A New Method to Determine the Desired Minimum Railway Embankment Dimensions

A. Kalliainen & P. Kolisoja
Laboratory of Earth and Foundation Engineering, Tampere University of Technology, Tampere, Finland

ABSTRACT: The dimensions of a railway embankment have a significant impact on the investment costs of a railway track. Due to the cold climate and the consequent harmful effects of seasonal frost in northern regions, embankments are typically constructed of relatively thick structural layers. The embankments have also traditionally had fairly steep slopes and narrow widths in order to cut construction costs. Introduction of higher allowable axle loads and traffic speeds is, however, exposing the embankment structures to a continuously increasing intensity of repeated loading which respectively increases the rate of permanent deformations taking place in the embankment structure. The problem described above has been studied at the Laboratory of Earth and Foundation Structures of Tampere University of Technology. The study is divided into four main parts: monitoring of full-scale test embankment sections located in the southwestern part of Finland, loading of laboratory scale instrumented test embankments, FEM-modeling and evaluation of the long-term deformation behaviour of an actual railway track line based on laser scanner measurements. This paper focusses on introducing the new method for determining the required embankment dimensions and describing a case study of the first practical application of the new method in Finland. In addition, the paper briefly discusses the most significant findings of the project, but a detailed analysis of the test results is presented elsewhere. The new method for assessing the required minimum embankment width is based on the amount of recoverable vertical displacement of the railway track measured from sleepers under a moving train load. So far, the new method has been tested in a renovation project between the cities of Tampere and Kokemäki where the suggested limit values have been observed to be realistic.

KEY WORDS: Railway track, embankment, width, deformation behaviour, permanent deformation

1 INTRODUCTION

Railway subballast layers consist of coarse-grained unbound granular materials. Such materials differ from most natural soils in their physical characteristics and response to applied cyclic loading. Granular materials do not have inherent strength as a continuum and cannot withstand tension. However, they can support a reasonable amount of shear stresses. Gravity and applied external forces create intergranular contact pressures and frictional forces that are able to resist the relative movement of particles. Granular interlocking also contributes to this type of strength. When such materials are compacted well, they have the ability to carry loads and distribute them onto lower layers or the subgrade. (Brecciaroli & Kolisoja, 2006)

The deformation resistance of an unbound granular material depends on the applied stresses. Under compressive stresses the behaviour of unbound materials is highly complex because of the existence of both resilient and permanent strains even at small levels of stress. Resilient strain response is important for the load-carrying capacity of the embankment whereas permanent strain response characterises the long-term deformation behaviour of the embankment. (Brecciaroli & Kolisoja, 2006)

A railway embankment is exposed to a large number of loading cycles during its service life. The permanent deformation due to a loading cycle is normally a fraction of the total deformation produced by each loading cycle. The gradual accumulation of a large number of such small plastic deformation increments can lead to excessive permanent deformation and even failure. For this reason understanding of the effect of the embankment dimensions in deformation behaviour under repeated loading is essential. (Kalliainen et. al. 2010)

In northern regions the total thickness of the structural layers of railway embankments is primarily determined by the design against the harmful effects of seasonal frost. Since practically no frost heave can be allowed to occur under railway tracks carrying normal speed passenger traffic, the embankment must typically be built up to a thickness of two or even two and a half metres. In the meantime, the embankments have traditionally been built with relatively narrow widths and steep slopes. For instance, the normal slope ratio in Finland has been 1:1.5 while the width of the embankment on top of the subballast has varied between 5.4 and 6.8 metres on straight track line depending on the highest allowable axle load and traffic speed. However, the introduction of higher allowable axle loads and traffic speeds is subjecting embankment structures to a continuously increasing intensity of repeated loading which is also increasing the rate of permanent deformations accumulating into the embankment structure. In other words, the embankment is widening as it deforms and the respective track movements require more frequent maintenance actions.

The most straightforward measures for increasing the internal stability of a railway embankment are to make the embankment wider and/or to reduce the slope steepness of the embankment. However, both of these actions translate into a 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 embankment construction or renovation. Therefore, if we consider both the construction costs on one hand and maintenance costs of the track on the other hand, optimisation of the embankment dimensions and shape have a major impact on the life cycle costs of a railway line.

