Influence of compaction on the deformation resistance of the sub-ballast layer

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Abstract. In railway practice, the results of static load tests are used most frequently to check the quality of compaction. However, the static load tests are preferably carried out to demonstrate the achievement of the required deformation resistance on the sub-ballast layers. The paper deals with the analysis of measured values of deformation resistance of the sub-ballast layer on the modernised track Považská Teplá - Žilina, depending on the compaction (achieved degree of soil compaction) and the possibility of mutual correlation of these qualitative parameters. In the analysis, the values of deformation resistance and compaction quality (degree of soil compaction) were used as part of the quality diagnostics of the performed work on the part of the modernised section of the line Považská Teplá - Žilina.

1 Introduction

The ability of the sub-ballast layers to withstand traffic loads in railway engineering is termed deformation resistance. This term was introduced in Slovakia for the first time in [1]. Until then, the term bearing value of the sub-ballast layers, or track bed was used. The sub-ballast layers are sufficiently deformation resistant if they are able to absorb a defined load without harmful (permanent) deformations and without breaking them. If the sub-ballast upper surface or the subgrade surface loaded with increasing load, then in principle the deformations can be shown according to figure 1.

![Figure 1. Soil behavior under load](image-url)
Initially, the load-induced deformations have a linear course and then a reverse (reversible), which can be characterized as elastic soil behavior. In another area, not only elastic, but also plastic (permanent) deformations occur due to the reduction in pore volume. When the breaking load (ultimate strength) is exceeded, deformations progressively develop under a constant load, which can be referred to as plastic behavior of the soil.

The deformation resistance of the sub-ballast layers or the subgrade surface can be expressed numerically eg. modulus of elasticity (static, dynamic, shear, volumetric), modulus of deformation (static, dynamic), reaction modulus, penetration modulus, CBR value or based on soil physical properties (moisture, plasticity index and consistency index). All these deformation characteristics indicate the relationship between load and deformation but differ significantly from each other in the boundary conditions of their detection [2]. For this reason, it is difficult to compare these deformation characteristics.

The following text of the paper will analyze the impact of the achieved degree of soil compaction on the deformation characteristic, which has the greatest application in railway engineering (in the diagnostic of the sub-ballast layers), namely the static modulus of deformation will be performed. The analysis will be performed on the basis of the measured values of the static modulus of deformation at the level of the sub-ballast upper surface determined during the diagnostic carried out in the modernised section of the line Považská Teplá - Žilina.

2 Characteristics of tested materials and applied method of diagnostic

This part of the paper will characterize the properties of built-in materials into the sub-ballast layer and test method for verification of deformation resistance and degree of soil compaction of the sub-ballast upper surface, which were used and identified on the assessed modernised section of the line Považská Teplá - Žilina.

2.1 Specification of material composition of the sub-ballast layer

The sub-ballast layer is the first structural layer of the sub-ballast layers located below the ballast bed (in the case of a conventional type of railway superstructure). Its main function is the spreading of the effects of line tonnage (traffic density) and load of the railway superstructure on the subgrade surface, eventually also the protection of the subgrade surface against adverse effects of water and frost. In some cases, the sub-ballast layer can only fulfill these functions if additional structural engineering measures are applied, such as:

- application of suitable geosynthetic materials and elements,
- improving or stabilisation the soil of the subgrade surface or changing the subsoil,
- application of waterproof materials in the groundwater protection area,
- incorporation of thermal insulation materials, etc.

The sub-ballast layer shall, by its grain size distribution and moisture, ensure sufficient compaction and deformation resistance of the structural layer and at the same time it shall comply with the filter criterion against the soil of the subgrade surface and the ballast gravel [3].

Within the diagnosed section of the modernised railway line Považská Teplá - Žilina, the sub-ballast layers were designed in accordance with TNŽ 73 6312 [1]. Structural and material composition of the individual structural layers resulted from the condition of ensuring a high-quality and safe railway for the train speed up to 160 km.h⁻¹. Based on these boundary conditions and in order to ensure the required deformation resistance at the level of sub-ballast upper surface \( E_{sub} \geq 60 \text{ MPa} \) (railway line built on the original earthwork), a sub-ballast layer fr. 0/63 mm of variable thickness, reinforced by geogrids (depending on the measured value of the deformation resistance of the subgrade surface identified in the geotechnical survey - figure 2) was designed in the sub-ballast layers. In the case of a railway line on a newly constructed earthwork, constructed of frost-resistant and pervious soil (crushed aggregate fr. 0/63 mm), the required value of the deformation resistance at the level of the sub-ballast upper surface \( E_{sub} \geq 80 \text{ MPa} \) was required. In this case, the sub-ballast layer was built of crushed aggregate fr. 0/63 mm thickness 0.30 m and placed on geotextile [4].
As the values of deformation resistance $E_0 < 6$ MPa were diagnosed at the level of the subgrade surface during the modernisation of the railway line section in question, the design documentation had to be changed. In the line sections with very low deformation resistance of the subgrade surface (less than 6 MPa) the subgrade surface was stabilized with lime and the sub-ballast layer was carried out by the original procedure according to figure 2 (depending on the deformation resistance of the subgrade surface after stabilization).

