Modeling of the effect of embankment dimensions on the mechanical behavior of railway track

Modélisation de l'effet des dimensions des remblais sur le comportement mécanique des voies ferrées

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ABSTRACT

Gradual accumulation of permanent deformations in railway track embankments caused by repeated train axle loads is an important problem in the Northern areas, where the track embankments must be built very thick because of design against harmful effects of seasonal frost. Based on long-term measurements performed at a test site located in Western Finland, both embankment width and slope angle are shown to have a marked effect on the accumulation rate of permanent deformations. The observed differences can be given a credible explanation when the results of 2D Finite Element Modelling are interpreted based on the mobilized level of shear strain in embankment sections with different width and slope angle.

RÉSUMÉ

L'accumulation graduelle de déformations permanentes des remblais de voies ferrées due aux charges continuelles des essieux des trains s'avère être un problème de taille pour les pays nordiques, où il est indispensable de construire des remblais particulièrement épais afin de résister aux effets négatifs provoqués par le gel. Des études de longue durée menées sur un site test situé dans l'ouest de la Finlande font apparaître que tant la largeur que l'angle d'inclinaison des remblais ont un effet notable sur les taux d'accumulation de déformations permanentes. Les différences observées reçoivent leur explication lorsque les résultats de la modélisation bidimensionnelle des éléments finis sont interprétés à partir du niveau mobilisé d'effort de cisaillement sur des sections de remblais de largeurs et angles d'inclinaisons divers.

Keywords : railway, track, embankment, width, slope, widening, permanent, deformation, strain

1 INTRODUCTION

In the Northern areas the total thickness of structural layers in railway embankments is primarily governed by the design against harmful effect of seasonal frost. Because practically no frost heave can be allowed to take place on railway tracks with normal speed passenger traffic, the embankment must typically be built up to two or even two and a half meters thick. Meantime, the embankments have typically fairly steep slopes, for instance in Finland track embankments are normally built using a slope ratio of 1:1.5. Introduction of higher allowable axle loads and traffic speeds is, however, exposing the embankments structures to continuously increasing intensity of repeated loading which is also increasing the rate of permanent deformations accumulating into the embankment structure. In practical terms the embankment is widening as it deforms and the respective movements of the track must be compensated by more frequent maintenance actions.

The most straightforward measures to increase the internal stability of a railway embankment are to make the embankment wider and/or to reduce the slope steepness of the embankment. Both of these actions mean, however, larger space requirement for the railway track and, above all, extensive increase in the use of high-quality non-frost-susceptible aggregate materials in connection with the embankment construction or renovation. Therefore, taking into account both the construction time costs on one hand and the maintenance costs of the track on the other hand, optimisation of the embankment dimensions and shape is an important issue regarding the life cycle costs of a railway line.

In a research project going on at the Laboratory of Earth and Foundation Structures of the Tampere University of Technology the above mentioned problem is being studied by in-situ monitoring of a full scale railway track embankment having sections that are shaped in different embankment widths and slope angles. The long term deformations of the embankment have been monitored for about three years in addition to which also the short term responses of the embankment structure have been measured while trains are passing over the monitoring sections. In addition, model scale (1:4) test structures with different embankment widths and slope angles have been tested in laboratory using a loading system consisting of five hydraulic actuators operating consecutively so as to simulate the loading effect of a moving train.

This paper is focusing on the observations made on the full-scale monitoring site located at Kokemäki, in Western part of Finland and on numerical modelling of the respective embankment behaviour. Other parts of the project will be reported in more detail elsewhere.

2 FULL-SCALE DEFORMATION MONITORING OF RAILWAY TRACK EMBANKMENT SECTIONS

2.1 *Kokemäki test site*

Full-scale monitoring of the accumulation of permanent deformations in a railway track embankment has been performed at a monitoring site located on the railway line between the towns of Kokemäki and Rauma in the Western part of Finland since autumn 2004. The test site consists of four consecutive embankment sections in three of which the shape has been carefully adjusted to correspond the standard embankment profiles given in the respective Finnish design codes (Finnish Rail Administration 2008). Each of the embankment section is 40 m long and the transition from one embankment type is made on a distance from 10 to 25 m

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(Figure 1). The width of the embankment on top of the substructure, i.e. below the ballast layer, varies from 5.4 m to 6.8 m while the slope ratio is 1:1.5 in three of the sections and 1:2 in one of the sections (Figure 2). Total height of the embankment on the Kokemäki monitoring site varies from 2.2 to 2.9 m.

Below the ballast layer made of crushed rock aggregate the embankments consists of non-frost-susceptible sandy material. The embankment is resting on about 10 m thick layer of fairly soft silt and clay below which there is a stiff layer of moraine. On top of the soft soil layer there is, however, about one meter thick dry crust layer.

