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INSTRUMENTATION AND MODELLING

OF RAILWAY CULVERTS

- **Pauli Kolisoja**
- **Erkki Mäkelä**

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Key words: instrumentation, FEM, multi-layer, linear elastic, modelling, railway, concrete culvert, stress, strain, temperature

SUMMARY

This report summarises the results obtained in a research project aiming at investigating the service life of concrete culverts in railway embankments under axle loads with various magnitudes. The performed analysis included in-situ measurement results from two instrumentation sites, one located in Toijala about 40 km south from Tampere and another at Peltolammi in the vicinity of Tampere, where strains and diameter changes of full scale culvert structures were recorded under normal train traffic in autumn 2000 and spring 2001. In addition to the measurements made from the culvert itself, at the Toijala instrumentation site also the embankment above and around the concrete culvert was instrumented to enable measurement of embankment strains and temperatures. The main research methods applied in the analysis were 2D and 3D Finite Element calculations supplemented by multi-layer linear elastic modelling. Furthermore, results from calculations made by hand according to the Finnish design code for concrete culverts were compared to the results obtained from the FE modelling.

In the beginning of the report a short summary of the measurement results obtained at the Tampere instrumentation site in spring 2001 is given. In addition, results from temperature measurements at the Toijala test site from winter period 2000–2001 are also shortly presented. When the results of response measurements at the Toijala and Tampere test sites were compared to the results of FE modelling it was observed that the results are very similar even if the FE models were known to be simplified both in terms of geometry and applied material models. Regarding the lateral stresses and strains, however, the agreement was rather poor. The main reason for that is assumed to be the isotropic nature of the material model used.

After the applicability of the modelling approach had been verified based on comparisons to the in-situ measurement results the main aspect of the study was to make a numerical sensitivity analysis of the critical strains in different kinds of reinforced concrete culverts installed at different depths and in different installation conditions. Thereby the aim was to estimate realisation of the expected 100 year life time of the concrete culverts. Studied culvert types included both circular culverts with and without footing. In the modelling calculations the culverts were loaded with axle loads varying from 50 to 350 kN.

According to the analysis performed all the culvert types which were studied can be expected to last for a period of 100 years with at least a grade *likely*. The grade *likely* is the third best grade on a six grade scale suggested in connection with this research. The suggested grades are based on Wöhler-curves presented for the strength of repeatedly loaded concrete material.

The minimum allowable covering thickness of concrete culverts in Finnish railways is nowadays 1,4 m and according to the results of this research it should not be reduced. The most efficient way of guaranteeing a long service life for a concrete culvert is to increase the strength of the culvert by improving the quality of concrete. Even if some culverts in some depths got grade *positive*, there is no reason to decrease the quality of concrete because of possible uncertainties involved e.g. in installation conditions of the culverts, inhomogeneity of the fill material etc. Furthermore, it was observed that the strains calculated by hand according to the existing design codes for concrete culverts proved out to be clearly higher than the strains calculated using the FE model and those measured in-situ provided that the hand calculations are made using the correct versions of the equations for bending moment and normal force.

PREFACE

This report summarises the main findings in a research project dealing with the mechanical modelling of concrete culverts commissioned by the Finnish Rail Administration. The project is constituting a part of the Nordic joint venture research project on railway culverts. The project has been carried out at the Laboratory of Foundation and Earth Structures at the Tampere University of Technology under the supervision of professor Pauli Kolisoja. The report has been compiled by professor Pauli Kolisoja and M.Sc. Erkki Mäkelä.

The progress of the project was controlled by a management group consisting of the following persons: Pasi Leimi (replaced by Matti Levomäki in June 2002) from the Finnish Rail Administration, Juha Heinonen from VR-Rata Ltd, Kari Koivunen from Abetoni Ltd, Seppo Petrow from the Finnish Association of Construction Product Industries and Pauli Kolisoja and Erkki Mäkelä both from the Laboratory of Foundation and Earth Structures at the Tampere University of Technology.

Helsinki, March 2003

Finnish Rail Administration
Maintenance Department

CONTENTS

1 INTRODUCTION

This report is a part of a research project of the Finnish Rail Administration investigating the mechanical behaviour and service life of concrete culverts in railway embankments. The report is summarising the main results of the multi-layer linear elastic and Finite Element modelling of two test sites. The earlier one of these was located near to the town of Toijala about 40 kilometres south from Tampere while the later one was in Peltolammi in Southern part of Tampere only about five kilometres away from the Tampere railway station. In addition, the report presents shortly the results of in-situ measurements performed at the Tampere test site in summer 2001 as well as the results of temperature measurements performed at the Toijala test site between the autumns 2000 and 2001. Furthermore, comparisons between the results obtained with 3D Finite Element model are compared to those of the hand calculation methods performed according to the existing Finnish design codes for concrete culverts.

The Finite Element modelling was consisting of two main stages. In the first stage performed with a 2D model the aim was to confirm the applicability of the FE model used for the concrete culvert itself by comparing the behaviour of the FE model to the results of full-scale loading tests of actual culverts performed in the test hall of the Department of Civil Engineering at the Tampere University of Technology (TUT). In the second stage 3D models corresponding both of the instrumentation sites were accomplished and the reliability of the modelling approach was evaluated by means of comparisons made to the results of in-situ measurements. After ensuring the reliability of the 3D FE model, a numerical study on the effect of culvert stiffness, shape, diameter and wall thickness, installation depth and embankment material on the stresses and strains of the concrete culverts under various axle loads was performed.

The main variables to be compared in the analyses described above were tangential strains at side, top and bottom of the inner wall of the culvert and the changes in vertical and horizontal diameter of the culvert. Furthermore, at the Toijala test site also the stresses and strains inside of the embankment material above and around the culvert could be compared. By means of these quantities together with the related multi-layer linear elastic modelling, the aim was to ensure that correct values of elastic parameters were used in the subsequent 3D Finite Element analyses.

In more detailed the results summarised in this report have been presented in two Finnish language reports by Mäkelä and Kolisoja (2001 and 2002)

2 INSTUMENTATION AND MEASUREMENTS AT THE TAMPERE TEST SITE

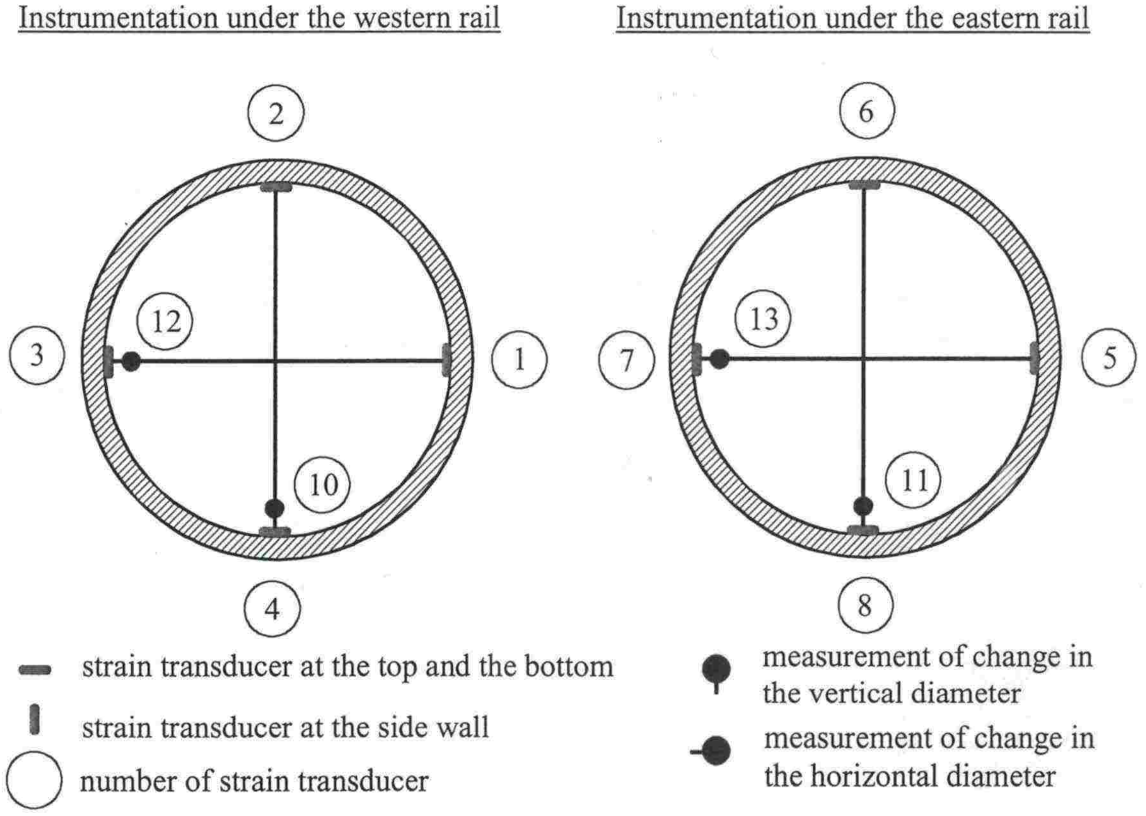
2.1 Instrumentation site

At the Tampere test site there were two parallel concrete culverts both having a diameter of 1200 mm and a wall thickness of 180 mm (Figure 2.1:1). The culverts were installed at a depth of about 1,4 m below the track.

Figure 2.1:1 A view to the Tampere test site.

2.2 Instrumentation

The quantities that were measured from one of the culverts shown in Figure 2.1:1 are indicated in Figure 2.2:1 together with numbering of the respective transducers. In addition to the measurements made from the culvert, the vertical and horizontal wheel loads were recorded with an instrumentation attached in both of the rails above the culvert.



Instrumentation under the western rail

Instrumentation under the eastern rail

Figure 2.2:1 Instrumentation of the culvert at the Tampere test site.

2.3 Examples of the measurement results

The in-situ measurements at the Tampere test site were performed on week 26 in June 2001. In Figures 2.3:1 to 2.3:6 some examples of the typical measurement results regarding the vertical wheel loads, strains at the side, top and bottom of the culvert inner wall as well as diameter changes in vertical and horizontal directions have been given, respectively.

All in all it can be concluded that the in-situ measurements succeeded well and an abundant amount of measurement signals from each of the measurement instruments were recorded under axle loads with various magnitudes.

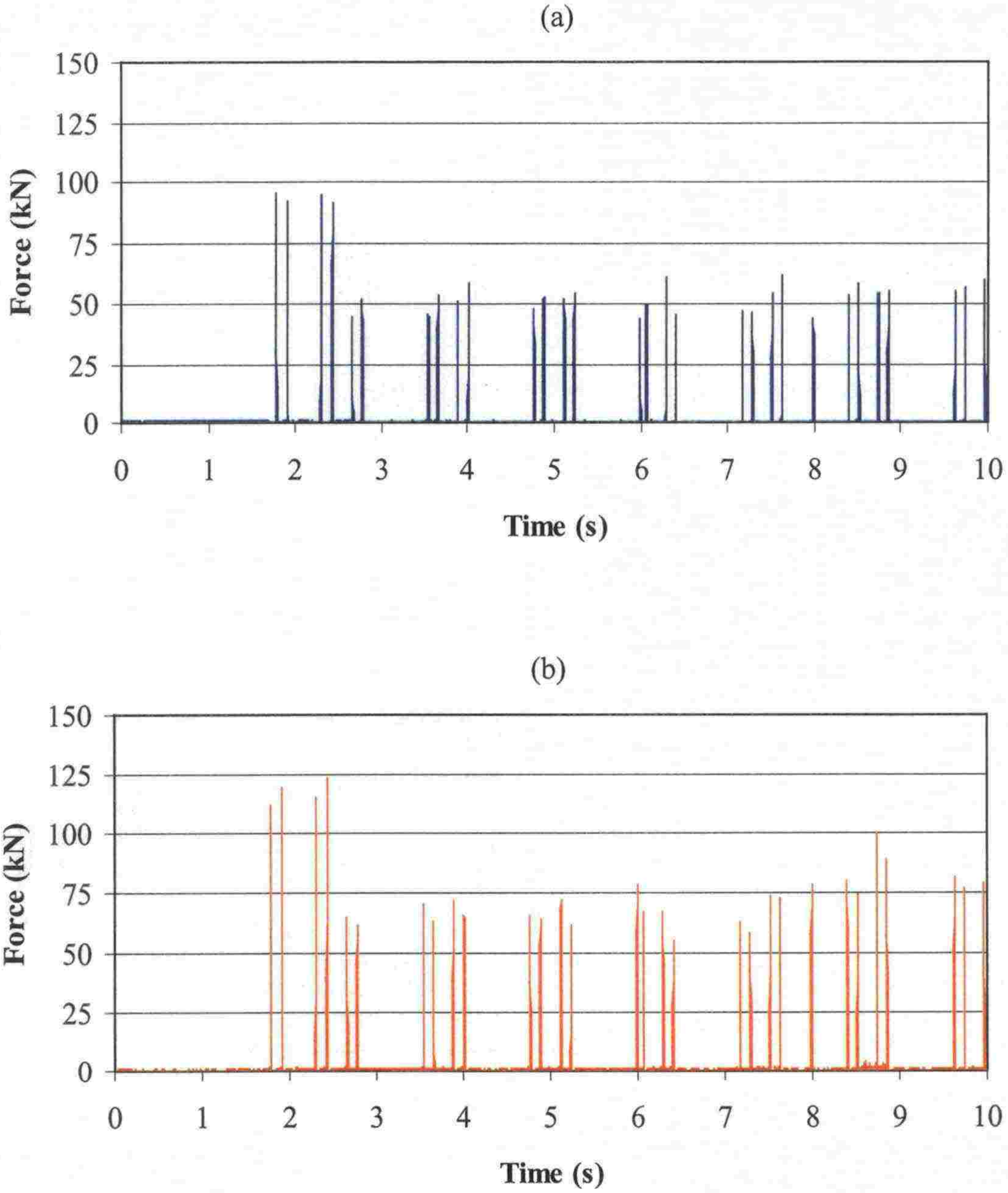


Figure 2.3:1 Vertical wheel loads of (a) the western and (b) eastern rail as a function of time under a passing-by train.

