\sigma_z]$), **bold** - bearing capacity is not ensured ($\sigma_z > [\sigma_z]$).

operation with axle loads up to 300 kN, and the limiting factor is ballast and subballast strength.

Margin of safety shortage causes accelerated ballast abrading and unstable track geometry. It leads to irregular stress distribution from rolling stock at the subgrade level and subgrade deformations (Petriaev, 2016). So to increase ballast and subballast bearing capacity special engineering solutions should be used.

5 SOLUTIONS FOR INCREASING BALLAST AND SUBBALLAST BEARING CAPACITY

The most used solutions for increasing ballast and subballast bearing capacity in Russia is increasing of ballast layer thickness and using of subballast (protective layers). Multiple case calculations were made to determine thickness of ballast and subballast for operation with axle loads from 230 kN to 300 kN. Calculation results of ballast layer thickness are shown in Table 3.

Table 3 shows that for axle loads with up to 250 kN is increasing of ballast layer thickness is quite effective solution for rising the bearing capacity. For 230 kN axle load ballast layer with 0.6 m thickness gives limiting stress values that hold the strength condition (inequation 1).

Table 3. Limit vertical stress values depending on ballast layer thickness.

Ballast layer thickness, m	Limit vertical stress values, MPa, in terms of operation with axle load, kN			
	230	250	270	300
0.5	*0.345*	**0.309**	**0.294**	**0.282**
0.6	0.417	*0.390*	*0.376*	**0.357**
0.7	0.462	0.447	*0.438*	*0.431*
0.8	0.484	0.469	0.458	*0.473*

Note. Type designation means: regular – bearing capacity is ensured (inequality 1 holds), *italic* - bearing capacity is ensured with no margin of safety ($\frac{[\sigma_z]}{\gamma_n} < \sigma_z \leq [\sigma_z]$), **bold** - bearing capacity is not ensured ($\sigma_z > [\sigma_z]$).

For 250 kN axle load 0.7 m ballast layer is needed to hold the strength condition, and for 270 kN – 0.8 m. It is worth noting that this ballast layer design is quite unconvenient for construction and maintenance. For 300 kN strength condition does not hold for thickness values 0.5-0.8 m. For thickness increasing from 0.5 to 0.6 m limit stresses rise about 25,4 %, for increasing from 0.6 to 0.7 m bearing capacity rises 15.7%. Rising of ballast layer thickness from 0.7 to 0.8 m gives an effect of only 6%. So

0.5-0.7 m thickness is more effective for bearing capacity rising. But this structural solution can lead to ballast instability in case of excessive thickness. Also, the thicker ballast layer is, the wider top of the subgrade should be. This causes extra construction costs.

Bearing capacity calculations were made for terms of operation with 270-300 kN axle load for substructure design with subballast of 0.1-0.5 m depth and friction angle 41°.

Calculation results and comparison with operating stress values (Figures 2-3) are given in Table 4.

Table 4. Limit vertical stress values depending on subballast thickness, MPa.

Subballast thickness, MPa	Axle load, kN	
	270	300
0.1	**0.454**	**0.445**
0.2	*0.479*	**0.46**
0.3	0.504	**0.48**
0.4	0.528	**0.502**
0.5	0.561	0.526

Note. Type designation means: regular – bearing capacity is ensured (inequality 1 holds), *italic* - bearing capacity is ensured with no margin of safety ($\frac{[\sigma_z]}{\gamma_n} < \sigma_z \leq [\sigma_z]$), **bold** - bearing capacity is not ensured ($\sigma_z > [\sigma_z]$).

Subballast thickness increasing for 10 cm gives limiting stress value rise 5.4% for 270 kN axle load and 4.3% for 300 kN axle load. Table 4 shows that strength condition holds for 270 kN axle load with subballast 0.3 m thickness, and for 300 kN strength condition holds with 0.5 m subballast.

Basing on case calculations, requirements for design and material of ballast layer and subballast were made for operation with axle load up to 300 kN (Table 5).

Table 5. Requirements for design and material of ballast and subballast

Properties	Axle load, kN			
	230	250	270	300
Material requirements				
Angle of internal friction φ, °	≥38	≥40	≥42	≥43
Design requirements				
Ballast layer thickness (under the sleeper), m	Traditional (0.4-0.45)	0.5-0.6	0.5 with subballast	
Subballast thickness, m	--	--	0.3	0.5

6 CONCLUSIONS

This paper shows case calculation results of ballast and subballast bearing capacity. Calculations base are values of limit and operating stress at the ballast surface under sleeper pad. Calculations were made for determined strength properties of embankment material and varying strength properties of ballast material. The following conclusions are drawn:

- The stated method allows to determine ballast layer bearing capacity and margin of safety availability.
- In case of margin of safety shortage one can increase ballast thickness and assess the most efficient thickness from the point of view of increasing limit stress values. Generally 0.5-0.7 m thickness is more effective for bearing capacity rising regarding construction costs.
- It is recommended to use subballast in case of car axle loads higher than 270 kN. Preferable subballast thickness can be determined. For shown case study it was set as 0.3 m for 270 kN per axle and 0.5 m for 300 kN per axle.

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