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The effect of the sub-ballast layer material to the performance of a railway embankment

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ABSTRACT Higher operating speeds and heavier axle loads cause greater demands on the existing railway structures. The railway network is relatively old in Finland and the materials used in the embankments vary significantly. This might induce an increased need for maintenance and problems for the rail traffic. The aim of this study was to determine indirectly by numerical modelling how susceptible the embankment is for permanent deformations to develop when the sub-ballast material used in the embankment does not meet the requirements of the current technical specifications. The material parameters used in the modelling for the sub-ballast layer were determined partly from literature and partly from the laboratory tests. The sub-ballast samples for laboratory testing were taken from an existing railway line in Finland, which has experienced increased maintenance needs due to seasonal movements in the embankment. The stiffness of the subsoil and the material parameters of the sub-ballast layer were varied in the calculations. Permanent deformations in the railway embankment have the greatest effect on the long-term performance of the structure. With the load levels used in the calculations it was observed that the service life of the structure is shorter if the sub-ballast material is in a loose state. The calculations also showed that the subgrade stiffness has significant impact on the generated permanent deformations in the embankment. Further research needs were detected regarding to the excess pore water pressures, the effects of the environmental factors and the dynamic load component caused by the rail traffic.

1 INTRODUCTION

Higher operating speeds and heavier axle loads cause greater demands on the existing railway structures. In Finland, the railway network is relatively old and the materials used in the embankments vary significantly. Due to the varying climate conditions in Finland, the embankments are quite thick which has usually ensured adequate embankment stiffness also in the means of structural capacity. The typical railway embankment structure (Fig. 1) consists of the ballast layer and two sub-ballast layers. In older railway structures the upper sub-ballast layer might be missing. Therefore the profounder understanding of the load carrying capacity of a railway embankment is needed to analyse the possible problems caused by the old materials on the existing railway lines which cause increased maintenance needs and disturbance for the rail traffic.

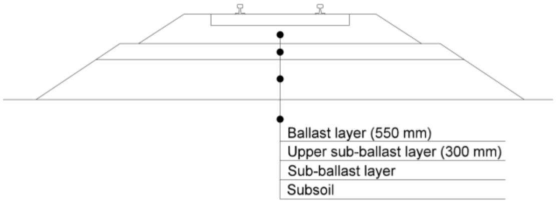

Figure 1. Typical railway embankment structure in Finland.

The permanent deformations have the greatest impact on the long term functionality of the railway structure. If the unbound layers have been saturated due to bad drainage, the excess pore water pressure can build up when the train passes. This decreases the effective stresses and lowers the structures ability to resist permanent deformations to develop (Indraratna et al. 2011). Also if the unbound materials used in the embankment become loose due to uneven settlements, freezing-thawing cycles or dynamic train load, more permanent deformations are likely to occur (Alkio et al. 2001).

To investigate the development of permanent deformations in the embankment, sub-ballast layer material samples were taken from two locations (P86 and P90) from Tampere-Seinäjoki railway line. They were tested in the laboratory in order to determine their gradation and strength and stiffness properties for the modelling of the railway embankment in Plaxis 2013 3D. The laboratory tests of the sub-ballast samples showed that their gradation (Fig. 2) does not meet the current requirements of technical specifications (INFRARYL 2010) in Finland. In these locations (P86 and P90) at Tampere-Seinäjoki railway line the 1960s built railway embankment has been founded directly on subsoil which consists of peat, silt and till layers. The overall stability has been improved by counterweight berms and mass stabilization beside the embankment. Despite these actions the seasonally occurred movements of the embankment have required regular maintenance and the speed limit has been reduced to 120 km/h for passenger trains in these locations.

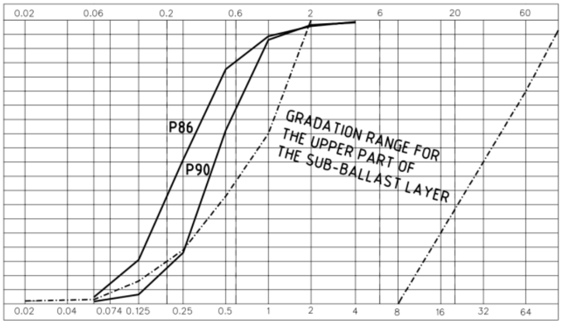

Figure 2. Gradation curves for the investigated P86 and P90 sub-ballast samples and the current requirements for the gradation of the upper part of the sub-ballast layer material according INFRARYL (2010).