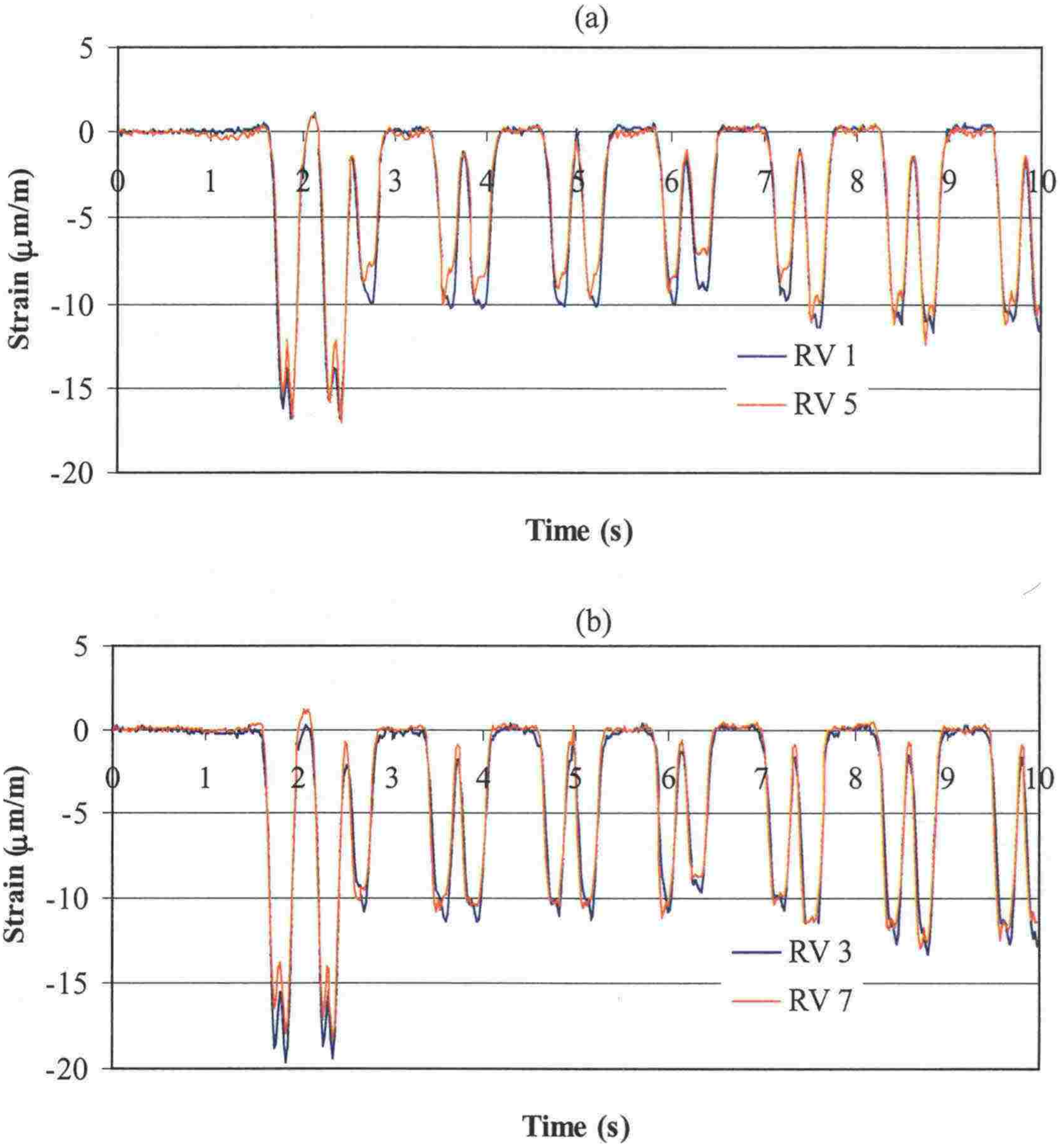


Figure 2.3:2 Compressive strains at the side of the culvert inner wall as a function of time under a passing-by train.

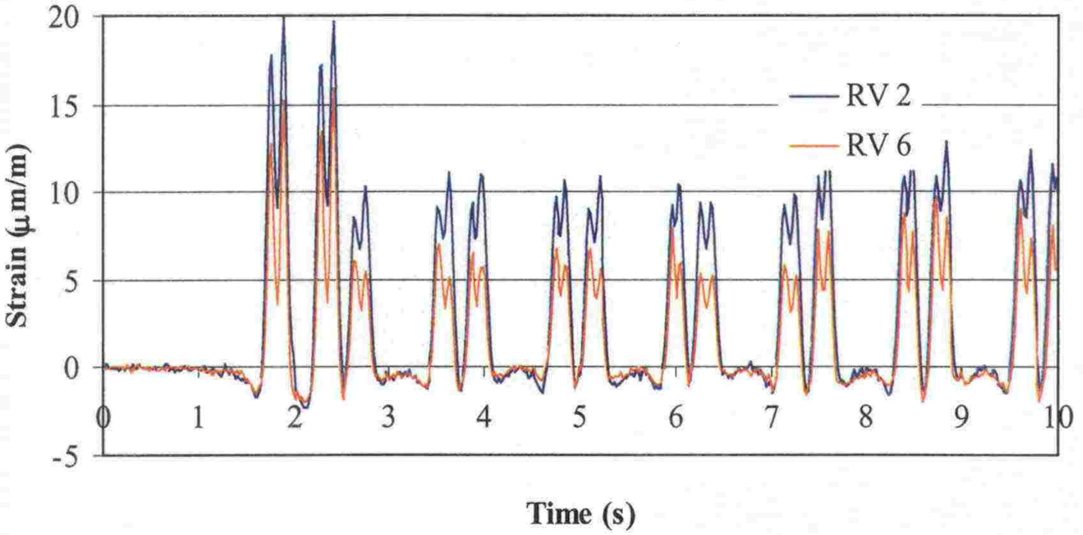


Figure 2.3:3 Tensile strains at the top of the culvert inner wall as a function of time under a passing-by train.

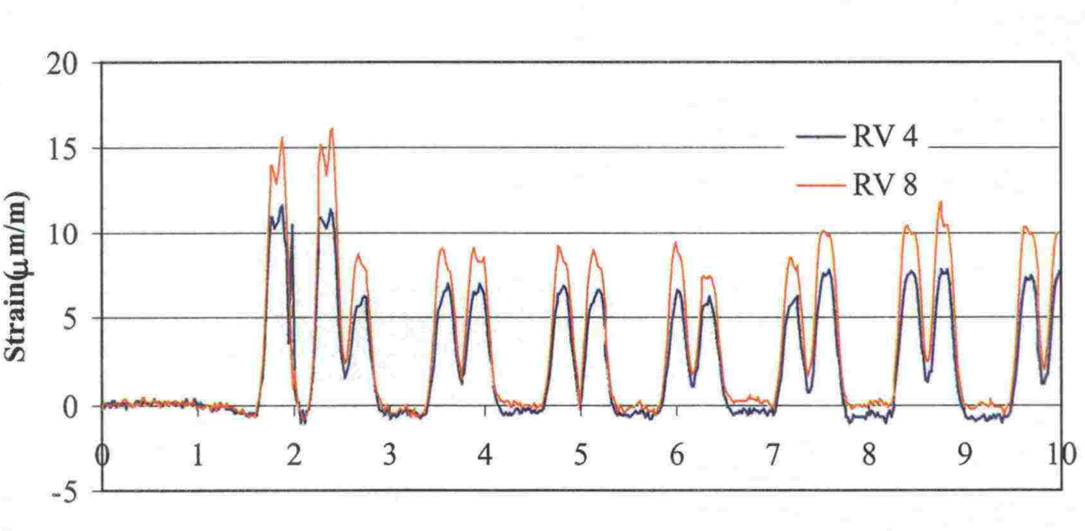


Figure 2.3:4 Tensile strains at the bottom of the culvert inner wall as a function of time under a passing-by train.

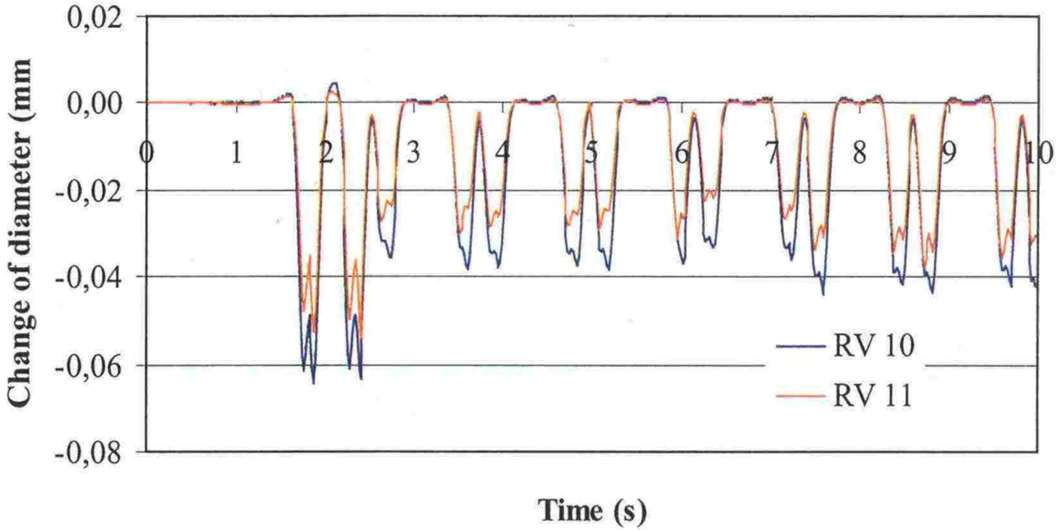


Figure 2.3:5 Change of the vertical diameter of the culvert as a function of time under a passing-by train.

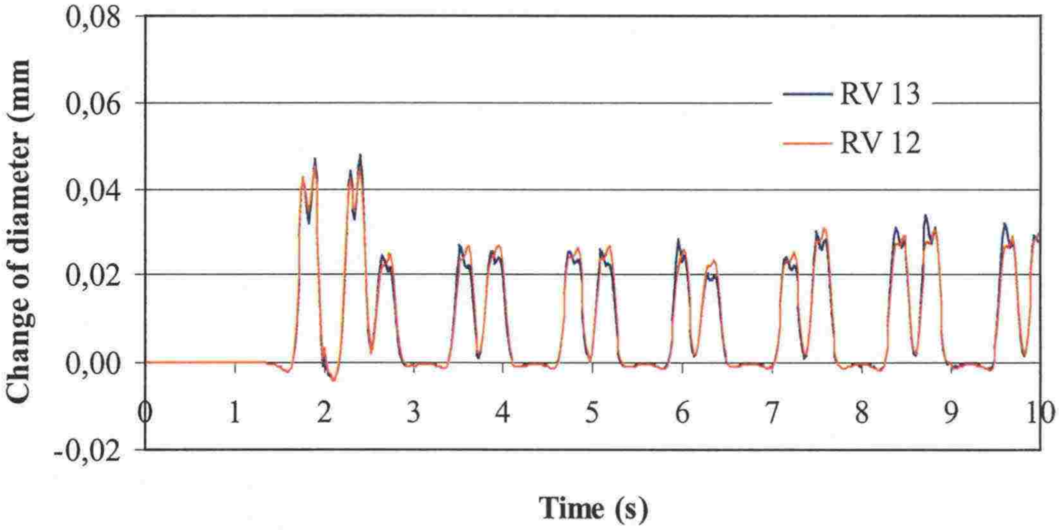


Figure 2.3:6 Change of the horizontal diameter of the culvert as a function of time under a passing-by train.

3 TEMPERATURE MEASUREMENTS AT THE TOIJALA TEST SITE

3.1 Performed measurements

In connection with the instrumentation of the Toijala test site in September 2000 a total number of 19 temperature sensors were installed in the embankment around and in the subsoil below the instrumented culvert. During the winter period 2000–2001 these sensors were recorded four times. In addition, two more measurement cycles were completed in autumn 2001 so as to enable comparisons in the initial conditions of the freezing period between two years to be made.

According to the information obtained from the nearest available weather station the winter 2000–2001 can be considered as a mild one, because the frost sum of that winter, less than 15 000 h°C, was lower than the maximum amount appearing statistically once in two years.

3.2 Results of the temperature measurements

Figure 3.2:1 presents the results of temperature measurements at various times in a longitudinal cross section on the instrumented culvert. Correspondingly, Figure 3.2:2 presents the results of temperature measurements in a longitudinal cross section of the railway embankment i.e. in a plane perpendicular to the axis of the culvert.

As main conclusions regarding the results of the temperature measurements the following remarks can be made:

- Two of the transducers located at the top of the subsoil i.e. 0,6 m below the base of the culvert have indicated slightly negative readings in March, while all of the other transducers below the culvert have remained at positive temperatures (Figure 3.2:1).
- The culvert has clearly lowered the temperatures of the embankment around it (Figure 3.2:2). That can be observed by comparing the temperature profiles on the same level but at different distances from the culvert. Consequently, the lowest temperatures have been quite logically measured in the embankment material above the culvert.
- Even during the moderately mild winter the freezing front near to the culvert has penetrated until to the frost susceptible cry crust clay material below the embankment. This clearly indicates a risk of frost heave at the culvert site on a heavier winter if no precautions to avoid the air flow trough the culvert are made.