2.2 Methodology of determination of deformation resistance and degree of soil compaction of the sub-ballast layer

Deformation resistance of the sub-ballast layers or in this case only the sub-ballast layer, was determined by a static load test carried out using the equipment shown in figure 3. The static load test is one of the oldest in situ tests, and it has been used informatively in our infrastructure since 1967 in railway substructure diagnostics.

Figure 2. Design of construction and material arrangement of the sub-ballast layer depending on the deformation resistance of the subgrade surface [4].

Figure 3. – Realization of static load test at the level of the sub-ballast upper surface.
The Static plate load tests (PLT) at the level of the sub-ballast upper surface were performed according to the methodology given in STN 73 6190 [5]. The PLT principle is based on measuring the pressing of a rigid circular load plate of 300 mm radius into the diagnosed structural layer (in our case the sub-ballast layer) as a result of the action of a particular static load. Measurement of the deformation resistance of the sub-ballast layer was carried out in two load cycles with a maximum contact stress value of 0.20 MPa, while the loading / unloading of the rigid circular load plate is realized in steps of 1/4 maximum pressure. The decisive cycle for determining the static modulus of deformation is the second load cycle, from which the value of the rigid plate settlement is obtained.

Static modulus of deformation \( E_s \) or in this case, \( E_{sub} \) is calculated from the measured values based on the Boussinesque theory of resilient semi-space by adjusting the relation:

\[
E_s = \frac{\pi}{2} \cdot \frac{p \cdot r}{y} \left(1 - \frac{y}{r}^2\right) \approx \frac{1.5 \cdot p \cdot r}{y} = 0.225 \cdot \frac{p}{y}
\]

where: 
\( E_s \) – static modulus of deformation, (MPa), 
\( p \) – contact stress under the load plate, (MPa) 
\( r \) – load plate radius, (m), 
\( y \) – total average settlement of the plate load, (m), 
1.5 – constant for \( \nu = 0.21 \).

If the first load cycle is also used from the load diagram and the static deformation modulus is calculated from it, the measured values of deformation resistance can be used to demonstrate the degree of soil compaction of any structural layer of the sub-ballast layers or subsoil. The static modulus of deformation from the second load cycle \( E_{def2} \) is larger than the static modulus of deformation from the first load cycle \( E_{def1} \), as the material of the test layer is compacted during the first load cycle. If the degree of soil compaction is very large (this corresponds to a large load plate settlement), then compaction was insufficient. According to STN 73 6133 [6], compaction is considered to be sufficient if for coarse-grained materials (in our case crushed aggregate fr. 0/63 mm) the degree of compaction is expressed as the ratio \( E_{def2}/E_{def1} \leq 2.6 \). As part of the diagnosed modernised section of the line, the compaction on the individual structural layers was carried out using a BOMAG vibratory roller, which also served as a counter-load in the performance of PLT.

The actual measurement of the static deformation modulus of the sub-ballast layer in the modernised (diagnosed) railway line section was in most cases performed every 200 m or the network of measuring points was condensed in cases of localization of areas with low deformation resistance.

3 Analysis of achieved results

Generally, the deformation resistance of any structural layer depends on the type and quality (physico-mechanical properties) of the layer material and the quality of its compaction (depends on the type of soil compaction equipment, compaction method and number of running gear). For this reason, we decided to identify the relationship between the degree of the soil compaction and the deformation resistance of the sub-ballast layer from the values measured by the diagnostics of the modernised section of the line Považská Teplá - Žilina. In the first phase of the analysis, the subject dependence was created for the crushed aggregate fr. 0/63 mm (sub-ballast layer) placed on the original earthwork - figure 4.

In total, 141 measured values were evaluated in the analysis. The deformation resistance values, expressed by the static modulus of deformation at the level of the sub-ballast upper surface (\( E_{sub} \)), varied between 60.8 MPa and 140.6 MPa and the degree of compaction values (\( E_{def2}/E_{def1} \)) between 1.13 and 2.6. figure 4 shows that it is not possible to create a dependence of the deformation resistance of the sub-ballast upper surface on the degree of soil compaction if the railway line is built on the original earthwork. It should be noted that in this case the value of deformation resistance \( E_0 \geq 30 \) MPa was required at subgrade surface level, but in many cases this condition was not met.
the sub-ballast layer built on the original earthwork of the railway line.

