# Instrumentation and mechanical modeling of a full-scale railway embankment

## La instrumentation et le modèle de la conportement mécanique du remblai de la voie ferrée

P.Kolisoja – *Professor, Tampere University of Technology, Finland*
E.Mäkelä – *Researcher, Tampere University of Technology, Finland*

ABSTRACT: Full-scale instrumentation of a railway embankment was performed on the railway line between Koria and Kouvola in South-Eastern Finland in the summer of 1999. The instrumentation and related modeling of the mechanical behavior of the embankment constituted a part of Finnish Rail Administration research project which is aiming at the introduction of 250 kN and 300 kN axle loads to some parts of the Finnish railway network. The results of the work indicate that a fairly simple multi-layer linear elastic model can be used to describe the vertical stiffness of track structures. A prerequisite for a successful modeling is, however, that the material properties of the layer materials and the subgrade are determined to correspond the appropriate stress and strain levels.

RÉSUMÉ: La instrumentation du remblai de la voie ferrée a fait dans l'intervalle des deux contrées en Finlande sud-est: Koria et Kouvola. La instrumentation et le modèle de la conportement mécanique du remblai est une partie de la programme scientifique de la Administration de Réseau Ferré Finlandaise.

## 1 INTRODUCTION

Due to the increasing amount of congestion in road traffic and the increasing awareness of the detrimental effects of the vehicular traffic induced pollution to the environment it is quite obvious that rail traffic will play a more and more important role in transportation of both passengers and freight in the future. However, to be competitive the rail traffic must provide shorter traveling times i.e., higher travelling speeds and more efficiency in freight transportation by means of increasing axle loads. Both of these trends set high requirements to the quality of track structures which should of course be able to be maintained with as low life cycle costs as possible.

In 1998 the Finnish Rail Administration (RHK) initiated a research project which aimed at investigating the possibilities for introduction of a maximum allowable axle load of 250 kN into use at least on some parts of the Finnish railway network. Meantime, the prerequisites for the introduction of a maximum allowable axle load of 300 kN at some later time were also studied. A short description of a full-scale instrumentation of a railway embankment performed as a part of that project is presented in this paper. In more detail the performed measurements and related analysis has been reported elsewere by Kolisoja et al. (2000).

## 2 INSTRUMENTATION

### 2.1 *Instrumentation site*

The instrumentation site was located some 150 km North-East from Helsinki on a two track railway line between the towns of Koria and Kouvola. On the instrumentation site the track was straight and the embankment was about two meters high. The subsoil underneath the embankment consisted soft clay layers up to a depth of about 22 meters where a stiff layer of moraine was encountered.

Due to the deep layers of soft clay under the embankment reasonably large settlements have obviously taken place at the instrumentation site during the more than one hundred years since the first embankment had been built. Compensation of these settlements with additional ballast material had resulted in an increase in the thickness of the ballast layer up to more than one meter. Since the embankment had altogether been built in a number of stages the composition of the embankment was not strictly according to any existing regulations. Consequently, just below the ballast layer relatively fine grained sandy material was encountered and it was underlyed by a coarser gravel that may once have been the actual embankment. A schematic picture of the embankment is shown in Figure 1 and the grain size distributions of the various layer materials are presented in Figure 2.

### 2.2 *Installed instruments*

The instrumentation was installed at three different levels inside the embankment. The installation depths were 0.5, 1.0 and 1.8 meters below the base of the sleeper. The instrumentation included a total of 16 strain transducers, ten of which were recording vertical strains and six lateral strains, and four pressure cells to monitor the vertical earth pressure. In addition to these, vertical and horizontal force components acting on the rails and the displacements of a sleeper were also recorded. In Table 1 a summary of the instruments installed inside the embankment is presented.

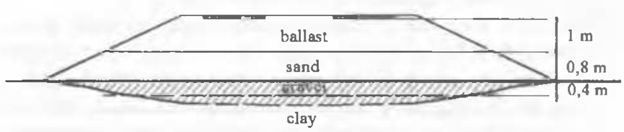


Figure 1. Schematic cross section of the embankment.

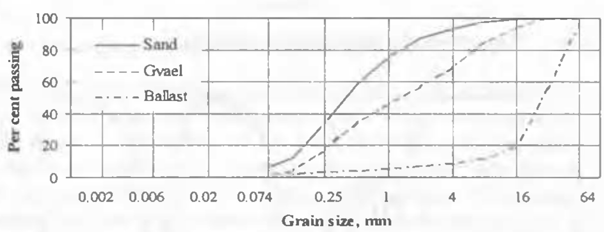


Figure 2. Grain size distributions of the layer materials.