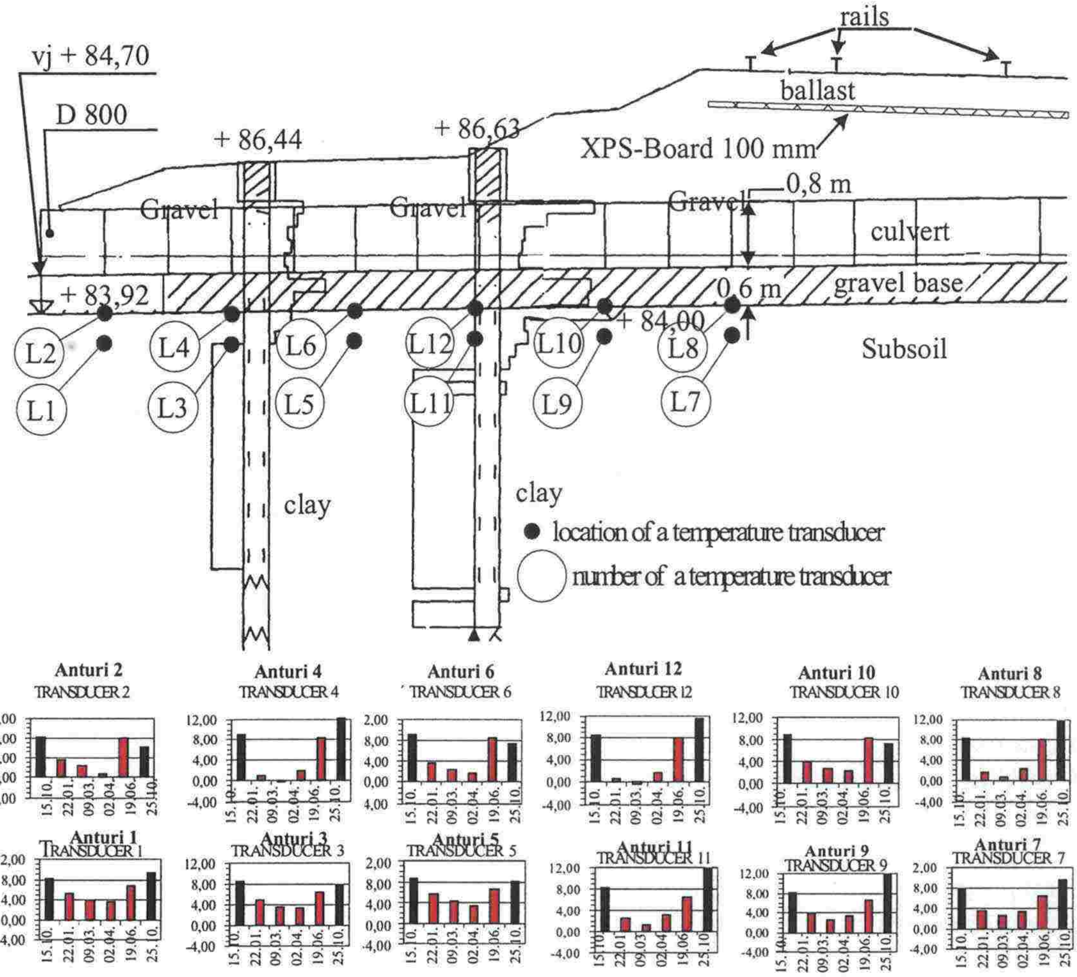


Figure 3.2:1 Results of the temperature measurements below the instrumented culvert.

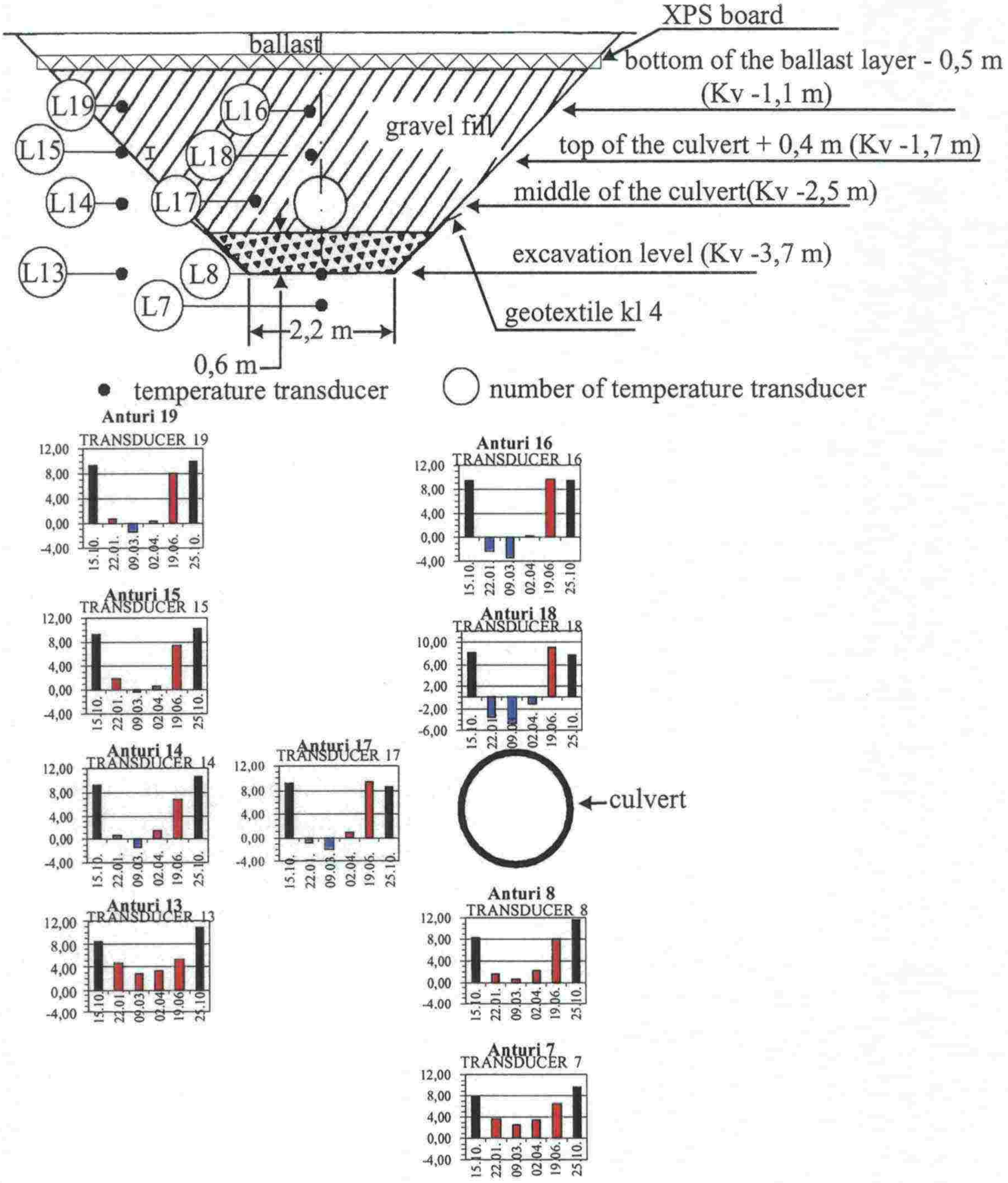


Figure 3.2:2 Results of the temperature measurements in a plane perpendicular to the instrumented culvert.

4 MULTI-LAYER MODELLING OF THE TOIJALA TEST SITE

4.1 Principle of the linear elastic modelling

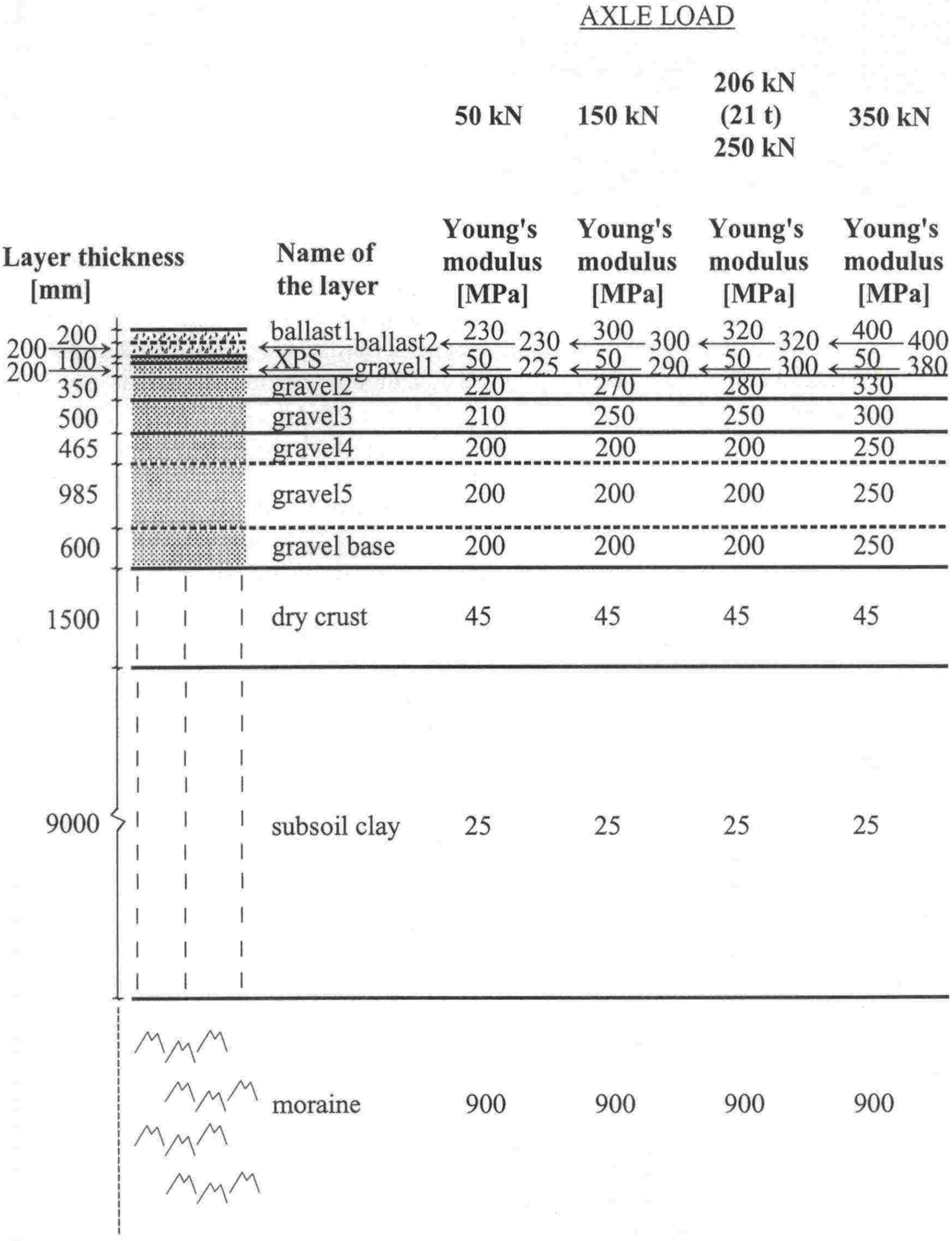
Multi-layer linear elastic modelling approach had been successfully utilised in the mechanical modelling of a railway embankment at an earlier instrumentation and in-situ measurement site located at Koria, about 100 km north-east from Helsinki. These measurements were performed and reported in connection with the Finnish Rail Administration's project aiming at investigating the prerequisites for increasing the allowable axle loads at least in some parts of the Finnish railway network (Kolisoja et al. 2000a). The report was published later on also in English (Kolisoja et al. 2000b).

In the same way as during the above mentioned project, the multi-layer linear elastic model of the embankment was accomplished using the commercially available BISAR programme developed by the oil company Shell. Due to the fact that the software has originally been developed aiming at applications in highway engineering, the axle load on top of the embankment model had to be described using a total number of ten evenly distributed circular loads. In the layers below the ballast this limitation is, however, not supposed to have any major effect on the distribution of vertical stresses and strains that were investigated and compared to the actually measured ones.

4.2 Results of the linear elastic modelling

In the multi-layer linear elastic model the railway embankment and the underlying subsoil were modelled by means of ten layers that were infinite in horizontal direction (Figure 4.2:1). The values of E modulus for the embankment layers were determined as a result of an iterative process in which the stress dependency of the modulus values was taken into account based on the results of large scale cyclic loading triaxial tests earlier performed at TUT. Correspondingly, the stiffness values of the subsoil were determined based on Resonant Column measurements performed also in the Laboratory of Foundation and Earth Structures at TUT.

The main target of the multi-layer linear elastic modelling in connection with this research was to derive the values of E modulus that were to be used as input values in the subsequent Finite Element modelling of the embankment. The values of E modulus corresponding to the various axle loads thus derived and verified by the in-situ measurements are presented in Figure 4.2:1.



AXLE LOAD

Layer thickness [mm]	Name of the layer	50 kN Young's modulus [MPa]	150 kN Young's modulus [MPa]	206 kN (21 t) 250 kN Young's modulus [MPa]	350 kN Young's modulus [MPa]
200	ballast1	230	300	320	400
200	ballast2	230	300	320	400
100	XPS	50	50	50	50
200	gravel1	225	290	300	380
350	gravel2	220	270	280	330
500	gravel3	210	250	250	300
465	gravel4	200	200	200	250
985	gravel5	200	200	200	250
600	gravel base	200	200	200	250
1500	dry crust	45	45	45	45
9000	subsoil clay	25	25	25	25
	moraine	900	900	900	900

Figure 4.2:1 Values of Young's modulus under different axle loads derived based on the multi-layer linear elastic modelling and calibrated by the in-situ measurements.

5 DIMENSIONING OF CONCRETE CULVERTS BY HAND CALCULATIONS

5.1 Design criteria in the hand calculations

The detailed procedure of dimensioning the required strength of concrete culverts is presented in national design codes 'Betoniputkinormit 2001'. Due to the numerous stages involved, the calculations are not presented here in detail. In general it can, however, be pointed out that the design is made according to three main criteria. At first, a reinforced concrete culvert must be able to carry a certain load without being cracked, secondly, another load without yielding, and thirdly, the culvert must be able to carry the yield load without collapsing until the change of the horizontal diameter is at least two per cent.

5.2 Results of hand calculations of the Toijala test site

As a results of hand calculations made according to the procedure presented in the design codes the values of stress and strain shown in Table 5.2:1 were determined for the concrete culvert with an internal diameter of 800 mm at the Toijala test site under an axle load of 250 kN. However, a correction that compensates an obvious error in the calculation of the moment and normal force as presented in the existing design codes was taken into account.

Table 5.2:1 Stresses and strains of the Toijala test site concrete culvert at the critical cross sections.

Hand calculation method	Stress [kPa]			Strain [μstrain]		
	Top	Side	Bottom	Top	Side	Bottom
Ordinary burial theory	7894,6	-8325,4	8246,5	197,4	-208,1	206,2
Average earth column method	5878,6	-6199,4	6140,6	147,0	-155,0	153,5
Embankment check	4183,9	-4412,3	4370,4	104,6	-110,3	109,3
Embankment check with side support	3725,2	-3928,5	3891,3	93,1	-98,2	97,3

Based on the hand calculations it could be concluded at firstly that resulting stresses and strains at the critical sections of the culvert depend fairly extensively on the applied calculation method i.e. on the assumptions that are made with regard to the earth pressure and load distribution. Consequently, the values of stress and strain are more than two times higher according to the method giving the highest values in comparison to the method giving the lowest ones. Secondly, it could be concluded that according to the hand calculations made taking into account the above mentioned correction to the design codes, the culvert would not withstand the applied loads even in the case of the mildest earth pressure load assumption.

A more detailed comparison between the results of hand calculations, the results of Finite Element modelling and the actual in-situ measurements will be presented later on in Chapter 7.6.