2 NUMERICAL MODELLING

The numerical modelling was performed with Plaxis 2013 3D. The aim was to analyse the stresses and strains in the railway embankment when a 250 kN train load is applied and to determine indirectly how susceptible the embankment is for permanent deformations to occur when the sub-ballast material used in the embankment does not meet the requirements of the current technical specifications.

The hardening soil model was used for the ballast and the upper sub-ballast layers, because it can model the hardening behavior of the soil under loading. The input parameters for these layers (Table 1) were determined from literature (Kalliainen et al. 2014). Static and cyclic triaxial tests were performed for the sub-ballast material samples of Tampere-Seinäjoki railway line and their results were used to determine the stiffness and strength parameters for the hardening soil small material model in a dense and loose state (Table 2) for both P86 and P90 materials. In addition bender element tests were made to determine the stiffness modulus of the sub-ballast materials at small strains.

Table 1. Input parameters for the ballast and the upper sub-ballast layer used for the hardening soil model.

	Ballast layer	Upper sub-ballast layer
Material model	HS	HS
Drainage type	Drained	Drained
γ_{unsat} (kN/m$^{3)}$	20	20
γ_{sat} (kN/m$^{3)}$	23	23
E^{ref}_{50} (kN/m^2)	250000	140000
E^{ref}_{oed} (kN/m^2)	210000	137000
E^{ref}_{ur} (kN/m^2)	500000	280000
M (-)	0,5	0,5
v_{ur} (nu) (-)	0,2	0,2
p^{ref} (kN/m^2)	100	100
K_0^{nc} (-)	0,300	0,384
c_{ref} (kN/m^2)	20	10
Φ (°)	45	38
Ψ (°)	10	5
R_f (-)	0,9	0,9

The rails were modelled with a beam element and the input parameters were determined to correspond to the rail profile (60E1) properties according to the European Standard EN 13674. The linear-elastic model was used to model the sleepers to correspond the K60 concrete material properties. The subsoil was modelled with a very simple linear-elastic material model. Three different stiffness values were used for the subsoil in the calculations in order to simulate different types of subsoil conditions and especially the effect of the subsoil stiffness. Stiffness values of 10 MPa, 50 MPa and 200 MPa were used in the calculations. The calculations were tested with even more lower stiffness than 10 MPa, but it led to numerical difficulties and it was observed that linear-elastic material model is not well suited to model low stiffness materials with large volume.

Table 2. Input parameters for the sub-ballast layer used for the hardening soil small material model.

Sub-ballast	P86 dense	P86 loose	P90 dense	P90 loose
Material model	HS small	HS small	HS small	HS small
Drainage type	Drained	Drained	Drained	Drained
γ_{unsat} (kN/m$^{3)}$	17,2	13,2	16,7	15,1
γ_{sat} (kN/m$^{3)}$	18,7	14,5	17,7	15,9
E^{ref}_{50} (kN/m^2)	50000	10000	31250	18750
E^{ref}_{oed} (kN/m^2)	50000	10000	31250	18750
E^{ref}_{ur} (kN/m^2)	125000	115000	140000	115000
M (-)	0,5	0,5	0,5	0,5
v_{ur} (nu) (-)	0,2	0,2	0,2	0,2
p^{ref} (kN/m^2)	100	100	100	100
K_0^{nc} (-)	Auto	Auto	Auto	Auto
c_{ref} (kN/m^2)	12	2	7	2
Φ (°)	37	34	35	34
Ψ (°)	7	4	5	4
R_f (-)	0,9	0,9	0,9	0,9
G^{ref}_0 (kN/m$^{2)}$	130300	50000	96600	68700
$\gamma_{0,7}$ (-)	0,0001	0,0003	0,0002	0,0002

In the initial calculation phase, the K0-procedure was used to produce the original stress state in the soil. The embankment (Fig 3.) was constructed in six phases. After the construction phases the deformations were set to zero. Then five loading cycles with point loads corresponding to a 250 kN train load were applied. It has been observed earlier (Pihlajamäki 2012) that the deformations and stresses in the embankment do not vary significantly after the fifth loading cycle when using the hardening soil model in Plaxis with similar cases. Therefore the stresses and deformations caused by the fifth loading cycle are analysed here.