Table 1. Summary of the installed instruments.

| Installation depth, m | Number of strain transducers | | Number of pressure cells |
|---|---|---|---|
| | Vertical | Lateral | |
| 0.5 | 4 | 2 | 2 |
| 1.0 | 4 | 4 | 2 |
| 1.8 | 2 | - | - |

Table 2. Summary of the traffic running over the instrumentation site.

| Type of train | Number of crossings |
|---|---|
| Test train with four axles of 250 kN | 10 |
| Tank train | 10 |
| Other type of freight train | 20 |
| Express train | 30 |
| Other passenger train | 5 |
| Maintenance equipment | 1 |

The strain transducers were manufactured at the Tampere University of Technology. In principle they were of a similar type to those developed in the Danish Road Institute and described in more detail by Macdonald & Baltzer (1997). Instead of LVDTs, however, capacitive proximity transducers were used in measuring the actual displacement between the two circular plates that were located at a distance of 100 mm from each other.

Correspondingly, in earth pressure measurements pressure cells manufactured at the University of Nottingham in England were used (Dawson & Little 1997).

## 3 MEASUREMENTS

### 3.1 *Performance of the measurements*

The actual measurements on the instrumentation site were performed in July 1999. The measurement period lasted for about 44 hours during which time the instrumentation was monitored under all of the passing-by normal train traffic. In addition, a special train with four axle loads of exactly 250 kN passed over the instrumentation site ten times at velocities from 40 to 100 km per hour. A summary of the train traffic during the measurement period is presented in Table 2.

### 3.2 *Measurement results*

As an example of the obtained measurement results the recorded values of vertical wheel loads, sleeper displacements, vertical compressive strains and vertical earth pressures at a depth of 1.0 m below the sleeper while the test train was crossing over the instrumentation site at a velocity of 40 km per hour have been presented in Figures 3-6, respectively.

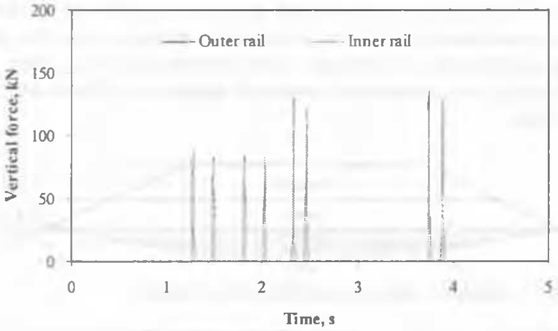


Figure 3. Vertical wheel loads under the test train.

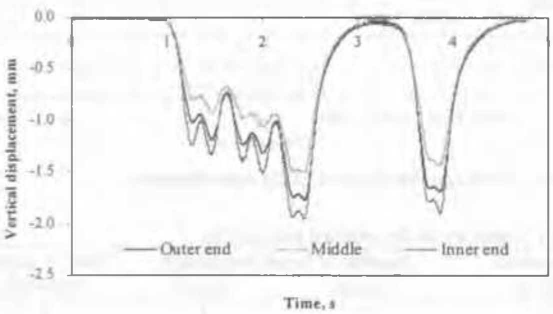


Figure 4. Sleeper displacements under the test train.

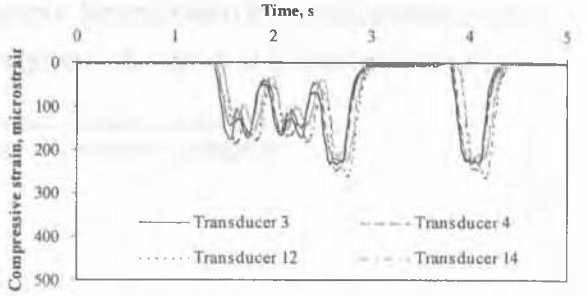


Figure 5. Vertical compressive strains at the 1.0 m level.