6 FINITE ELEMENT MODELLING OF THE CULVERT ELEMENT LOADING TESTS

6.1 Aim of the 2D FE modelling

In connection with the previous stage of the research project a culvert element corresponding to those installed in the railway embankment at the Toijala test site was test loaded at TUT. The loading arrangement during the loading test was prepared according to the guidelines given in the Finnish design codes for concrete culverts 'Betoniputkinormit 2001' (Figure 6.1:1).

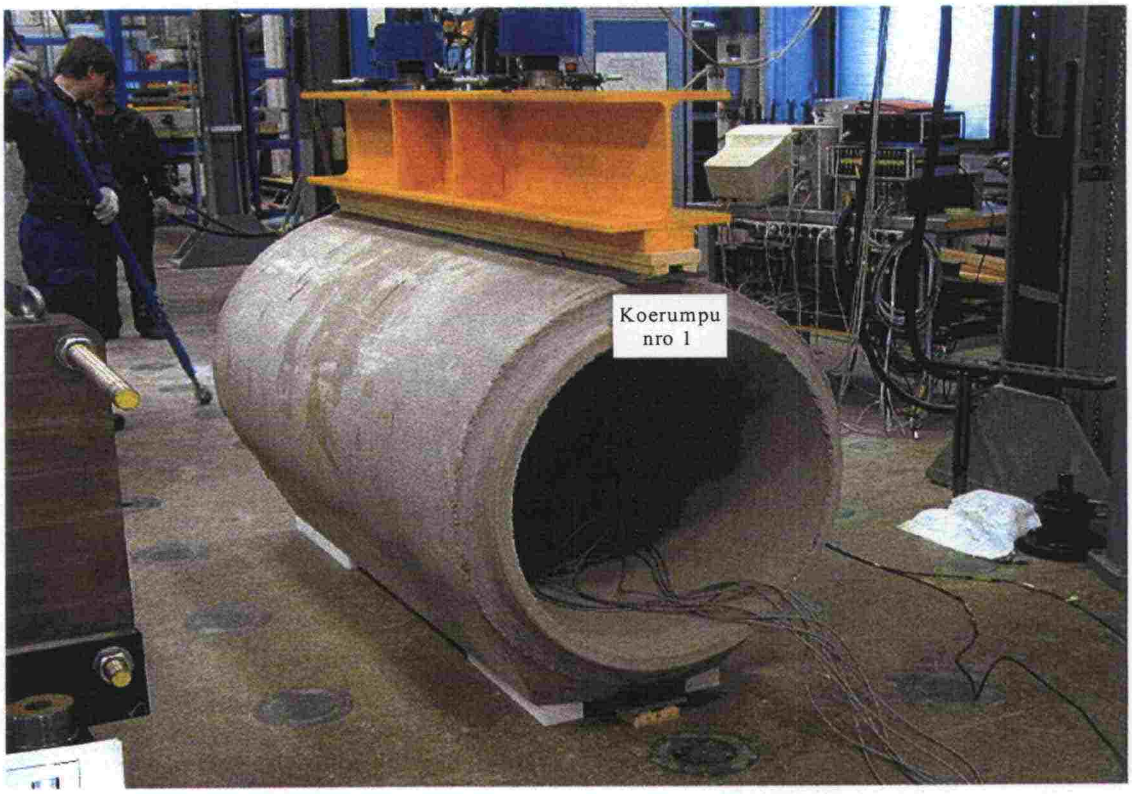


Figure 6.1:1 Loading arrangement in the loading test of the concrete culvert at TUT.

The aim of the loading test and the subsequent 2D Finite Element modelling of the loading test accomplished using the PLAXIS (1998) software was twofold. At first the correctness of the value of Young's modulus to be used for the culvert in the actual 3D Finite Element modelling of the test site was confirmed. Simultaneously, the loading test provided an opportunity to test the applicability of the Finite Element model of the culvert only in well defined loading conditions.

6.2 Comparison of the FE model to the measurement results

During the loading test diameter changes of the culvert element in vertical and horizontal directions as well as tangential strains at the sides, top and bottom of the inner wall of the culvert were recorded. As examples of the analyses that were performed Figures 6.2:1 and 6.2:2 present a comparison between the results obtained from the FE model with various values of Young's modulus and the measurement results recorded during the loading test. In Figure 6.2:1 the comparison is made regarding the diameter change in horizontal direction while in Figure 6.2:2 the modelled and measured values of tangential strain at the top of the inner wall of the culvert are shown.

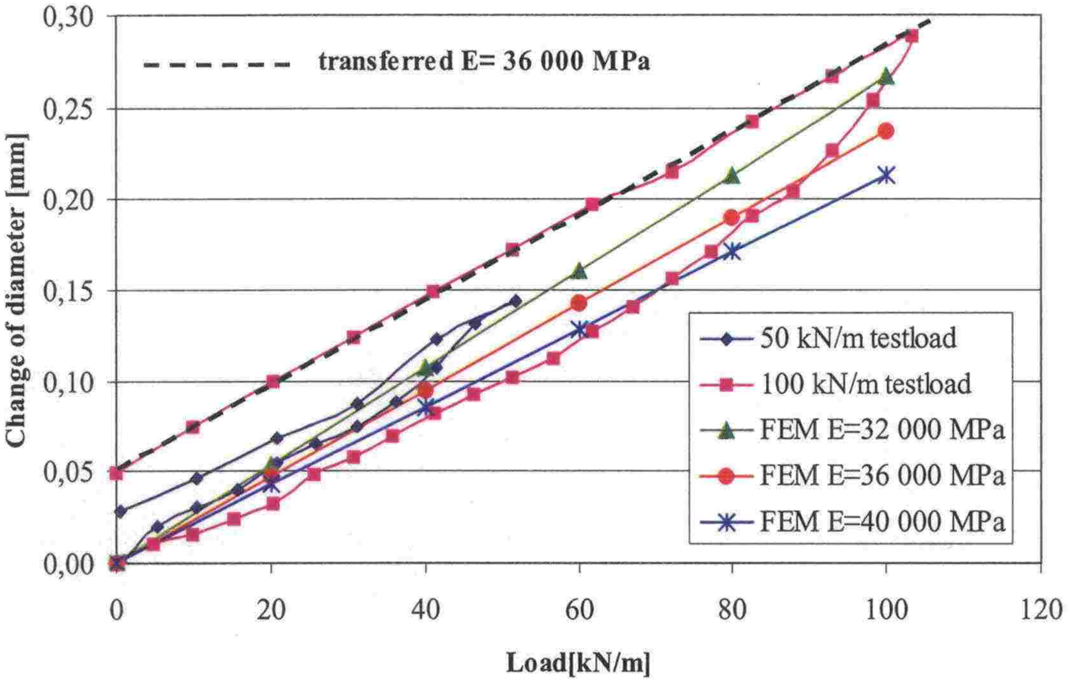


Figure 6.2:1 Comparison of the modelled and measures values of diameter change in horizontal direction.

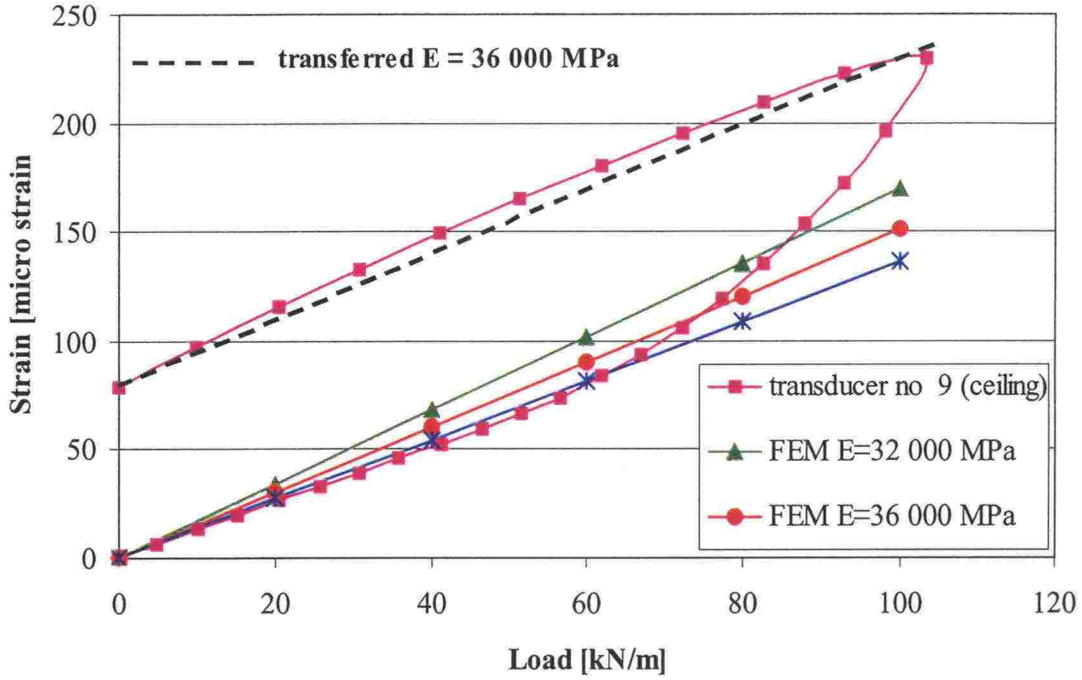


Figure 6.2:2 Comparison of the modelled and measures values of tangential strain at the top of the culvert inner wall.

From both of the figures it is quite obvious that relation between the applied load and the response of the culvert element is essentially linear until to the load of about 60 kN/m at which also the first cracks were visually observed to appear in the culvert element. Because the actual loads at the test site could be assumed to remain on that range, the value of Young's modulus to be used in the subsequent 3D Finite Element modelling calculations was fixed to 40 000 MPa. Incidentally this happened to be the same value that was derived based on the compressive strength of the concrete specimen drilled out from the culvert element.

One further example of the results of the FE modelling is shown in Figure 6.2:3 which presents the distribution on vertical and horizontal stresses in the culvert element during the loading test. Based on this figure it is quite obvious that in this loading arrangement the critical points regarding the tensile stresses could be expected to be at the mid height of the outer wall and at the top and bottom of the inner wall of the culvert element.

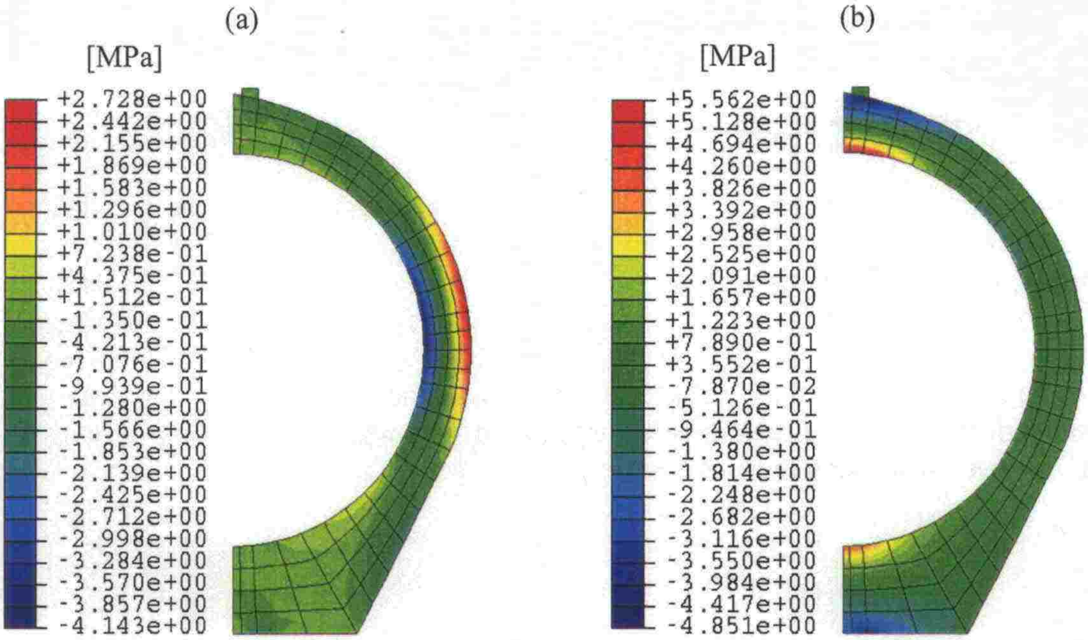


Figure 6.2:3 Distributions of (a) the vertical and (b) the horizontal stresses in the culvert element during the loading test.

7 MODELLING OF THE INTERACTION BETWEEN THE EMBANKMENT AND THE CONCRETE CULVERT

7.1 Properties of the FE model

A schematic cross section of the two track railway embankment at the Toijala instrumentation site is shown in Figure 7.1:1. Due to the practical feasibility limits regarding the size of the calculation model, only the shaded area of the cross section was taken into account in the 3D Finite Element model. Since the vertical plane in between the rails was defined as a plane of symmetry, the actual calculation model corresponded rather to one track railway embankment. However, this was not considered as a major limitation, because the train load was always acting only at the instrumented track during the measurements.

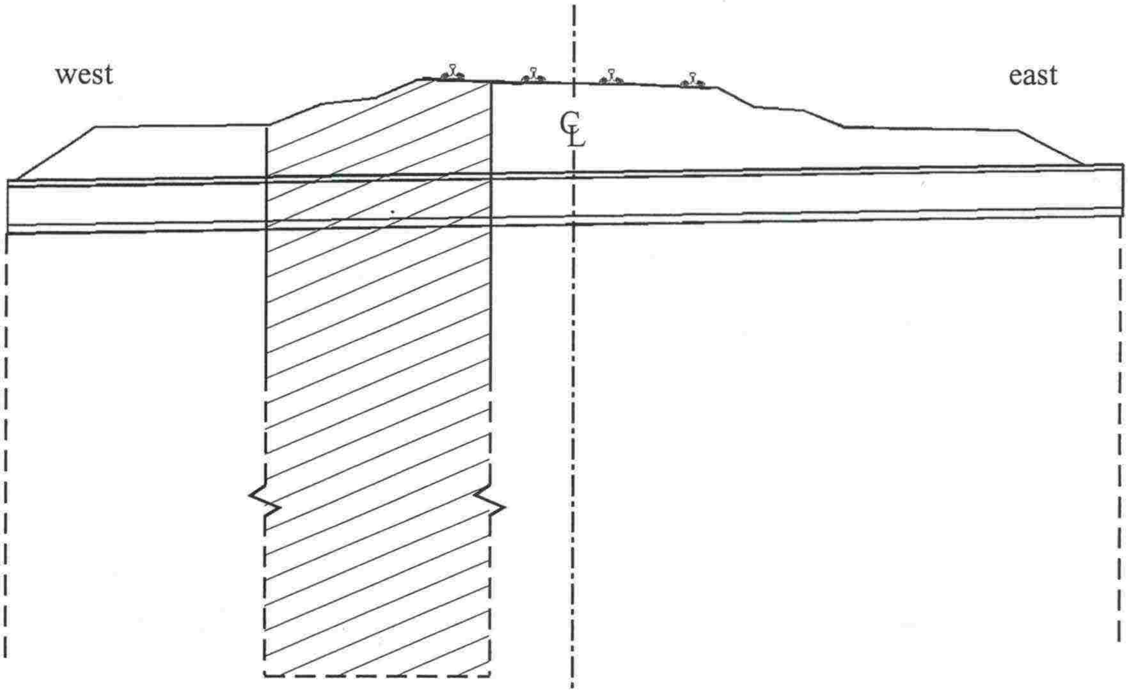


Figure 7.1:1 Schematic cross section of the Toijala test site.