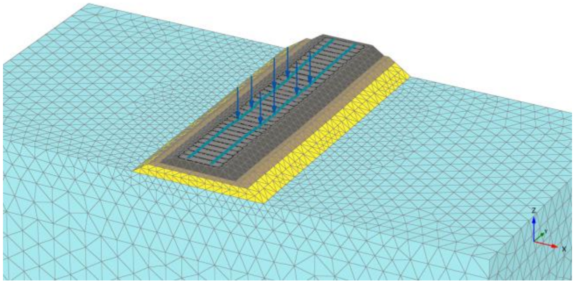

Figure 3. Generated model in Plaxis 2013 3D.

3 RESULTS

The deformations and stresses induced by one loading cycle were analysed. Therefore the long term development of the permanent deformations has to be analysed indirectly. The momentary settlement of the sleeper, shear stresses in the sub-ballast layer, vertical stress distribution and stress paths were analysed in more detail.

3.1.1 Momentary settlement of the sleeper

In Figure 4, the vertical settlement of the sleeper is presented with different subsoil stiffness. With relatively thin 1,6 m embankment the subsoil stiffness has the greatest effect on the sleeper settlement. When the subsoil stiffness is very low or high, the differences between the sub-ballast materials seem to decrease. Surprisingly, the biggest difference between the sub-ballast materials appeared when the subsoil stiffness was 50 MPa. Also when loose materials are used in the sub-ballast layer the settlements are relatively bigger. With a higher embankment the sub-ballast material would probably be more dominant in comparison with the 1,6 m embankment.

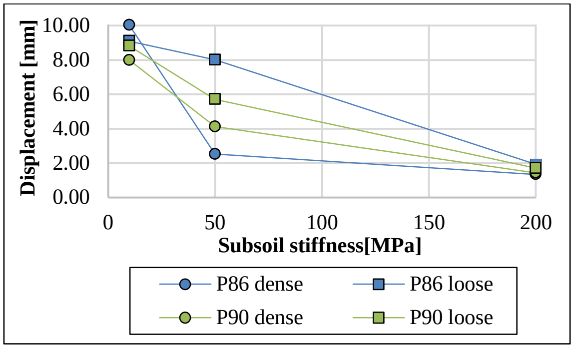

Figure 4 The momentary settlement of the sleeper due to the train load with different sub-ballast materials and subsoil stiffness.

3.1.2 Shear strains

The maximum shear strains occur in the upper part of the sub-ballast layer. It is assumed that larger shear strains indicate accumulation of the permanent deformations (Kalliainen et al. 2009). The results (Fig 5.) show again that the stiffness of the subsoil is the dominant factor, which affects the order of the shear strains in the sub-ballast layer. The differences between the sub-ballast materials in a loose and dense state are also apparent. When the materials are in a loose state, bigger shear strains occur. This indicates more permanent strains to develop in the structure in a long run. Overall the most critical case seems to be when the subsoil has low stiffness and the sub-ballast material is in a loose state.

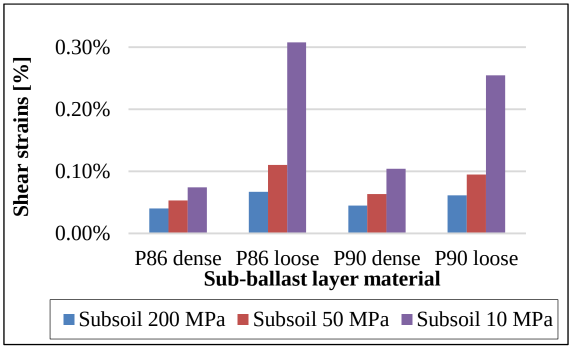

Figure 5 The developed shear strains in a reference point in the sub-ballast layer with different sub-ballast layer materials and subsoil stiffness.

3.1.3 Vertical stress distribution

In Figure 6, the vertical stress increment induced by the load under the rail for material P86 is presented. The stress increment is largest when the sub-ballast material is in a dense state and the subsoil stiffness is high, because the structure gives the stiffest response to the applied load. The differences in the stress distribution between the dense and loose sub-ballast materials with the same subsoil stiffness can be seen clearly in the ballast and the upper ballast layers. In the sub-ballast layer the subsoil obviously has the greatest impact on the stress distribution. The stress distribution curve clearly shows that the ballast and the upper sub-ballast layers have overall the biggest effect on the stress distribution in the embankment. Therefore their quality and stress distribution properties are important in the perspective of the total functionality of the embankment.