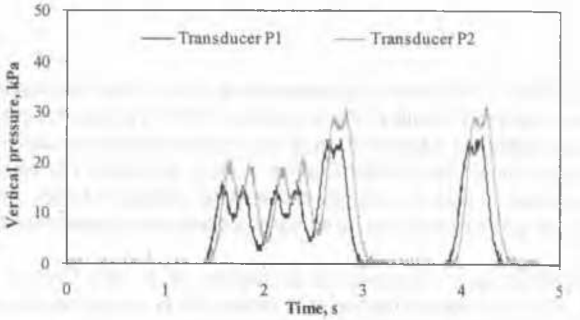


Figure 6. Vertical earth pressures at the 1.0 m level.

As Figures 3-6 indicate the measurements succeeded technically fine and reasonable results were obtained even from the ballast layer (Fig. 8) even thou beforehand it was considered to be too difficult a material for any instrumentation to give meaningful results.

## 4 MODELING

### 4.1 *Material parameters*

Material parameters for modeling the mechanical behavior of the embankment structure were determined at the Geotechnical Laboratory of the Tampere University of Technology. In the case of embankment materials the applied test method was large scale, test specimen diameter 300 mm, cyclic loading triaxial test while the stiffness of the subgrade clay was determined using resonant column and so called bender element measurements. The testing equipment and techniques which were used in the determinations have been described earlier in more detail e.g., by Kolisoja (1997) and Souto et al. (1994).

According to the test results the stiffness of the subgrade clay at shear strain levels lower than $10^{-4}$ varied in terms of shear modulus depending on the stress level from 15 to 25 MPa in the upper four meters of the clay layer and from 8 to 20 MPa in the softer layer beneath. Correspondingly, the determined parameters of the kθ model of Equation 1 (Brown & Pell 1967) for the embankment materials were as shown in Table 3.

$$M_r = k_1\theta_0\left(\frac{\theta}{\theta_0}\right)^{k_2} \quad (1)$$

where $M_r$ = resilient modulus; $k_1$=modulus number; $k_2$=stress exponent; $\theta$=sum of the principal stresses and $\theta_0$=reference stress, 100 kPa.

Table 3. Parameters of Equation 1 for the embankment materials.

| Layer material | Material parameter | |
|---|---|---|
| | $k_1$ | $k_2$ |
| Ballast (screened) | 2000 | 0.50 |
| Ballast (unscreened) | 1750 | 0.50 |
| Sand | 1635 | 0.38 |
| Gravel | 2265 | 0.50 |

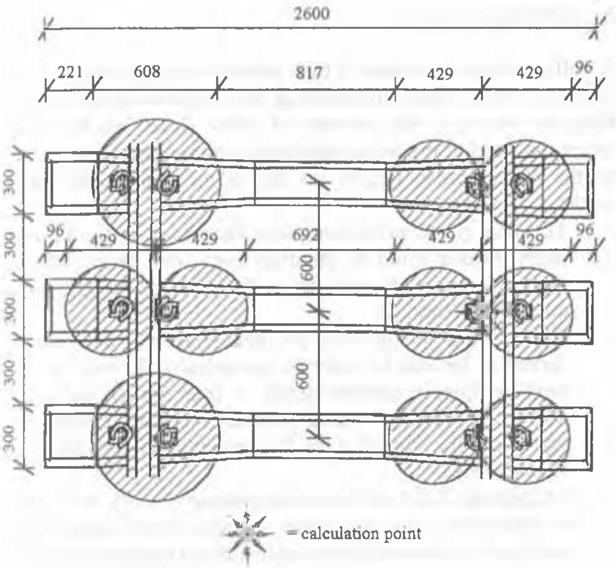


Figure 7. Load configuration in the calculation model.

## 4.2 *Modeling approach*

Vertical stiffness of the embankment structure was modeled using a multi-layer linear elastic modeling approach. The calculations were made with the aid of computer program BISAR-PC provided by the oil company Shell (1995). The program assumes the layers to be infinite in the horizontal direction and each of them to have a constant value of stiffness. In order to improve accuracy of the calculations the physical layers were divided into sublayers with thicknesses not exceeding 0.4 m.

Due to the fact that the program didn't support direct use of the non-liner material model of Equation 1, an iterative procedure was applied in the calculation of the stresses and strains of the embankment structure. During the first iteration a reasonable estimate for the value of resilient modulus of each embankment layer was made and the stresses at different depths inside the embankment were solved. Based on the stress levels thus obtained new estimates for the modulus values of each calculation layer were made using Equation 1 and the stresses and strains of the structure were solved again. This procedure was repeated until the changes in the obtained modulus values decreased marginal. Normally it took only about three iterations.