Figure 1. Shaping of the embankment sections at the Kokemäki monitoring site.

2.2 *Measurements performed*

Monitoring of accumulated permanent deformations in the different pavement sections has been made according to the following principles:

- In each of the pavement sections measurements have been made at two cross sections 10 m apart from each other.
- In each of the measurement cross sections six reference points have been grouted into the sandy embankment material.
- The reference points have been installed symmetrically on both side slopes of the embankment at vertical distances of 0.25 m, 0.75 m and 1.50 m from the bottom of the ballast layer.
- After installation in November 2004 xyz-coordinates of the reference points have been measured twice a year using a tachymeter until August 2007.

The observed widening in each of the embankment sections about one year and about two years after installation of the reference points has been indicated in Table 1. In Figure 2 the average widening of each embankment section has been visualized by exaggerating the horizontal displacements 50 times.

Immediately it can be seen that the differences between the embankment sections are distinct. For instance, widening of the narrowest embankment section, width 5.4 m, has been more than twofold in comparison to the widest embankment section, width 6.8 m, in the same time interval. Correspondingly, when widening of the two embankment sections having a width of 6,0 m at the top of the substructure are compared, it can be observed that the one with side slopes 1:1,5 has been deforming about two times more than the one with side slopes 1:2.

The reference points were observed to move not only in horizontal direction but also in vertical direction. In general they were moving downwards a distance that was of the order of 10 to 20 mm during the first two years. However, because the installed instrumentation did not enable separation of possible on-going consolidation settlement of the soft subgrade layer from the actual embankment deformations in vertical direction, the results are not presented here.

3 MECHANICAL MODELLING OF THE TRACK EMBANKMENT BEHAVIOUR

3.1 *Finite Element Modelling*

Mechanical modelling of the track embankment was made with PLAXIS version 8. PLAXIS is a finite element program that has been developed specially for the analysis of deformation and stability in geotechnical engineering projects. (Plaxis version 8)

PLAXIS contains several different material models. Only the material model used in this study is introduced here. The Hardening-Soil model (HS) is an advanced model for the simulation of soil behaviour. Limiting states of stresses are described by means of the friction angle, φ, the cohesion, c, and the dilatancy angle, ψ. Soil stiffness is described by using three different input stiffnesses: the triaxial loading stiffness, E_{50}, the triaxial unloading stiffness, E_{ur}, and the oedometer loading stiffness, E_{oed}. All these stiffnesses relate to a reference stress, 100 kPa in this study. In HS model all stresses increase with pressure and the yield surface is not fixed in principal stress state, but it can expand due to plastic straining. (Plaxis version 8)

In this study, modelling was made with linear elasticity for subgrade layers and HS model for embankment layers. HS model was chosen for the embankment layers because majority of strains caused by train load are reversible. However, a part of the strain is always permanent. With HS model the stiffness of embankment is more appropriate in both sides of the yield surface i.e. when subjected to deviatoric loading, the soil stiffness decreases simultaneously with the development of irreversible strains. (Plaxis version 8) Linear elasticity was considered to be suitable for the subgrade layers in this study because repeated loading should not induce a marked amount of plastic straining in the subgrade. This assumption was also checked by using Mohr-Coulomb material model for subgrade layers and practically no plastic straining was observed to appear in the calculations.

Due to the nature of the 2D Finite Element Model, the sleepers and train load were modelled as a one meter long part of track. In Finland the normal sleeper spacing is 0.61 m. Consequently, for one meter of track there are 1.64 sleepers. At first, the bending stiffness of a sleeper was calculated with the known concrete type (K64). After that, the sleepers were modelled as a plate element which has the same bending stiffness as the actual sleepers have per one meter of track. Position and width of the distributed load at each end of the virtual sleeper was determined to correspond the typical Finnish track structure having a gauge width of 1524 mm and a 150 mm wide contact area under both rails. The intensity of vertical load per one meter of track was calculated by assuming a combination of two consecutive bogies i.e. a set of four axels, each of them carrying an axel load of 25 tons, at a distance of 1.6 m from each other. By converting the load per meter value thus obtained, 153 kN/m, as a distributed load below the rails an approximation of 510 kN/m^2 was obtained.

The embankment material parameters used in the modelling and summarized in Table 2 have been evaluated based on extensive experience from large-scale repeated loading triaxial testing with similar type of coarse grained materials (Kolisoja 1997) and also verifications made by taking use of actual response measurements made from the track embankment on an earlier instrumentation site (Kolisoja et al. 2000). The selection of subgrade materials parameters has in turn been somewhat more approximate. In addition to rough estimates made based on available ground investigation results consisting mostly of

Swedish weight soundings and shear vane tests, the subgrade stiffness values have been somewhat adjusted to make the modelled values of vertical displacement under the train load more compatible with the actually measured vertical displacements at the monitoring site. The values of Young's modulus actually used in the modelling were 50 000 kN/m^2 for the silty subgarde layer and 100 000 kN/m^2 for the dry crust layer.