A research project at the Laboratory of Earth and Foundation Structures at Tampere University of Technology studied the above-mentioned problem based on model scale test structures having different embankment widths and slope angles using a loading system consisting of five connected hydraulic actuators operating consecutively so as to simulate the loading effect of a moving train. In addition, the problem has been studied by in-situ monitoring of a full-scale railway track embankment with sections of different widths and slope angles. The embankment sections used in this project are illustrated in Table 1. The long-term deformations of the embankment were monitored for about three years and the short-term responses of the embankment structure were measured while trains passed over the monitored sections. The behaviour of both model-scale test embankments and full-size railway track sections were also modelled by the Finite Element Method using PLAXIS software. Several different types of models were created using both two and three dimensional models.

Table1. The embankment types investigated in the project.

Embankment type	Width (m)	Slope angle ratio
Embankment A	5.4	1:1.5
Embankment B	6.0	1:1.5
Embankment C	6.8	1:1.5
Embankment D	6.0	1:2

2 SIGNIFICANT FINDINGS OF THE PROJECT

The two most significant findings of the project were the essential role of subgrade stiffness in the deformation behaviour of a railway embankment and the observation that recoverable vertical displacement does not appear to vary essentially as a function of embankment dimensions.

Full-scale monitoring of the accumulation of permanent deformations in a railway track embankment has been performed at a monitoring site along the railway line connecting the towns of Kokemäki and Rauma in Western Finland between 2004 and 2007. The test site consisted of four consecutive embankment sections, which had been carefully shaped to correspond to the dimensions presented in Table1. The observed widening of each of the embankment sections about one and two years after installation of the reference points is indicated in Figure 1, which exaggerates the average widening 50 times.

It can be seen immediately that the differences between the embankment sections are distinct. For instance, the narrowest embankment section (width 5.4 m) has widened more than twice as much the widest embankment section (width 6.8 m) in the same time interval. Correspondingly, comparison of the widening of the two embankment sections 6.0 m wide at the top of the substructure reveals that the one with side slopes of 1:1.5 deformed about twice as much as the one with side slopes of 1:2.

The recoverable amount of vertical displacement under a moving train load was also measured at the full-scale test site. The measurements were performed and calculations done as in the new method presented in Chapter 3 with the exception of the placement of the displacement sensors. At the monitoring site, sensors were placed in five consecutive sleepers. The results illustrated in Table 2 clearly indicate that resilient behaviour does not explain the differences in the accumulated rate of long-term widening of the track.

Table2: Measured recoverable vertical sleeper displacements of different test sections under a moving train load at Kokemäki test site.

Embankment type	Resilient vertical sleeper displacement under moving train load (mm)
A	0.92
B	1.02
C	0.90
D	0.98