Since the available computer program had its origin in calculation applications related to highway structures, the input of loads into the multi-layer model was not straightforward either. In BISAR-PC the loads are assumed to be evenly distributed over areas which are circular in shape. In the meantime, the maximum number of simultaneous loads is ten.

As suggested by Raymond (1985) the axle load was assumed to be divided over three successive sleepers in such a manner that when the axle is just above the centre sleeper, 50% of the total load is transmitted to the underlying ballast layer via that sleeper. In the meantime, both of the neighboring sleepers transmit 25% of the total load. The vertical line on which the observation points in the calculation procedure were located was then placed under the cross section point of the central line of the middle sleeper and one of the rails (Fig. 7). Further, the effective contact area of each of the sleeper end was replaced by either one or two circular contact areas and the contact pressure was set to correspond the correct value of vertical force resultant at each sleeper end. Consequently, an equivalent loading arrangement shown in Figure 7 was obtained.

## 4.3 *Embankment behavior under 250 kN axle load*

The distribution of vertical compressive strains obtained as a result of calculations performed according to the principles presented in section 4.2 and using the material properties determined in the laboratory as explained in section 4.1 is shown in Figure 8. The same figure also presents the measured values of compressive strain at the three instrumentation levels while the embankment was traversed by a 250 kN axle of the test train.

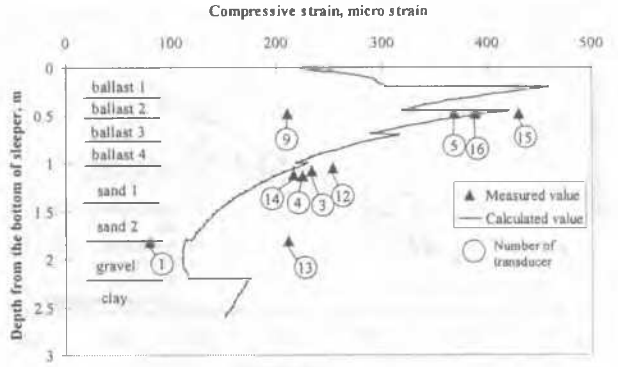


Figure 8. Calculated and measured distribution of compressive strains caused by a passage of a 250 kN axle load.

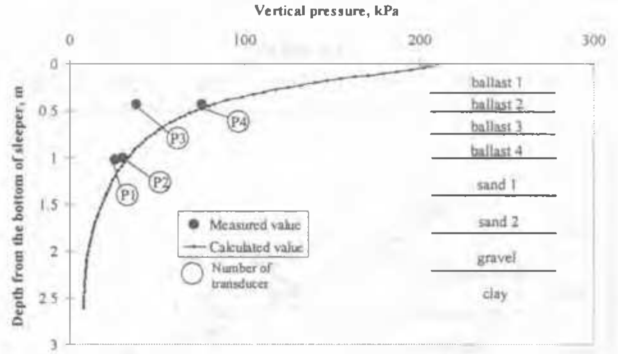


Figure 9. Calculated and measured distribution of vertical pressure caused by the passage of a 250 kN axle load.

As can be seen from Figure 8 the modeled behavior corresponds quite well to the measurement results. The only major exceptions are one of the strain transducers installed inside of the ballast layer and one of the transducers at the lower installation level. A fairly obvious reason for the first mentioned exception is the very coarse grained nature of the material, but in the later case the reason is supposed to be either a fault in the transducer itself or a mistake in the installation of the transducer.

Correspondingly, the calculated and measured distribution of vertical pressure as a function of depth is shown in Figure 9. The correspondence of the modeled and measured values is again observed to be very satisfactory excluding transducer P3 which was located in the middle of the very coarse grained ballast material. In fact, the maximum grain size of the material was in this case about the same as the diameter of the pressure cell, because of which fairly scattered results are something to be expected.

## 4.4 *Embankment behavior as a function of axle load*

Since the main purpose of the project was to investigate the effect of axle load on stresses and strains which are prevailing in the various components of the track structure and the embankment it is interesting to compare the calculated distribution of stresses and strains as a function of axle load. Regarding the vertical pressure at a depth of 0.5 m below the sleeper the comparison is made in Figure 10 in which the values recorded with pressure cell number P4 are compared to those calculated using the multi-layer linear elastic approach explained above. The measurement results of Figure 10 include an average value of the four axle crossings of the test train, a tank train with fairly large variation of different axle loads and a crossing of a maintenance equipment with four exceptionally light axles.