Table 1. Observed widening of the embankment sections in millimetres at the Kokemäki monitoring site.

Embankment		Distance from the bottom of the ballast layer (m)	Monitoring period	
Width	Slope		One year	Two years
5.4 m	1:1.5	0.25	29	63
		0.75	30	66
		1.50	34	78
6.0 m	1:1.5	0.25	42	57
		0.75	40	61
		1.50	40	83
6.8 m	1:1.5	0.25	11	26
		0.75	14	31
		1.50	17	39
6.0 m	1:2	0.25	15	21
		0.75	14	35
		1.50	28	50

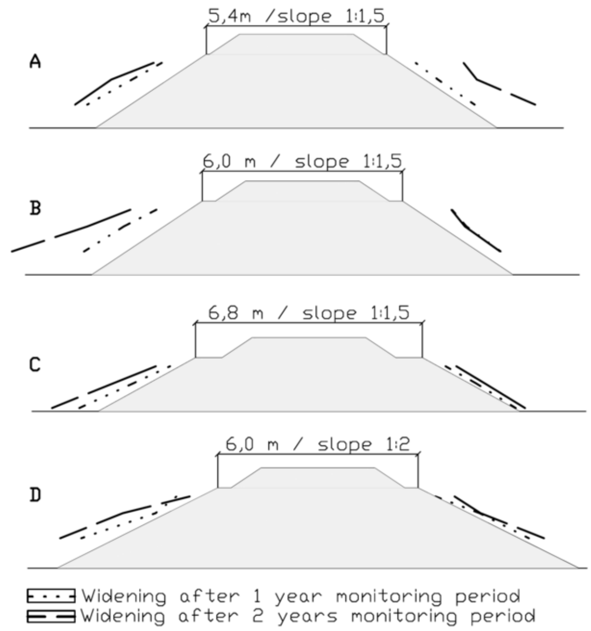

Figure 2. Average widening in each of the embankment sections after one year and after two years exaggerated by 50 times.

3.2 *Analysis of modelling results*

Traditionally the approaches to model the accumulation of permanent deformations in a repeatedly loaded granular material have been aiming to find out a mathematical relation between the accumulated plastic strain and the number of load repetitions. In some of the very early attempts, trials were also made to correlate the plastic strain rate to the respective elastic (i.e. resilient) strain (e.g. Veverka 1979). Linear relation between elastic and plastic strains has, however, since then been shown not to be a valid approach for instance by Sweere (1990).

Table 2. Material parameters used for the ballast layer and the embankment material in PLAXIS modelling.

Parameter		Value	Value	Unit
Material	Identification	Ballast	Embank-ment	-
	Material model	HS	HS	-
	Type	Drained	Drained	-
	γ_{unsat}	20	20	kN/m^3
	γ_{sat}	23	23	kN/m^3
Permeability	k_x	1	1	m/day
	k_y	1	1	m/day
Stiffness	E^{ref}_{50}	150000	75000	kN/m^2
	E^{ref}_{oed}	155200	77610	kN/m^2
	E^{ref}_{ur}	300000	150000	kN/m^2
	Power	0.5	0.5	m
	ν(nu)	0.2	0.2	-
	p^{ref}	100	100	kN/m^2
	K_0^{nc}	0.342	0.342	-
Strength	c_{ref}	20	20	kN/m^2
	Φ	45	45	°
	Ψ	5	5	°
	$c_{increment}$	0	0	kN/m^2/m
	y_{ref}	0	0	m
	R_f	0.9	0.9	-

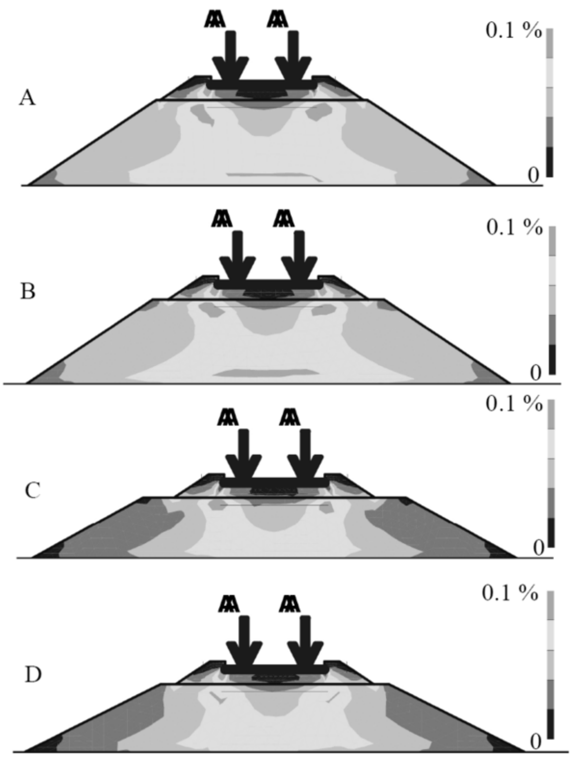

Figure 3. Shear strain distribution in each of the embankment sections modeled using the PLAXIS FEM software.