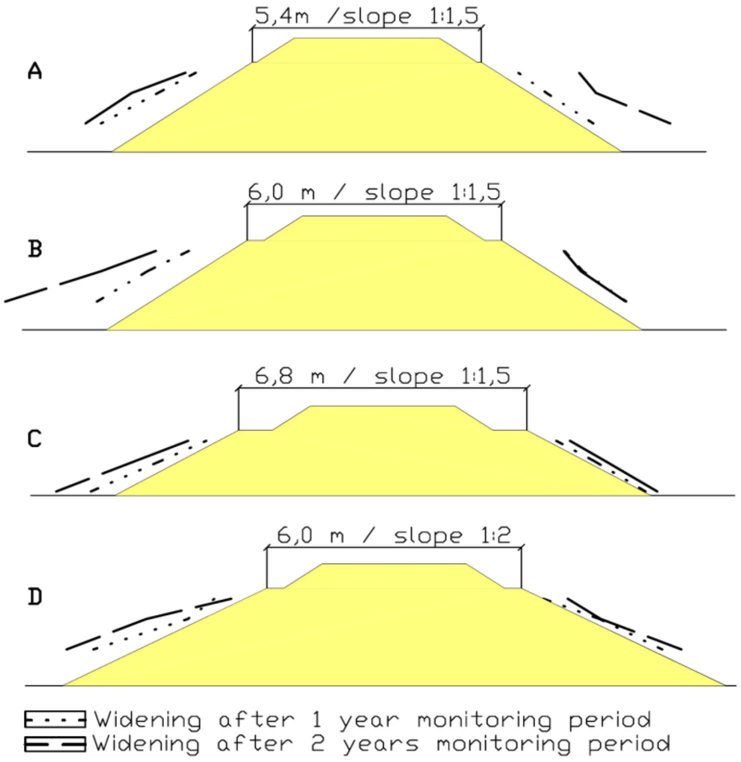

Figure1: Average widening of the monitored embankment sections after one and two years exaggerated 50 times. (Kolisoja & Kalliainen 2009)

After receiving encouraging results concerning the effects of the embankment dimensions on the long-term deformation behaviour of a railway track embankment, a series of instrumented model-scale test embankments was built in a laboratory. As in the case of the results from the full-scale test site, embankment dimensions also had a marked effect on the long-term deformation behaviour of test embankments in flexible subgrade conditions. When the embankments were placed on a flexible subgrade consisting of a 100 mm polystyrene mat between the constructed embankment and a bare concrete floor, the observed widening of the embankment was significantly greater than in tests performed on a bare concrete floor. The results clearly indicate that under stiff subgrade conditions the embankment does not face a notable amount of permanent deformation as shown in Figure 2. Meantime, on a more flexible subgrade the amount of permanent deformation that accumulates into the embankment structure is remarkable, and appropriate embankment dimensions can reduce subsequent widening considerably. (Kalliainen & Kolisoja 2011)

The resilient deformation behaviour of the model-scale test structures was observed to be quite similar to the measured behaviour of the full-scale railway track under repeated loading. As illustrated by Figure 3, the recoverable displacements of the track were clearly uncorrelated with the embankment dimensions until shear failure of the embankment. (Kalliainen & Kolisoja 2011)