The deformation resistance of the subgrade surface was considerably uneven and the deformation resistance of the sub-ballast layers was ensured only through the sub-ballast layer reinforced by geogrids (see figure 2). In order to eliminate the influence of the reinforcing materials in the structure of the sub-ballast layer or insufficient deformation resistance of the subgrade surface to the examined dependence, analysis of measured values was performed for a part of the railway line built on a new earthwork (embankments). The dependence of the deformation resistance values determined at the level of the sub-ballast upper surface with the degree of soil compaction of the sub-ballast layer for the railway line built on new earthworks (embankments) is shown in figure 5.

In total, 50 measured values were evaluated in the analysis. The deformation resistance values, expressed by the static modulus of deformation at the level of the sub-ballast upper surface \( E_{sub} \), varied between 80.4 MPa and 140.6 MPa and the degree of compaction values \( \frac{E_{def2}}{E_{def1}} \) between 1.11 and 2.6. figure 5 shows that it is equally not possible to create a relevant dependence of the deformation resistance of the sub-ballast upper surface on the degree of soil compaction if the railway line is built on the new earthworks (embankments). It should be noted that in this case the value of

\[
y = -0.004x + 2.2699 \\
R^2 = 0.0368
\]
deformation resistance $E_0 \geq 40$ MPa was required at subgrade surface level, which was in all cases met.

In the last phase of the analysis, the dependence of the monitored parameters (deformation resistance of the sub-ballast layer from the degree of its compaction) was created within individual coherent parts of a building (CPB 48 - CPB 52) or within station and interstation sections of the diagnosed railway line. A more detailed specification of individual CPB is given in the paper entitled „Analysis of results of deformation characteristics measurements of embankments and transition zones of a modernised line Považská Teplá – Žilina“ [7] published in this Proceedings. In this analysis, the best determination coefficient for CPB 50 (interstation section between the railway stations Bytča and Dolný Hričov) was achieved - figure 6. The CPB 50 has a length of approximately 3.5 km, of which almost half of the CPB is built on a new earthwork.

![Figure 6. – Dependence of degree of soil compaction and static deformation modulus of the sub-ballast layer determined within CPB 50.](image)

In total, 33 measured values were evaluated in the analysis. The deformation resistance values at the level of the sub-ballast upper surface ($E_{\text{sub}}$), varied between 62.5 MPa and 140.6 MPa and the degree of compaction values ($E_{\text{def}}/E_{\text{def}0}$) between 1.11 and 2.6. Figure 6 shows that the dependence of the deformation resistance of the sub-ballast upper surface on the degree of soil compaction in this case is better than in figure 4 or figure 5, but the determination coefficient is still too small. Within the other CPB, the determination coefficient $R^2 \leq 0.2$ was reached and therefore the dependence is not relevant.

4. Conclusions
The paper is linked to the issues published in [7] and [8]. The aim of these papers was to provide a comprehensive overview of the quality of construction work carried out in one of the diagnosed line sections (the modernised section of the line Považská Teplá – Žilina), which is part of the trans-European Corridor no. Va. In the paper the analysis was performed and the dependence between the deformation resistance of the sub-ballast layer and the degree of its compaction from the values obtained by static load tests was searched. In the first phase of the analysis, the dependence was monitored in railway line sections built on the original earthwork and subsequently in railway line sections built on the new earthworks (embankments). Within this phase, an unacceptable coefficient of determination $R^2 < 0.1$ was achieved (see figures 4 and 5).
Subsequently, the dependence was monitored within individual coherent parts of a building (CPB) or in interstation and station sections of the railway line in question. At this stage of the analysis, the highest coefficient of determination for the interstation CPB 50 was achieved, namely \( R^2 = 0.294 \) (figure 6), which is higher coefficient but still insufficient.

On the basis of the above, it can be stated that the obtained dependence between the deformation resistance of the sub-ballast layer and the degree of its compaction has a very low informative value, as the achieved coefficients of determination are very low. The deformation resistance of the sub-ballast layer depends not only on the compaction (type of soil compaction equipment, compaction method and number of running gear), but is fundamentally influenced by the deformation resistance of the subgrade surface, the quality (physico-mechanical properties) and thickness of the sub-ballast layer material and by applying geosynthetic to the sub-ballast layers (in our case to the sub-ballast layer). Given that all these influences changed from one place to another in the diagnosed section of Považská Teplá - Žilina, the values of deformation resistance had considerable variance as well as the achieved degree of compaction. It is therefore logical that, in this case of the diagnosed track section, an acceptable correlation could not be established.

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