Further, taking into account the existence of a plane of symmetry also in the vertical direction along the axis of the culvert, the final 3D FE model accomplished using the ABAQUS (2001) software was as shown in Figure 7.1:2. As the figure indicates, the wheel load is applied on top of the model via two sleeper halves and a quadrate of one sleeper on which the load is distributed as suggested by Riessberger (1998) in relations (0,5 x) 50 % - 20 % - 5 %. As already mentioned in Chapter 4 the values of Young's modulus for the coarse grained layers of the embankment presented in Figure 7.1:2 have been determined based on large scale cyclic loading triaxial tests performed at TUT and for the subsoil layers by means of Resonant Column tests performed also at TUT and verified by the in-situ measurements made from the embankment.

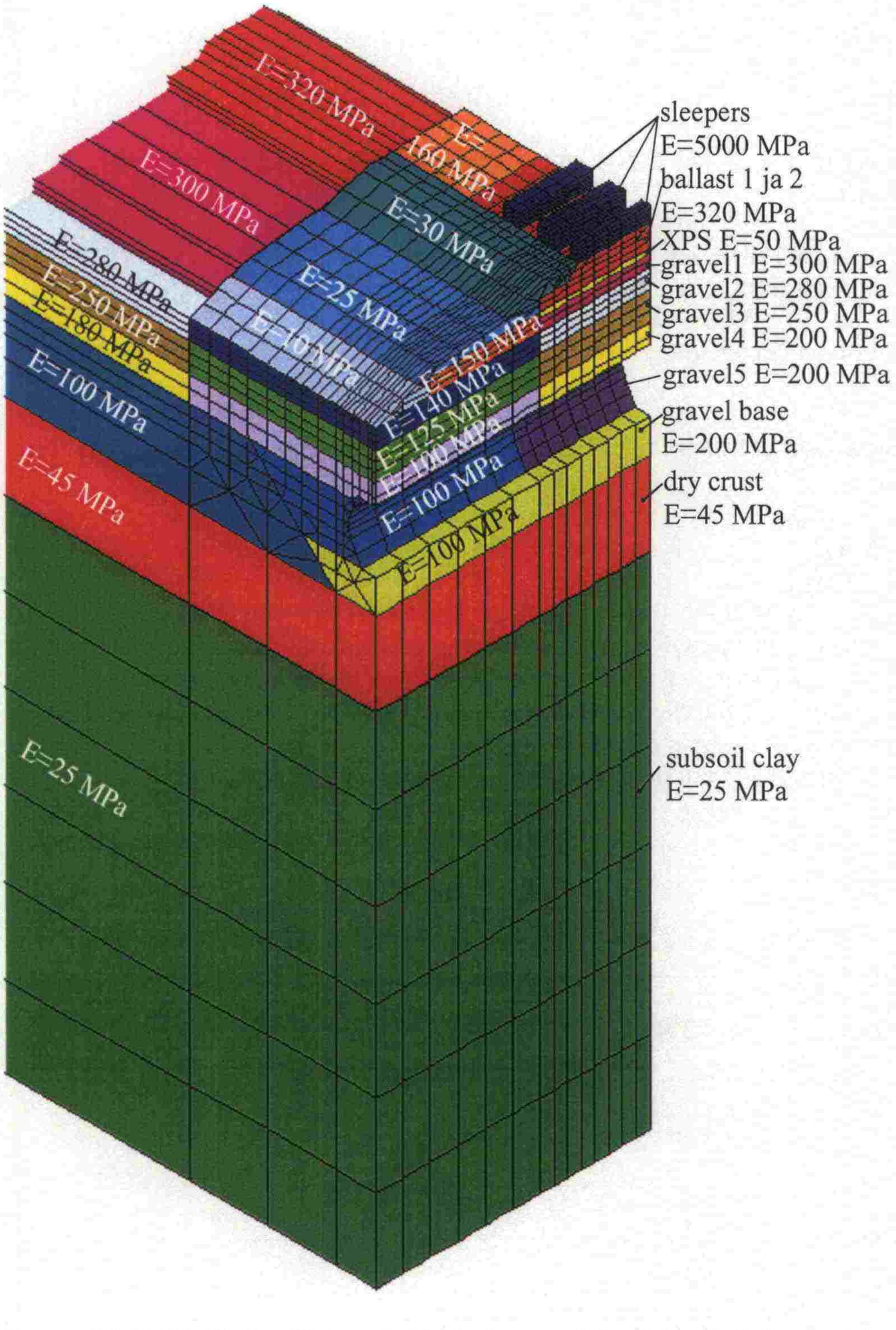


Figure 7.1:2 3D Finite Element calculation model of the Toijala test site and the respective values of Young's modulus used for each part of the model under an axle load of 206 kN.

Linear elastic material model was used for all of the embankment layers, the subsoil and the culvert (see Chapter 6.2). In the case of the embankment materials, however, the stress dependent nature of the stiffness of the materials was taken into account by selecting modulus values corresponding to the actual axle load (see Chapter 4).

At the boundaries of the FE model the boundary conditions were defined as follows:

- At the bottom of the model all of the displacement components were fixed.
- At the sides of the model displacements were allowed to take place freely in the vertical direction.
- In the longitudinal direction out of the culvert the embankment was modelled using infinite elements.
- Movement of the culvert was prevented in the longitudinal direction.

7.2 Comparison between the FE model and the measurements at the Toijala test site

7.2.1 Culvert

Regarding the culvert at the Toijala test site comparisons between the results of the FE modelling and in-situ measurements have been presented in Figures 7.2:1 to 7.2:4. In Figure 7.2:1 the comparison is shown for the change in the vertical diameter of the culvert, in Figure 7.2:2 for the change in the horizontal diameter of the culvert, in Figure 7.2:3 for the tangential strain at the side wall of the culvert and in Figure 7.2:4 for the tangential strain at the top of the culvert, all as a function of the axle load.

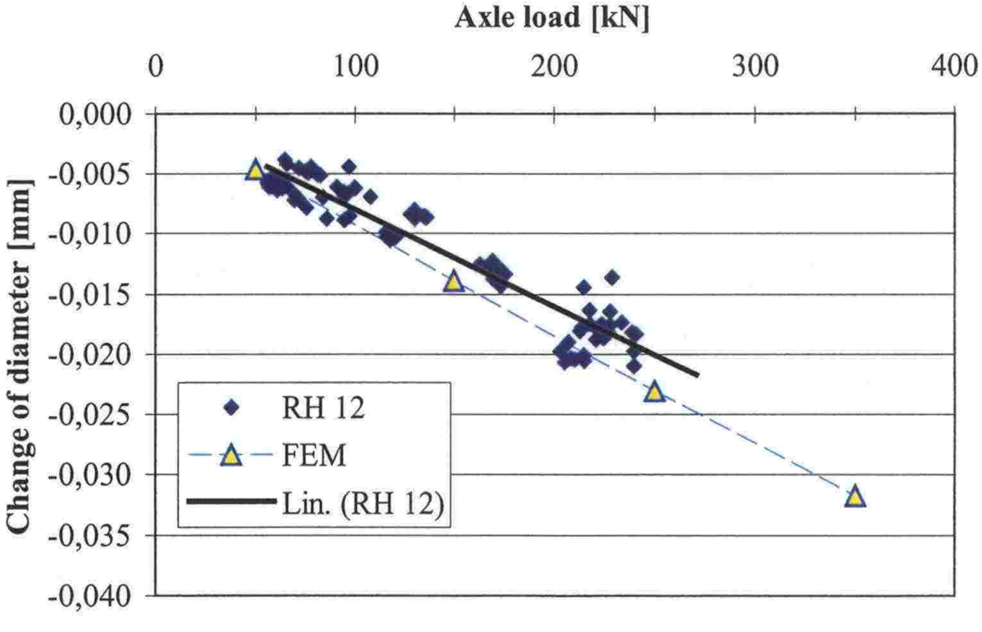


Figure 7.2:1 Comparison of the measured and modelled values of change in the vertical diameter of the culvert at the Toijala test site.

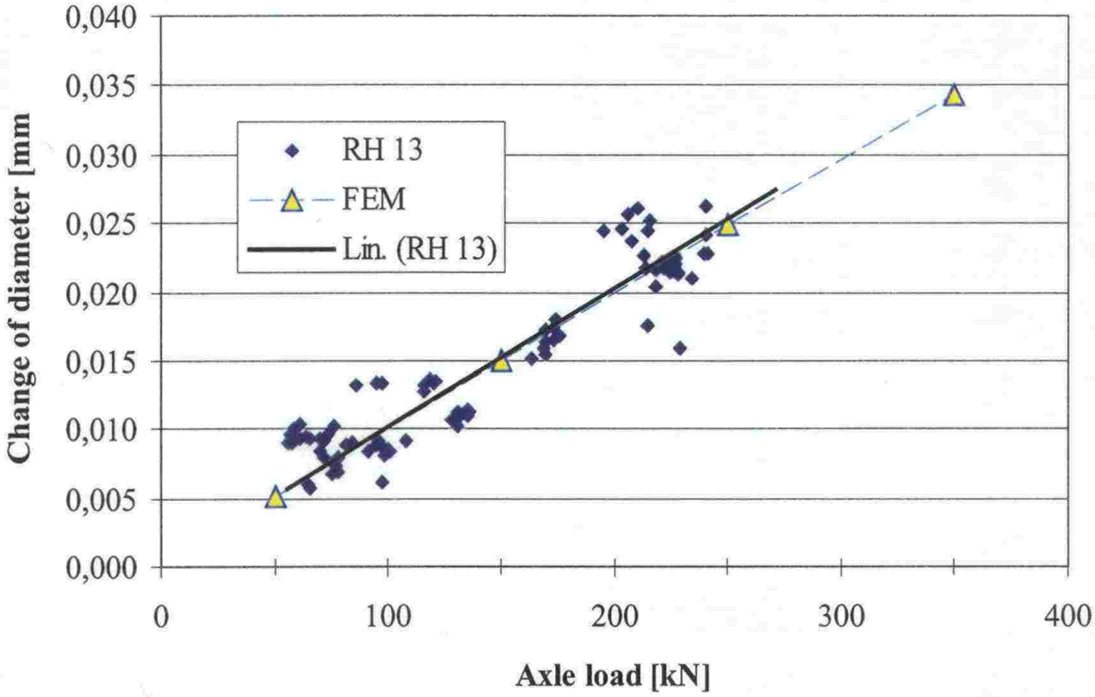


Figure 7.2:2 Comparison of the measured and modelled values of change in the horizontal diameter of the culvert at the Toijala test site.

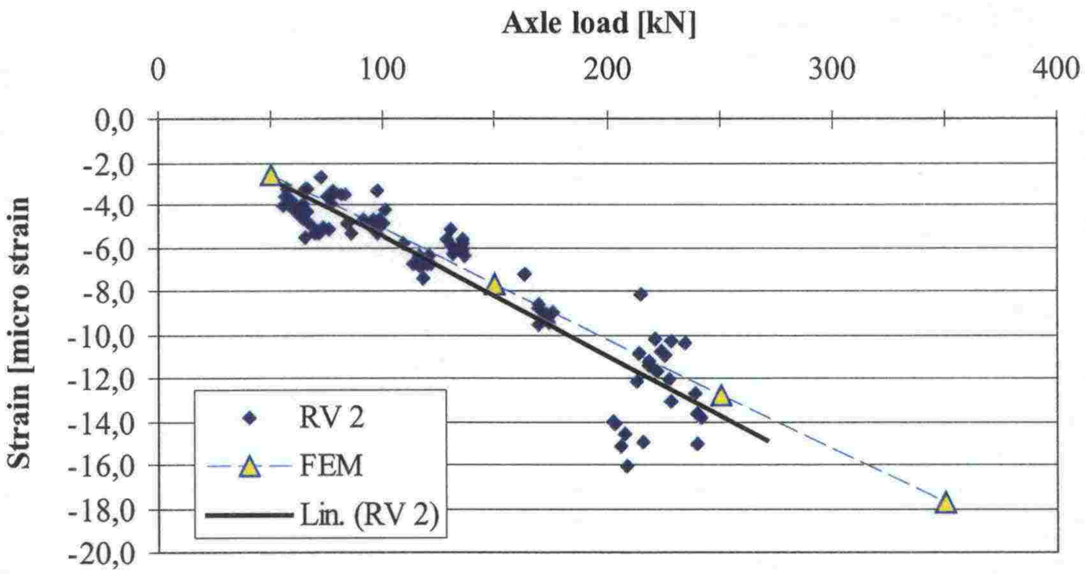


Figure 7.2:3 Comparison of the measured and modelled values of tangential strain at the side wall of the culvert at the Toijala test site.