Later on more fundamental attention has been put on analysing the level of mobilized shear stresses in relation to the shear strength of the material (e.g. Hoff 1999) and following basically the same line of thought new formulations of the so-called shakedown concept has been suggested (Werkmeister 2003).

Some recent results from Heavy Vehicle Simulator (HVS) tests indicate (Korkiala-Tanttu 2008) that the relation between resilient and respective plastic strain rate in an unbound granular material is far from linear, but there seems to be a distinct threshold value below which the accumulation rate of permanent strain is low, while exceeding that resilient threshold strain level means rapidly increasing plastic strain rate. In the case of crushed rock aggregates corresponding typical base course materials in Finnish low volume roads this threshold value has been observed to be of the order of slightly below 0,1 % in terms of vertical strain below the wheel path (Figure 4). Very similar results concerning the resilient strain and plastic axial strain rate in large-scale repeated loading triaxial tests have been obtained in some earlier test series with two different crushed rock aggregates by Kolisoja (2002).

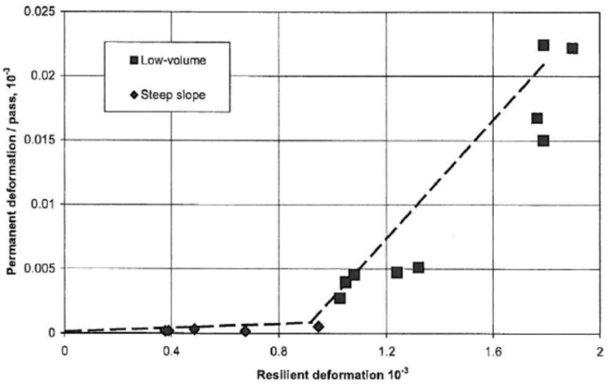

Figure 4. Relation between resilient strain and plastic strain rate in crushed rock base course aggregate loaded using a HVS device (Korkiala-Tanttu 2008).

Even though similar test results are at least not yet available for the actual embankment material of the Kokemäki monitoring site and it is likely that due to the smaller average grain size of the material the threshold strain level may be somewhat lower than that in Figure 4, it is fairly obvious that basically the same type of behaviour could be observed even with it. Therefore, when comparing the recorded amounts of widening of the different embankment sections indicated in Table 1 and Figure 2 to the respective modelled values of shear strain under a heavy train load, a plausible explanation to the observed differences can be given.

In the two narrowest embankment section (sections A and B) the mobilized level of shear strain is throughout the embankment of the order of 0.04 to 0.08 % while in the widest embankment (section C) the field of that high shear strain is not extending to the sides of the embankment. Instead, there are large volumes of stabilizing material towards the side slopes of the embankment in which the shear strain level is in between 0.02 to 0.04 % i.e. obviously well below the critical threshold value. The same remark holds also true for the embankment section D whose width at the top of the subgrade is the same as that of section B, 6.0 metres, but in which the side slope is 1:2 in stead of 1:1.5.

Once again it must be pointed out that the actual embankment materials are different from those in Figure 4 and the above analysis is presented in terms of shear strain and not in terms of axial strain as the available test results, but still the results are qualitatively very coherent with each other.

4 CONCLUSIONS

Long-term widening measurements of four full-scale track embankment sections have been performed on a monitoring site located at Kokemäki in the Western part of Finland. The obtained results indicate clearly that both the embankment width and slope angle have a marked effect on the accumulation rate of permanent deformations in a repeatedly loaded track embankment. In the narrowest embankment sections widening was observed to be more than two times faster than in those which were either wider or had less steep slopes.

The experimentally observed differences in the embankment deformation rate could be given a credible explanation by analysing the Finite Element Modelled behaviour of the different embankment sections based on the mobilized levels of shear strain in each embankment type.

Based on some further modelling exercises not presented in detail here, it can be assumed that under identical volumes of repeated loading induced by train traffic a similar railway track embankment located on a soft soil area can be assumed to be more susceptible to permanent deformations and subsequent widening than an embankment located on stiff subgrade. If this assumption can be validated in further studies to be performed in the near future, it is going to have a big practical implication on the requirements that are set in the respective design codes concerning the required embankment width of railway tracks.

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