Correspondingly, in Figure 11 the calculated values of verti-

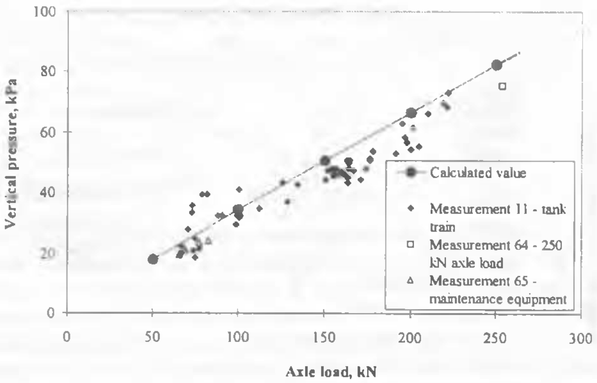


Figure 10. Comparison of the measured and calculated vertical pressures 0.5 m below the sleeper as a function of axle load.

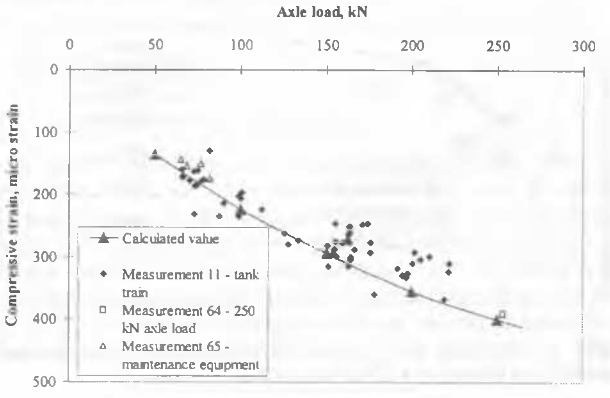


Figure 11. Comparison of the measured and calculated vertical strains 0.5 m below the sleeper as a function of axle load.

cal compressive strain at the same depth are compared to those recorded with strain transducer number 16. The comparison is made under the same trains as in Figure 10.

As can be observed in Figures 10 and 11 the recorded values of stresses and strains correspond again very well to the values obtained as a result of multi-layer linear elastic modeling. A noteworthy feature in the presented results is also that the relation between axle load and vertical pressure is essentially linear i.e., the shape of stress distribution is not depending on the stress level. On the contrary, relation between axle load and vertical compressive strain is distinctively non-linear. This reflects the effect of stress dependent value of resilient modulus of the embankment materials (Eq. 1) i.e., the embankment structure becomes the stiffer the higher the axle load.

### 4.5 *Effect of embankment width*

At this point it is good to remember that in the multi-layer linear elastic modeling approach the embankment layers were assumed to be infinite in horizontal direction which is certainly not the case in reality. Therefore it might be even dangerous to directly extrapolate the results presented above e.g. to an axle load of 300 kN since at some point the stresses in the embankment are inevitably approaching a failure condition which in turn will mean a sharp increase in the deformations of the structure.

In fact some very preliminary trials to take into account the effect of embankment width were also made in this project with the aid of a 2D Finite Element program PLAXIS. Even if these trials gave qualitatively meaningful results as far as the combined effect of embankment width and axle load was concerned it seems quite obvious that there is still quite a lot more work to be done before a definite answer can be given to the question what is a sufficient embankment width with regard to different axle loads.

## 5 CONCLUSIONS

A full-scale instrumentation of a railway embankment was performed on the railway line between Koria and Kouvola in South-Eastern Finland in the summer of 1999. Based on the experiences obtained at the instrumentation site and the latter analysis of the measurement results the following conclusions can be made.

- Technically the instrumentation succeeded well and meaningful results could be obtained even from layers which at the beginning were considered to be too coarse grained for any instrumentation.
- A fairly simple multi-layer linear elastic model was observed to be able to describe realistically the vertical stiffness of railway embankments. A prerequisite for that is, however, that the material parameters of the embankment layers and the subgrade are determined at correct stress and strain levels.
- Estimation of the sufficient embankment width with regard to different maximum values of axle load requires more work to be done and more sophisticated analysis tools to be used.

## ACKNOWLEDGEMENTS

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