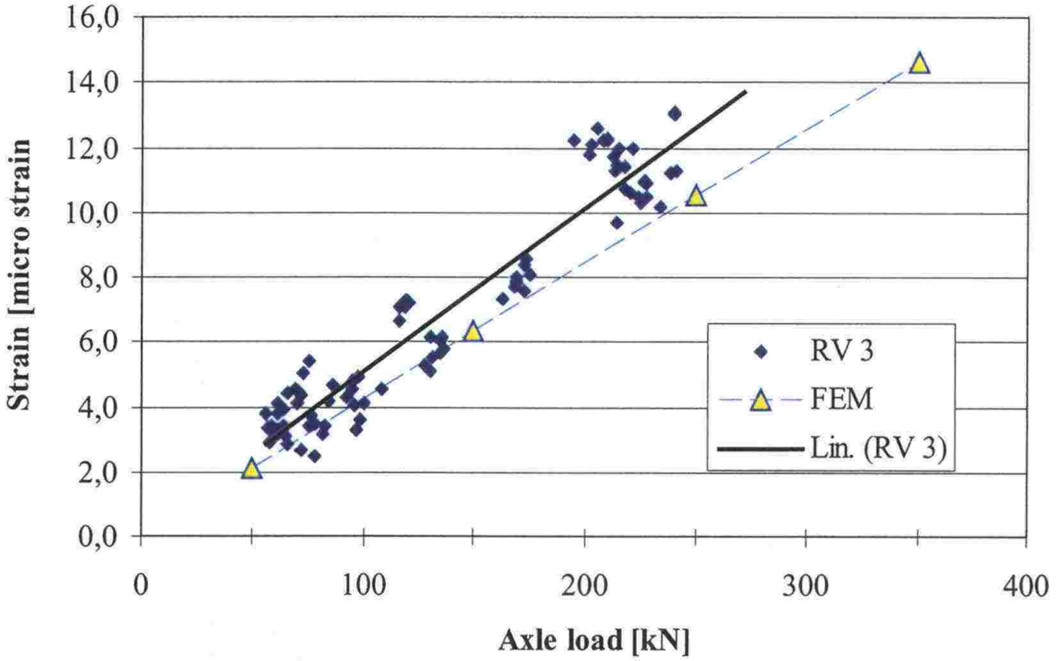


Figure 7.2:4 Comparison of the measured and modelled values of tangential strain at the top of the culvert at the Toijala test site.

As the comparisons shown in Figures 7.2:1 to 7.2:4 indicate, a general conclusion regarding the success of the FE modelling was that the results were even surprisingly good keeping in mind e.g. all the simplifications that are known to be made as far as the geometry of the model and the applied material models are concerned.

7.2.2 Embankment

Two examples of the comparisons between the measured and modelled values of vertical strain at different levels inside the embankment are given in Figures 7.2:5 and 7.2:6. In Figure 7.2:5 the comparison is made for the strains at 1,1 m below the track and in Figure 7.2:6 for the strains at 1,7 m below the track i.e. at about the level of the top of the culvert. At this point it is, however, good to note that the results obtained with some of the transducers were not as similar to the calculated ones as in the given examples. Another important remark regarding the results is that as the axle load was approaching to 250 kN the discrepancy between the calculated and measured values tended to increase (Figure 7.2:5). **This could indicate that it may be fairly risky to extrapolate the obtained results much beyond the loads covered by the measurements.**

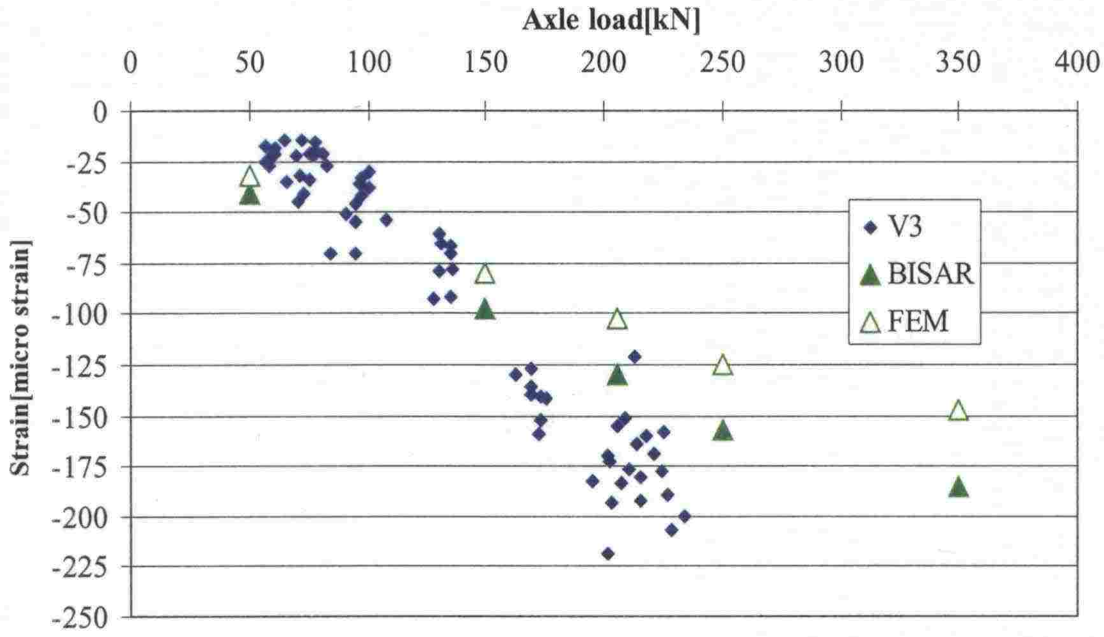


Figure 7.2:5 Comparison of the measured and modelled values of vertical strain in the embankment 1,1 m below the track.

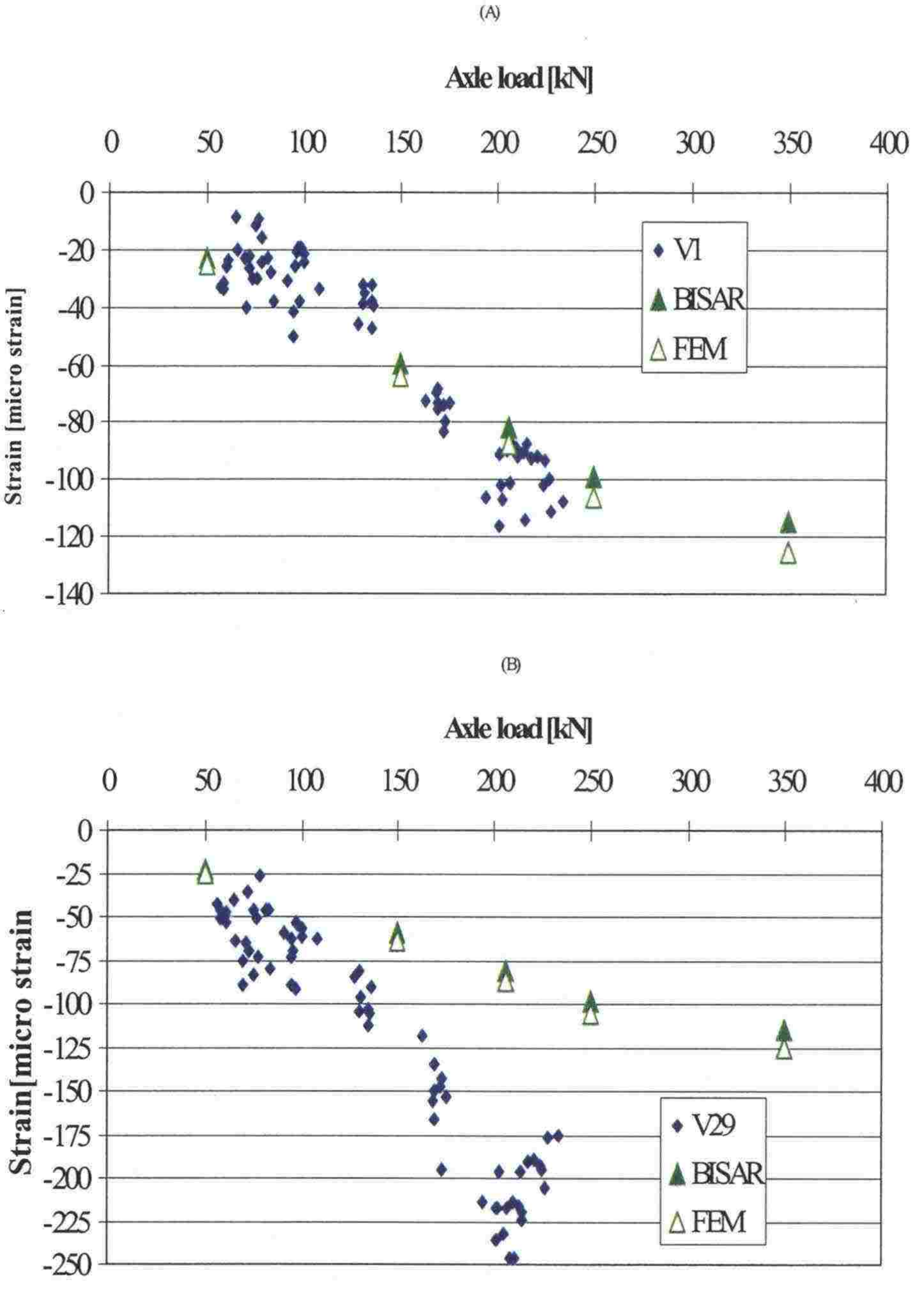


Figure 7.2:6 Comparison of the measured and modelled values of vertical strain in the embankment 1,7 m below the track.

One more important remark regarding the differences between the measured and modelled behaviour of the embankment is visualised in Figure 7.2:7 presenting the values of horizontal strain of the embankment at a depth of 1,7 m below the track in normal direction to the embankment. As the figure indicates deformations in the horizontal direction are much larger than the calculated ones suggesting that the actual behaviour of the embankment materials is essentially anisotropic unlike the embankment materials in the calculation model.

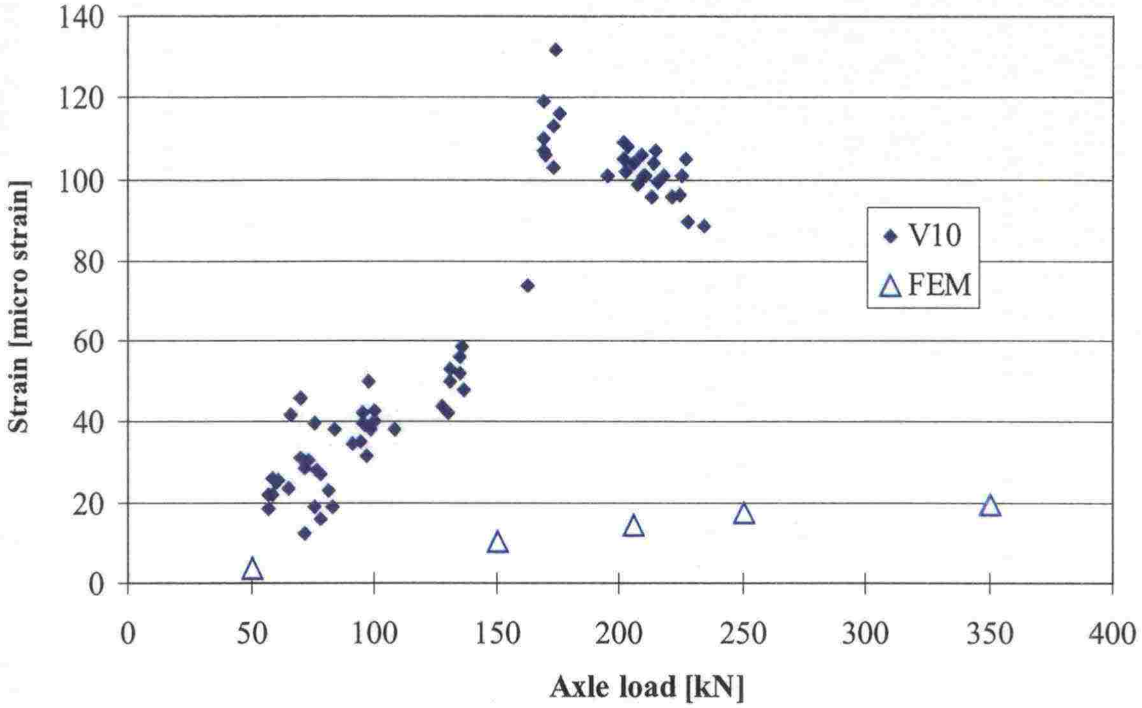


Figure 7.2:7 Comparison of the measured and modelled values of horizontal strain in the embankment 1,7 m below the track.

7.3 Comparison between the FE model and the measurements at the Tampere test site

7.3.1 Culvert

Symmetry of the embankment and the culvert was taken into account in the FE calculation model of the Tampere test site in principle in the same way as explained above for the Toijala test site. The values of Young's modulus utilised in the model were also of the same order except for the culvert material and the subsoil. In the first mentioned case the value was decreased from 40 000 MPa to 35 500 MPa based on the measured compressive strength of the concrete while the later one was increased to 100 MPa based on much stiffer nature of the subsoil at the Tampere test site.

As examples of the comparisons between the measured and modelled values of the various types of responses at the Tampere test site Figures 7.3:1 to 7.3:4 present again the changes in the vertical and horizontal diameter of the culvert as well as tangential strains at the side wall and top of the culvert, respectively. In this case the measured values are now presented in all cases for two parallel transducers.

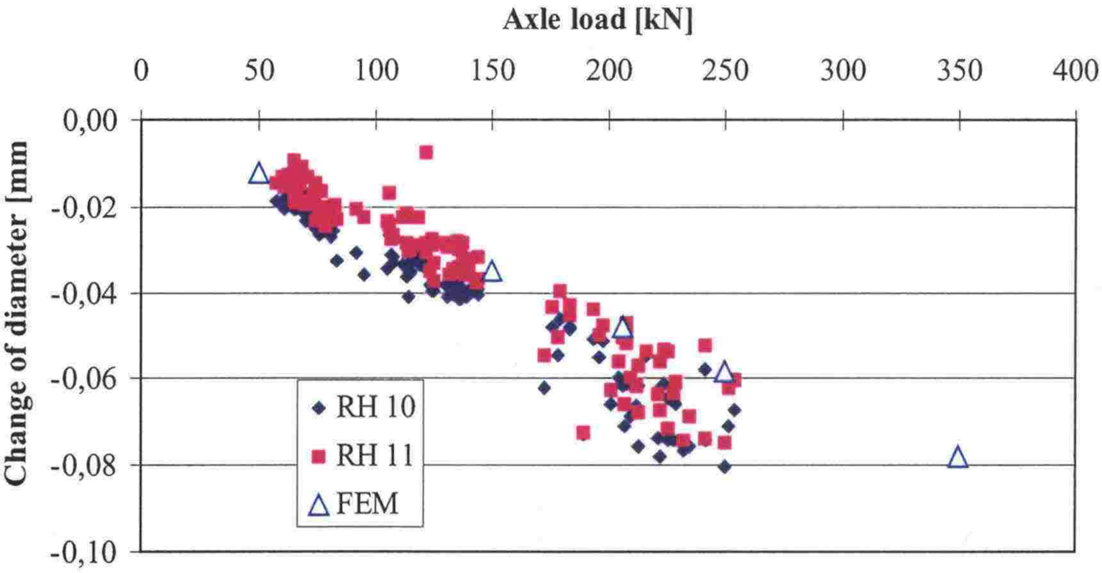


Figure 7.3:1 Comparison of the measured and modelled values of change in the vertical diameter of the culvert at the Tampere test site.