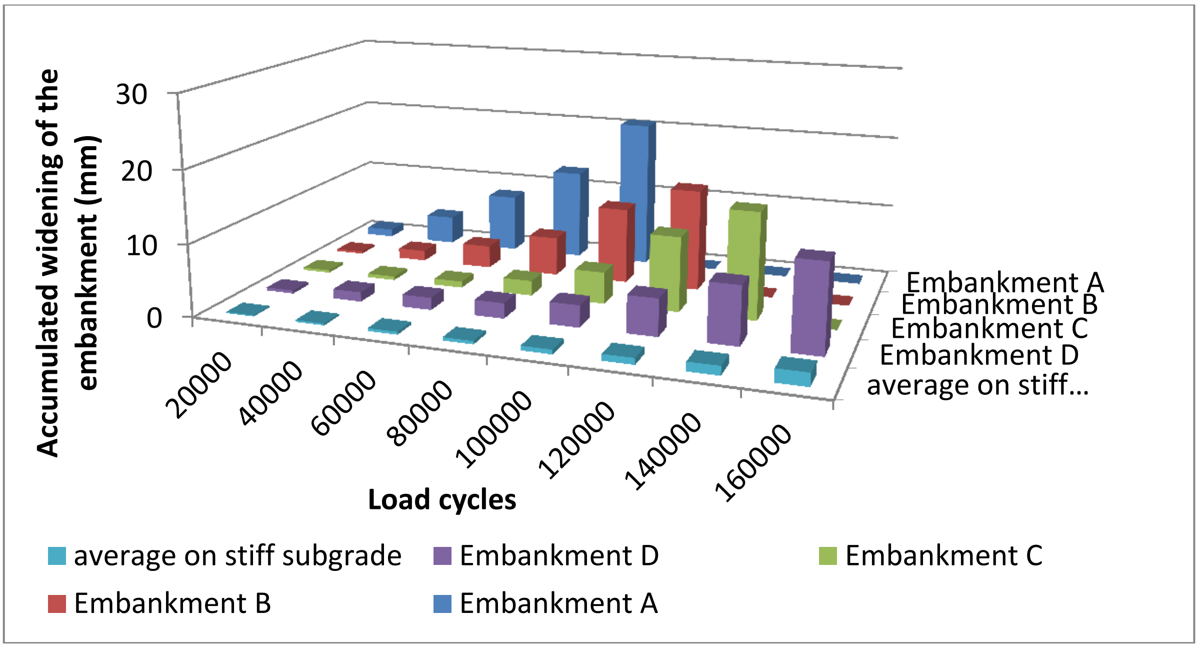

Figure2: Accumulated embankment widening measured on top of the embankment slope in model-scale test series. Embankments A, B, C and D rested on top of a 100 mm thick polystyrene mat. The loading level of the tested embankments was increased after each 20,000 cycles. The loading levels corresponded to those of Figure3. Modified after (Kalliainen & Kolisoja 2011)

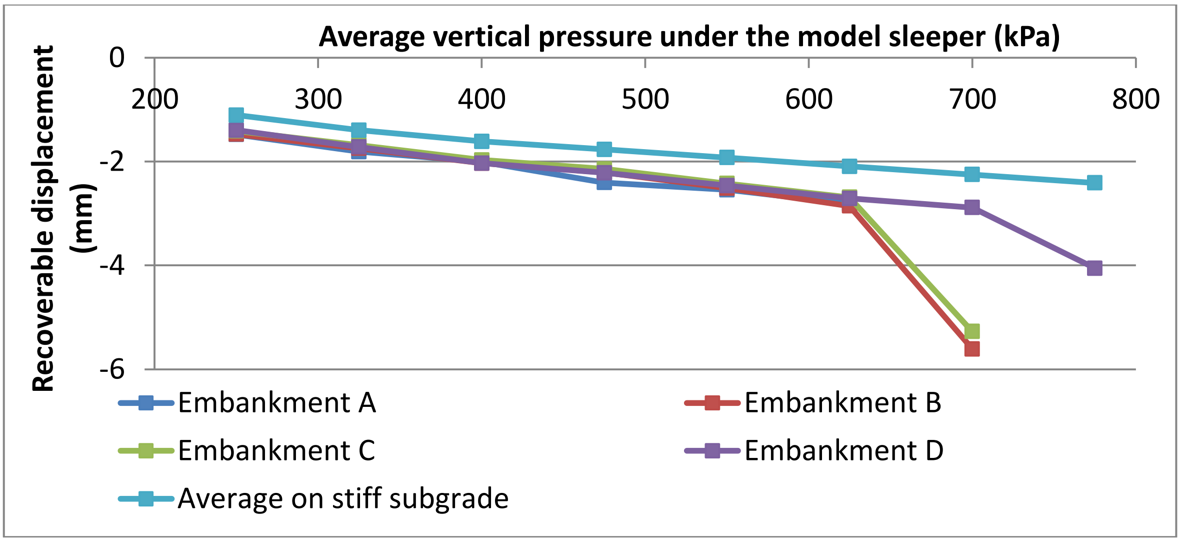

Figure3: Measured recoverable vertical displacement of the model-scale test structures. Modified after (Kalliainen & Kolisoja 2011)

The results of several measurements were also compared to the mechanical model created with PLAXIS 3D software. The model was adjusted to the repeated loading situation and was verified against actual response measurements on the track embankment at an earlier instrumentation site (Kolisoja et.al. 2000). The model and parameters are presented in detail elsewhere (See e.g. Kalliainen 2012). Table 3 shows the results for vertical displacement of the embankment structure at different stiffnesses of the subgrade. The subgrade of the model consisted of two layers; a one-metre dry crust layer on top of a nine-metre subgrade layer. The calculated values strongly suggest that the results obtained from the full- and model-scale tests appear to be reliable.

The most significant output from the modelling was the observation of mobilising level of shear strain into the embankment structure as an explanatory factor of the long-term behaviour of the embankment. Figures 4 and 5 illustrate the simulated shear strain levels in a soft soil area and under stiff subgrade conditions under a single sleeper and axle load. They clearly indicate that in flexible subgrade areas expanded embankment dimensions support the embankment structure and decrease the amount of mobilised shear strain levels towards the embankment slopes whereas under stiff subgrade conditions that additional support does not seem to decrease the mobilisation of shear strain into the embankment structure.