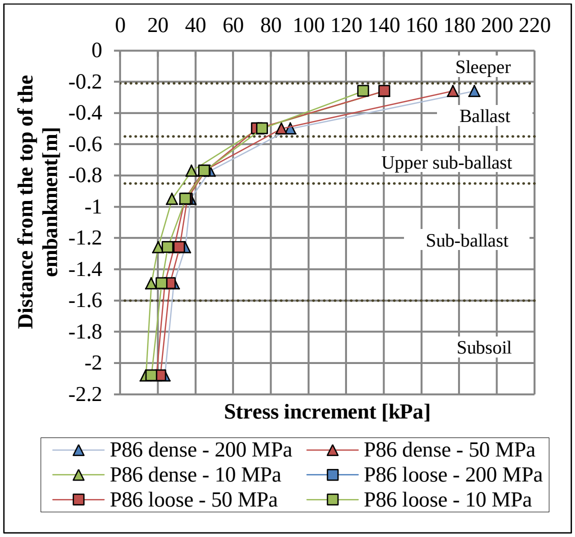

Figure 6 The vertical stress increment induced by the load under the rail for material P86.

3.1.4 Stress paths

The amount of permanent deformations increases when the stress state of the material approaches failure. This has been indicated in triaxial tests made for unbound aggregates (Korkiala-Tanttu 2005). Therefore stress paths provide information on the permanent strains susceptibility of the material in a specific stress state. In Figure 7, the stress paths at the top and in the middle of the sub-ballast layer are presented. The stress paths at the top of the layer approach the 80 % limit of the critical state line. This indicates that more permanent deformations are likely to occur.

Due to the theoretical background of the hardening soil material model, the limit for the increasing permanent deformations is likely higher than it would be if observed the results of triaxial tests, where the permanent deformations start to occur more rapidly when the stress path reaches 60 % of the critical state line. When the subsoil stiffness was 10 MPa, the shape of the stress path in the sub-ballast layer was not realistic due to the possible numerical problems with relatively low subsoil stiffness.

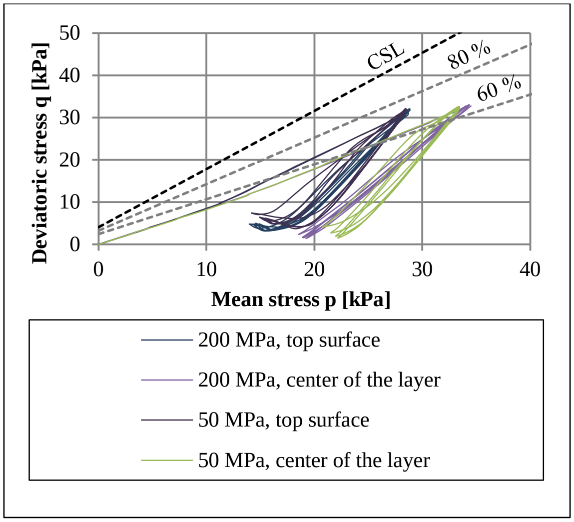

Figure 7 The stress paths for the P86 loose material with 50 MPa and 200 MPa subsoil stiffness at the top and center of the sub-ballast layer.

4 CONCLUSIONS

The calculations made with Plaxis 2013 3D clearly showed that if the sub-ballast layer is in a loose state more permanent deformations are likely to occur. Therefore the situations in the railway environment when the sub-ballast layer material might get into a loose state should be avoided. Also the significance of the subsoil stiffness was apparent and even more notable than the sub-ballast layer material properties when the embankment height was 1,6 m. The calculations were performed in a drained state so the real displacements are likely to be even bigger if the sub-ballast material is saturated and if excess pore water pressure is possible to develop during the train passage. Also other environmental factors like freezing-thawing cycles or the dynamic load component of the train load have not been taken into account here, but which have a great impact on the total functionality of a railway embankment.

If similar sub-ballast layer materials to the Tampere-Seinäjoki railway line are used in the embankment, it should be taken care of the fact that they do not get into a loose or saturated state. In situations of that kind it seems that their bearing capacity properties are not sufficient, which might be seen as increased permanent deformations, maintenance needs and disturbance for the rail traffic as noticed in two locations at Tampere-Seinäjoki railway line.

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