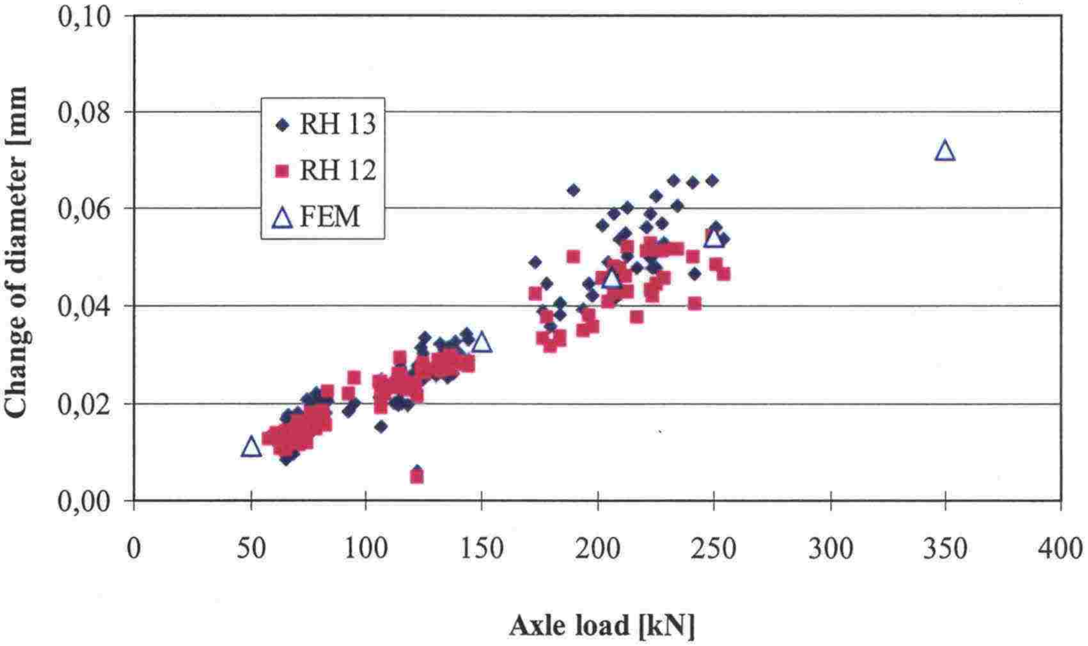


Figure 7.3:2 Comparison of the measured and modelled values of change in the horizontal diameter of the culvert at the Tampere test site.

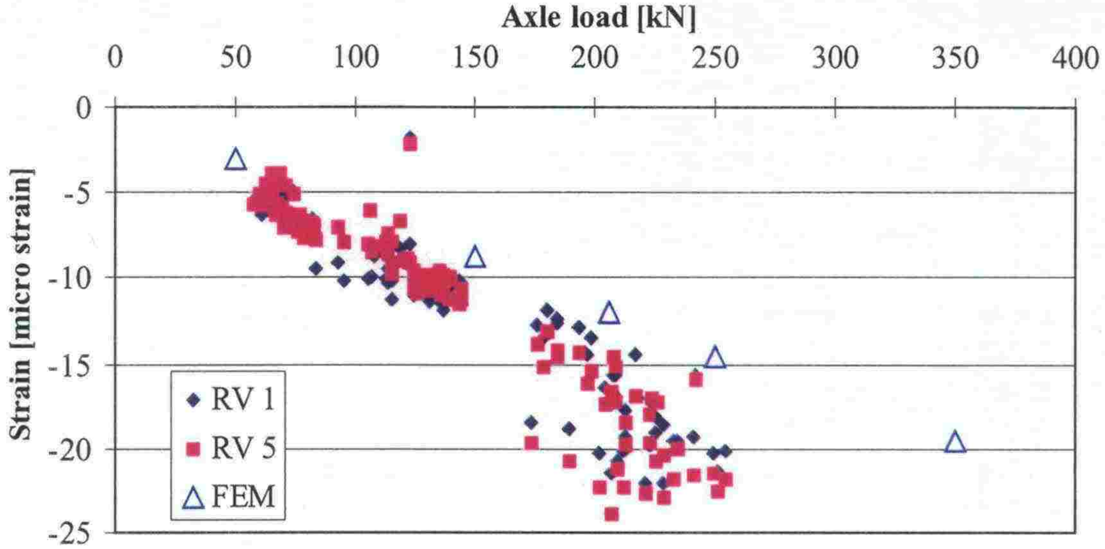


Figure 7.3:3 Comparison of the measured and modelled values of tangential strain at the side wall of the culvert at the Tampere test site.

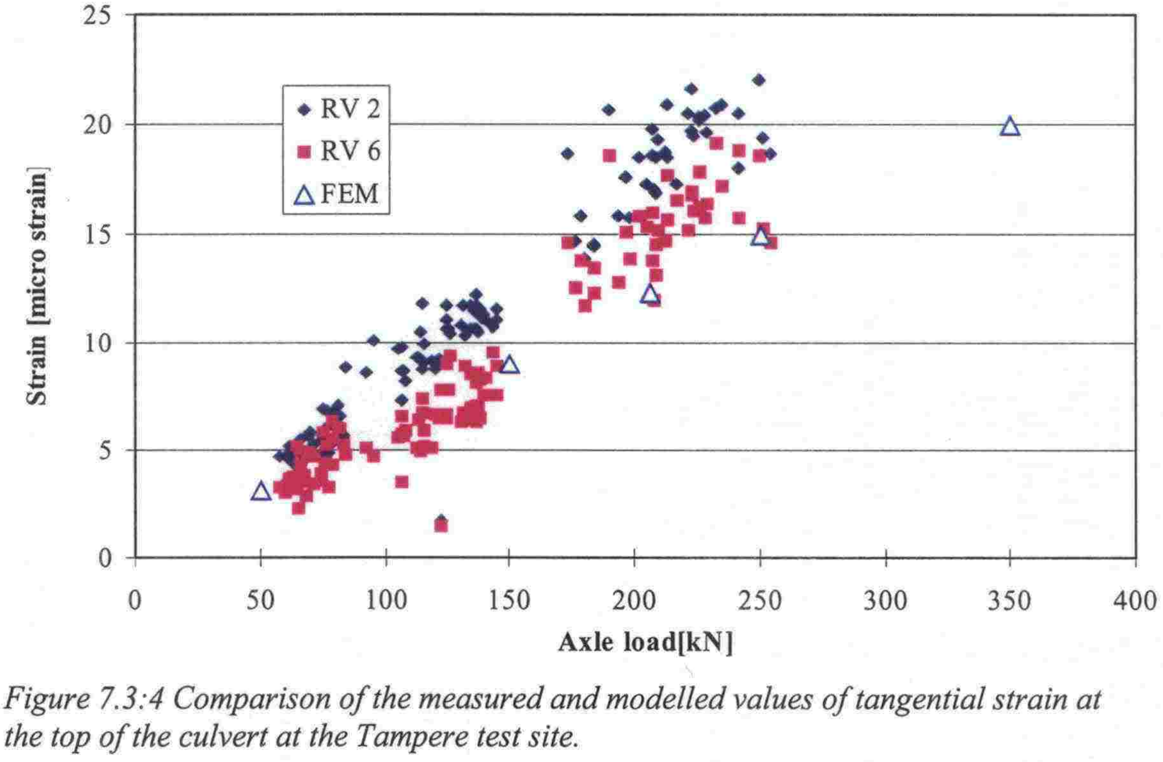


Figure 7.3:4 Comparison of the measured and modelled values of tangential strain at the top of the culvert at the Tampere test site.

Basically in the same way as in Chapter 7.2.1 above it can be concluded that the measured and modelled values of culvert deformations fit to each other very well. Consequently, it can be concluded that the 3D Finite Element calculation model has been proved to be accurate enough for estimating the responses of the various types of concrete culverts at different installation depths as will be presented in more detail in the subsequent chapters.

7.4 Estimation of the service life of concrete culverts under repeated loading

Estimation of the performance and respective service life of concrete culverts located in the railway embankment and exposed to repeated loading caused by the train traffic was based on the Wöhler curves schematically presented in Figure 7.4:1. According to the figure, the compressive strength of concrete under repeated loading conditions in relation to the compressive strength under monotonous loading is decreasing in a more or less linear relation to the logarithm of the number of load applications until 2×10^6 load repetitions. Consequently, if the number of load repetitions corresponding to the service life of 100 years of the culvert is 2×10^6 or more, the allowable compressive stress is only half of the compressive strength of the material under monotonous loading. In the same way the level of allowable repeated tensile stress is also reduced alongside with the increasing number of load repetitions. In the case of tensile stresses, however, the allowable stress at 2×10^6 load repetitions is only 33 % of the respective tensile strength under monotonous loading conditions.

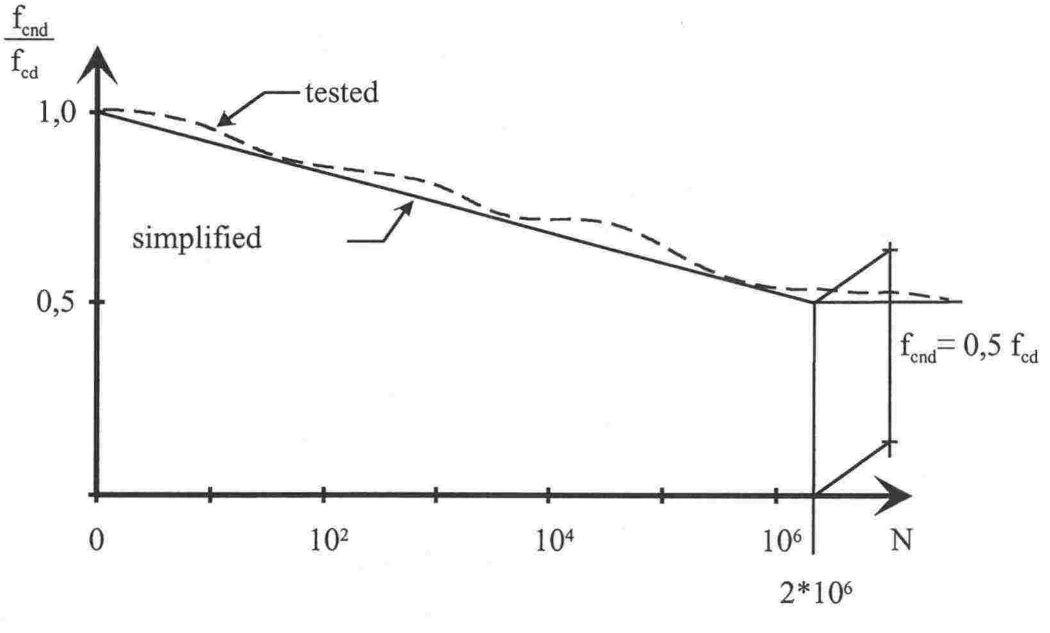


Figure 7.4:1 Principle of the simplified Wöhler curve.

Combining the above mentioned idea to the results of the loading tests performed earlier in the Laboratory of Foundation and Earth Structures at TUT regarding the appearance of the first cracks, it was concluded that the culvert can be assumed to have a service life of at least 100 years if the total tensile strain in the culvert under the combined effect of embankment weight and the train load would remain under 34,7 µstrain. The respective limit value for the compressive strains was concluded to be 47,5 µstrain. Therefore it was obvious that the critical distress would always be the tensile stress either at the top or bottom of the inner wall of the culvert or at the outer side wall of the culvert.

By combining the distresses caused by the train load and the weight of the embankment material itself a six grade classification for the expected service life of the culverts based on the tensile stresses was suggested. The classification is presented in Table 7.4:1. In Table 7.4:1 the notation IC stands for the initial compressive strain estimated to be caused by the lateral earth pressure in the embankment. Respectively, the limit value of 105 μstrain for the tensile strain corresponds roughly to the appearance of the first tensile cracks in the culvert element during the loading test (Chapter 6).

Table 7.4:1 Service life classification for concrete culverts based on tensile stresses.

Loading	Tensile train [μstrain]					
Train only	<34,7	<34,7	<34,7	>34,7	>34,7	>34,7
Train+embank-ment	<34,7	<34,7+IC	<105	<105	105< and <105+ IC	>105 +IC
Probability to reach the 100 year service life	Positive	Very likely	Likely	Unlikely	Very unlikely	Not fulfilled

7.5 Effect of the studied variables on the concrete culvert distresses

7.5.1 Summary of the calculated variations

First of all the calculations included a number of variations regarding the installation depth, diameter and shape of the concrete culvert. A summary of these variations is given in Figure 7.5:1. In the figure the installation depth should be understood as the distance between the top of the culvert and the level of the bottom of the sleepers.

Since the ratio between the culvert wall thickness and the diameter is slightly varying from one culvert size to another, a summary of the wall thickness/diameter ratios corresponding to the investigated culvert types is presented in Figure 7.5:2.

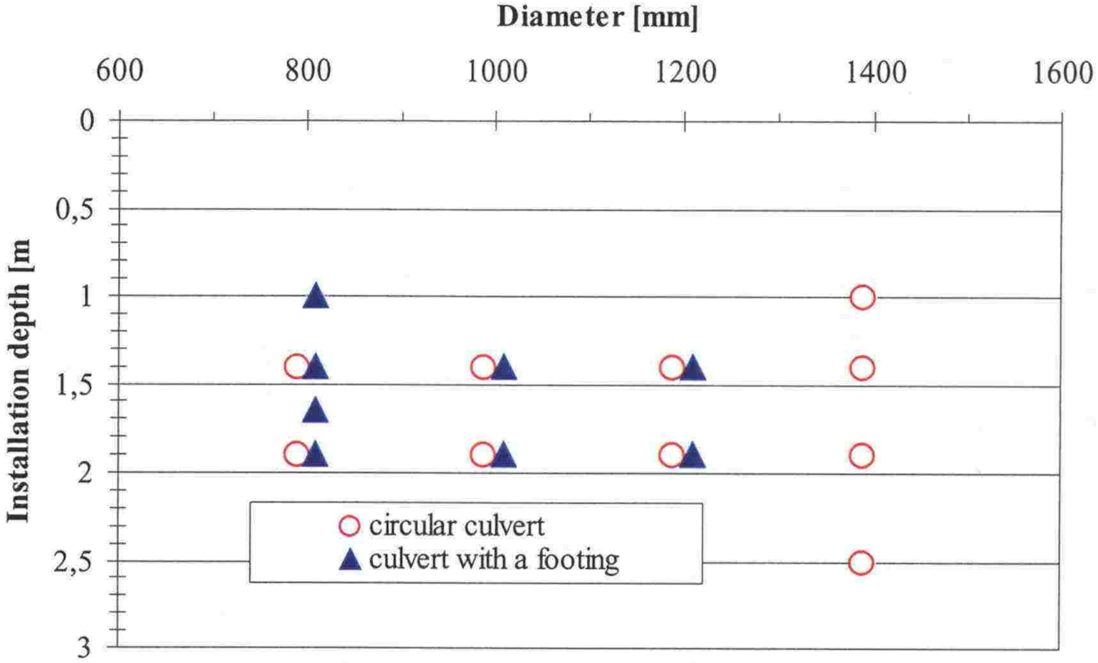


Figure 7.5:1 A summary of the geometrical variations in the performed calculations.