Table3: Modelled vertical compressions (mm) of the railway track structure under 25 tonnes axle load. The values were calculated by subtracting the vertical displacement at the top of the subgrade from the vertical displacement determined under the sleeper.

Embankment type	Subgrade / Dry crust stiffness (MPa)					
	10/50	50	10/100	40/100	120	480
A	0.44	0.58	0.44	0.57	0.56	0.65
B	0.44	0.58	0.44	0.54	0.55	0.64
C	0.41	0.50	0.40	0.49	0.55	0.63
D	0.43	0.56	0.43	0.55	0.55	0.63

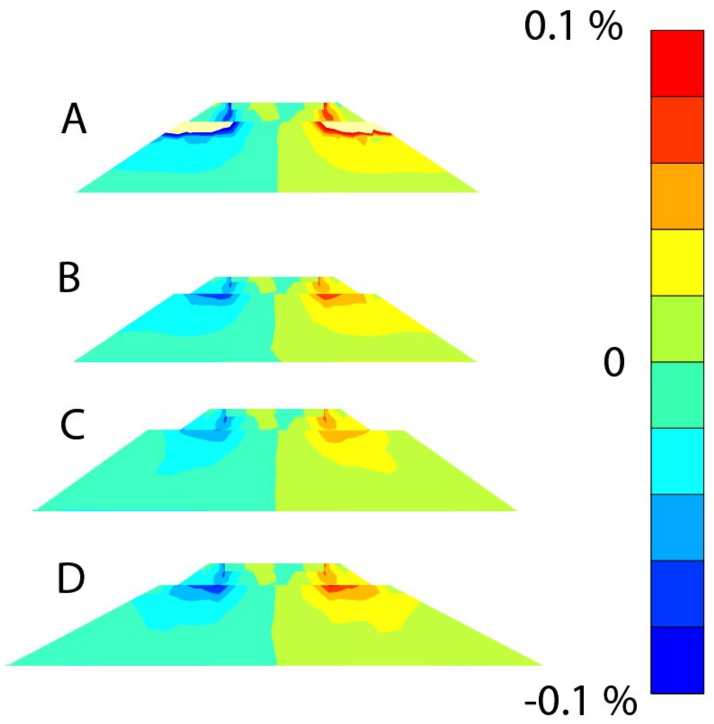

Figure4: Levels of shear strain mobilising into the embankment structure in cross-sections of 3D Finite element simulations under soft subgrade conditions.

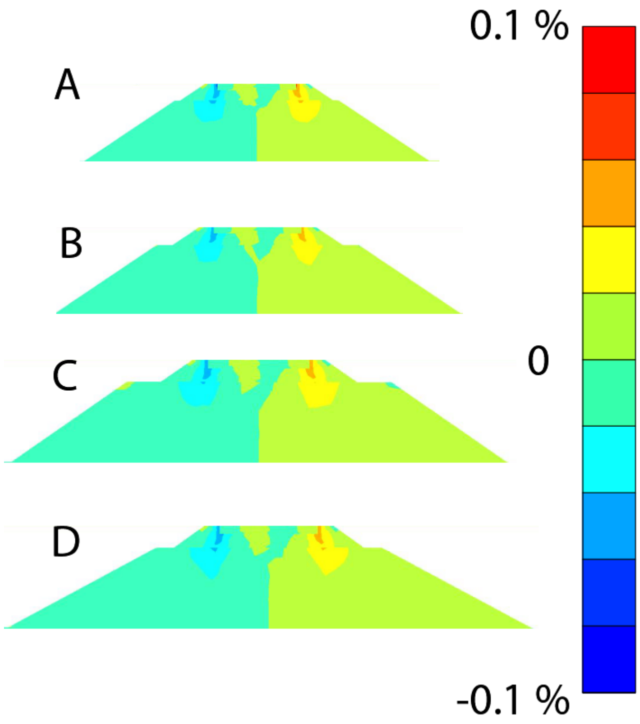

Figure5: Levels of shear strain mobilising into the embankment structure in cross-sections of 3D Finite element simulations under stiff subgrade conditions.

With the help of 3D modelling it was possible to verify the importance of subgrade stiffness and the fact that the vertical deformation of the railway track structure itself was almost independent of the embankment dimensions.

3 A NEW METHOD TO DETERMINE THE REQUIRED MINIMUM WIDTH OF A RAILWAY EMBANKMENT

The present method for defining the required embankment width in Finland is based solely on desired maximum axle load and traffic speed. However, the observations made during the project strongly suggest that the long-term permanent deformation of an embankment is highly dependent on subgrade stiffness. A new method has been suggested for converting these observations into practice. The new method was developed for the axle load of 25 tonnes on existing railway network.

The new method is based on the measured recoverable displacement of the embankment under a moving train load. The type of loading is set to the most common locomotive type in Finland which has an axle load of about 22 tonnes. The recoverable deformation of the embankment is measured at the centre of sleeper and the measurement procedure is fixed as described in the following paragraphs.

The railway track is first divided into sections with similar subgrade conditions. One set of measurements is performed on each section.

Then, the recoverable vertical displacement of each section is measured from the middle of five sleepers. Each measurement section includes 21 sleepers. Five of the sleepers are instrumented, each followed by four sleepers without instrumentation (Figure 6) to decrease the scatter of track stiffness resulting from local variations in the condition of the ballast layer. The recoverable vertical displacement is measured at the centre of a sleeper in order to minimise the variance in measured results due to changes in the support given by the ballast layer to a single sleeper during the service life.

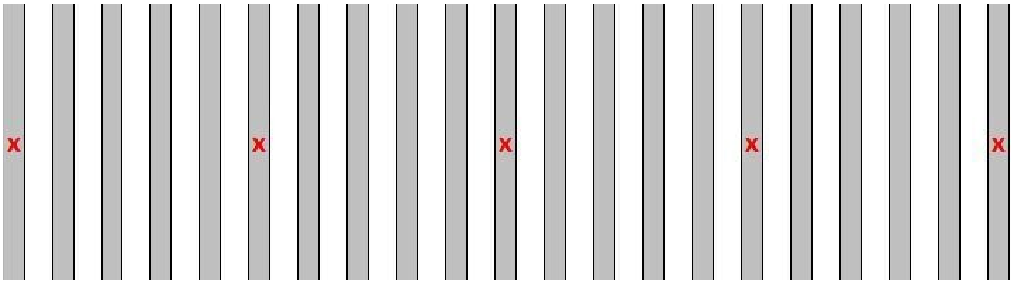

Figure6: Positioning of measuring devices across a measurement section.

The final step of the procedure involves calculating the average recoverable vertical displacement of each section excluding the highest and lowest measured values from the calculation. The calculated average value determines the required embankment width as shown in Figure 7. The required minimum width of the embankment thus determined is applied as such to the straight section of the railway track and to curved sections if the radius of the curve is larger than 3000 metres. When the radius of the curve is smaller than 3000 metres, it is recommended that the width of the outside curve is increased by 0.4 metres.

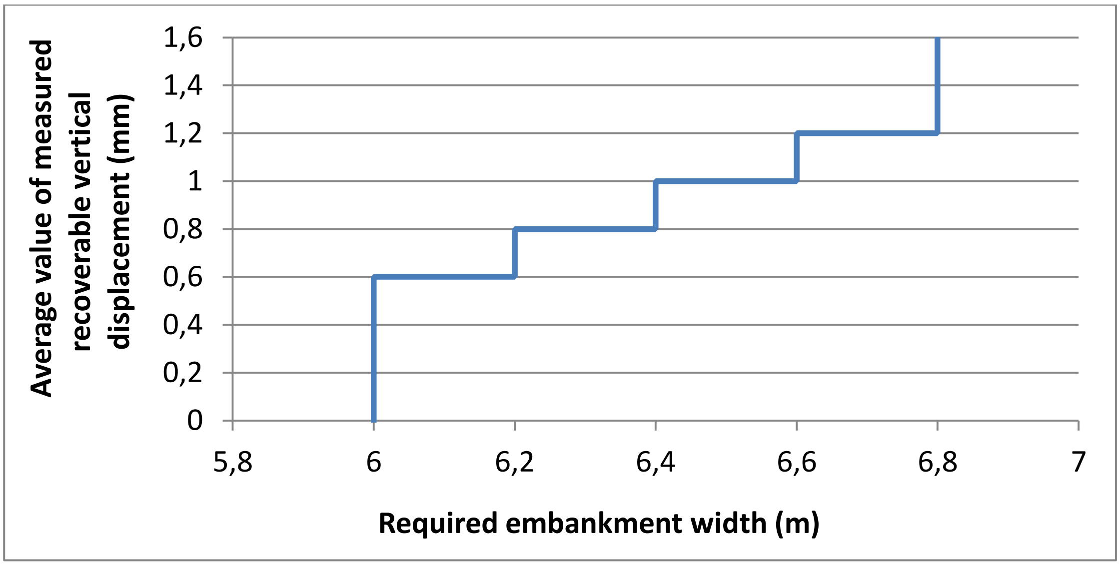

Figure7: Required embankment width as a function of measured average recoverable vertical displacement according to the new guideline. (Kalliainen 2012)

4 A CASE STUDY ON THE USE OF THE NEW GUIDELINES

The new method was tested for the first time in a track renovation project on the rail line linking the cities of Tampere and Kokemäki in Western Finland. The line under renovation is about 84 km long. A total of 86 sections were measured to determine the required embankment width.

As recoverable vertical deformation was measured, the current embankment width was also checked at most sections to verify the new method. The embankment width of some sections was not checked since the line is partly double track. The current embankment width of 74 sections was greater than the required minimum according to the new method. Table 4 shows the gathered data classified by required embankment widths. Based on these values, the new method appears to have a reasonable range of limiting values.

Table4: The total number of measured sections divided into required embankment width fragments at the first implementation project of the new method. (Kalliainen 2012)

Recoverable vertical displacement of the track (mm)	Required embankment width (m)	Number of sections
< 0.6	6	9
0.6 to 0.8	6.2	26
0.8 to 10.	6.4	26
1.0 to 1.2	6.6	10
>1.2	6.8	15

Yet, the new method has some disadvantages. Almost 20% of the measured sections had a large (> 0.5 mm) standard deviation in measured displacement values. That was most likely due to the nature of the ballasted track where the condition of the track components, particularly that of the ballast layer, varies a lot especially when the track is at the end of its life cycle. On the other hand, in over 40% of the measured sections standard deviation was relatively small (< 0.15 mm). This indicates that the method is relatively reliable as long as the condition of the instrumented sleepers is investigated before the measurement is performed. In most cases, a large standard deviation occurred when the ballast layer under instrumented sleepers was heavily fouled and the alignment of the sleepers was not optimal. Since the new method only describes the performance of track correctly at one point at a time, the limit values were set somewhat conservatively. (Kalliainen 2012)

CONCLUSIONS

Based on the results obtained from the full-scale test sections and model-scale test series, it is clear that the stiffness of the subgrade has a significant role in the deformation behaviour of the railway embankment under repeated loading. In stiff subgrade conditions the amount of permanent deformation accumulating in the embankment structure appears relatively small whereas in more flexible subgrade conditions that amount can vary widely depending on the dimensions of the embankment. The level of recoverable vertical deformation under a moving train load obviously also correlates with subgrade stiffness. However, embankment dimensions do not seem to have a marked effect on the amount of recoverable vertical deformation of the embankment.

Finite Element Modelling allowed verifying the results of full- and model-scale tests. The experimentally observed differences in embankment deformation rate can be explained plausibly by analysing the modelled behaviour of the different embankment sections based on the mobilised levels of shear strain in each embankment type.

When a railway embankment is in flexible subgrade conditions, most of the recoverable vertical displacement of the embankment results from deflection of the subgrade. On the other hand, deflection within the railway track structure itself is nearly constant regardless of the prevailing subgrade conditions. According to the new guideline created, recoverable vertical displacement of the track is measured, and a reasonably accurate assumption regarding the subgrade stiffness can be made based on the achieved value. The first implementation of the project findings appeared promising. The major part of the results obtained were inside the proposed value range. The new guideline will allow determining the problematic sections of a railway line and direct resources into the appropriate sections during the renovation of the existing rail lines.

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