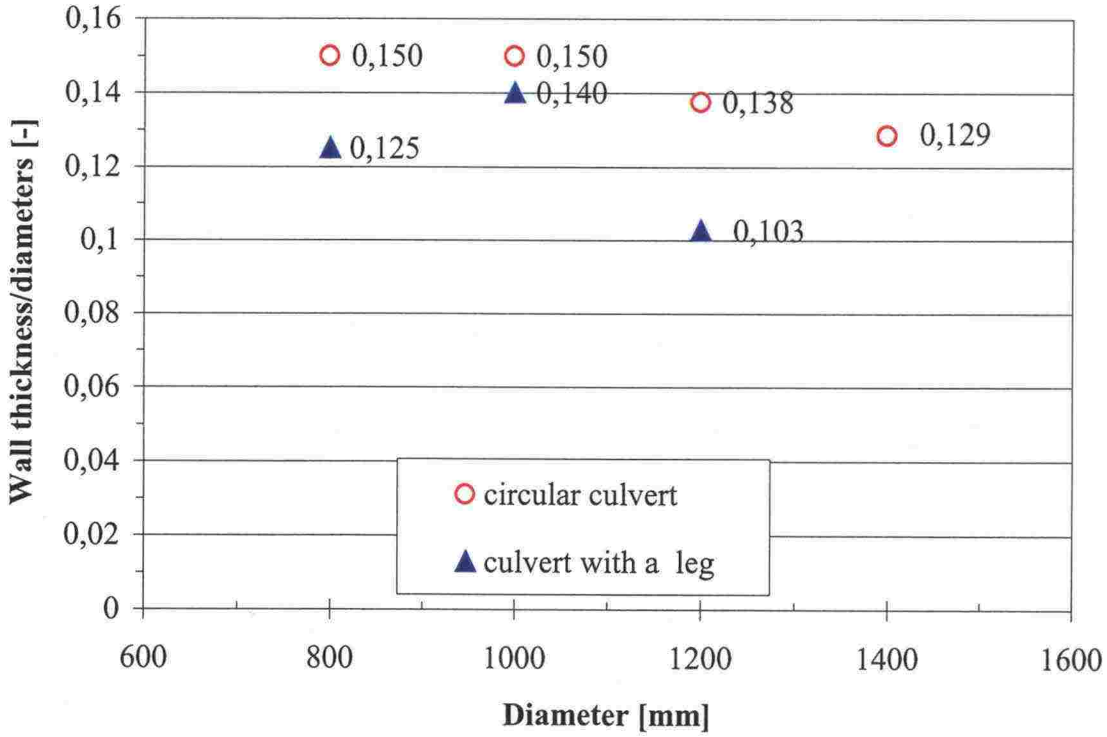


Figure 7.5:2 Summary of the wall thickness/diameters ratios of the investigated culvert types.

In addition to the geometrical variations summarised in Figure 7.5:1 the performed series of calculations included also the analysis of the effect of the following variables:

- Stiffness of the concrete was varied in terms of the value of Young's modulus from 30 000 MPa to 40 000 MPa.
- Stiffness of the embankment material was reduced either 25 % or 50 % in comparison to the values determined based on the in-situ measurements and the subsequent linear elastic modelling calculations (see Chapter 4).
- Two different stiffness values of the subsoil were investigated.
- The axle loads of 206 kN (21 tons), 250 kN and 350 kN with respective values of the Young's modulus of the embankment layers were analysed.

7.5.2 Concrete culvert at the Toijala test site

The calculated tensile strains due to the weight of the embankment material alone at the top and bottom of the inner wall and at the side of the outer wall of a culvert corresponding to the concrete culvert at the Toijala test site at different installation depths are shown in Figure 7.5:3. As Figure 7.5:3 indicates the tensile strains are increasing in almost linear relation to the installation depth.

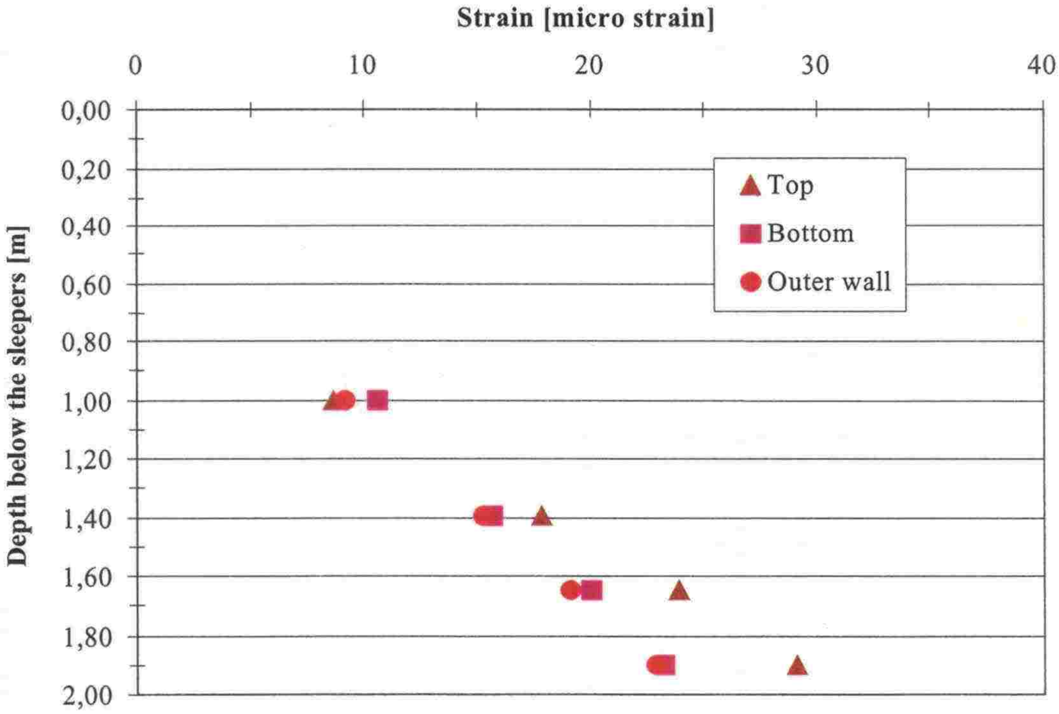


Figure 7.5:3 Tensile stains due to the weight of the embankment material in a concrete culvert similar to the one installed at the Toijala test site as a function of the installation depth.

Correspondingly, the tensile strains due to the axle loads of 206 kN (21 tons), 250 kN and 350 kN at the top and bottom of the inner wall and at the side of the outer wall of a culvert corresponding to the concrete culvert of the Toijala test site at different installation depths are shown in Figure 7.5:4. Quite expectedly the strains are now decreasing in relation to the installation depth of the culvert. The decrease is, however, not as liner as in the case of increase in tensile strains due to the weight of the embankment material as indicated in Figure 7.5:3.

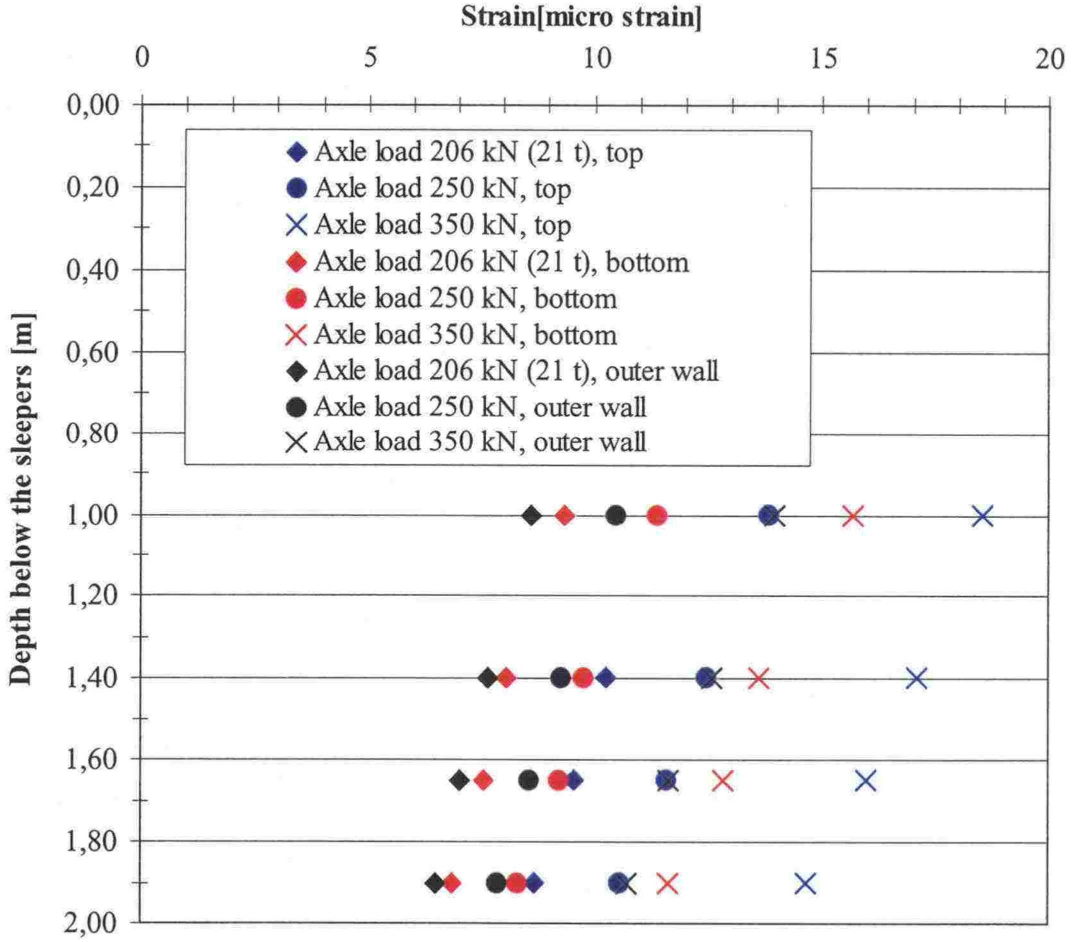


Figure 7.5:4 Tensile strains due to the train load in a concrete culvert similar to the one installed at the Toijala test site as a function of the installation depth.

Combining the results presented in Figures 7.5:3 and 7.5:4 Figure 7.5:5 shows the respective values of the total tensile strain due to both the weight of the embankment and the various train loads. As Figure 7.5:5 indicates the expected service life of 100 years is reached at least with the grade very likely for the axle load of 250 kN at all of the investigated installation depths. Only in the case of axle load 350 kN the grade is decreased to likely at installation depths larger that 1,5 meters. With regard to the tensile strains at base of the inner wall and at the side of the outer wall it can be concluded that the likelihood of reaching the expected service life is at least as good as in the case of tensile strains at the top of the culvert. The same holds even more true regarding the compressive strains experienced at the critical sections of the culvert due to the much higher value of the critical strain level in the case of compressive strains.

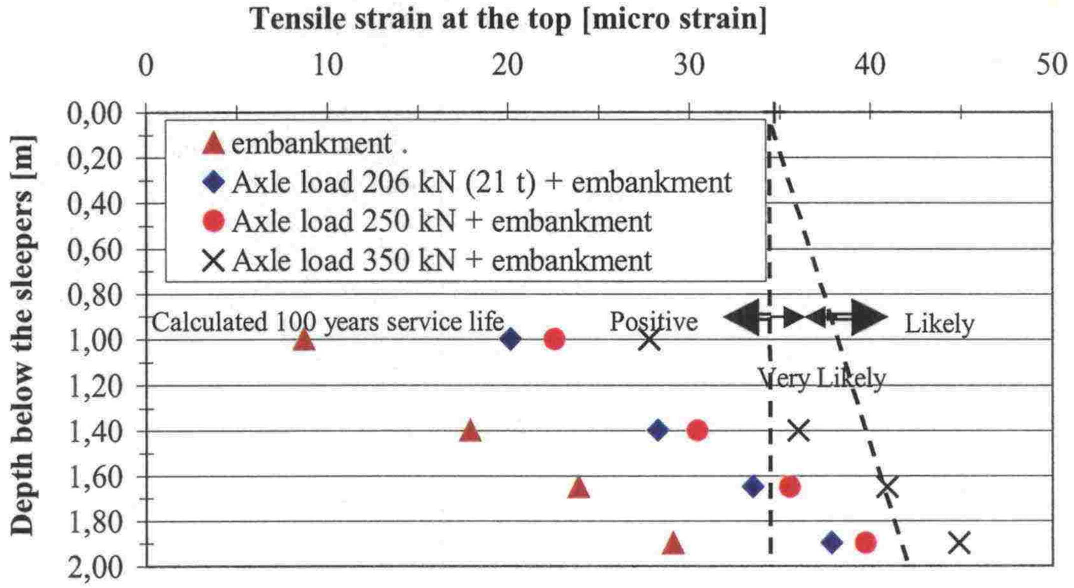


Figure 7.5:5 Total tensile strains at the top of the inner wall of a concrete culvert similar to the one installed at the Toijala test site as a function of the installation depth.

7.5.3 The effect of stiffness of the concrete

The effect of stiffness of the concrete was studied by investigating again the tensile strains at the top of the culvert inner wall in the case that the stiffness of the concrete would be 35 500 MPa in stead of the 40 000 MPa found appropriate for the culvert actually installed at the Toijala test site. The results of this investigation are summarised in Figure 7.5:5.

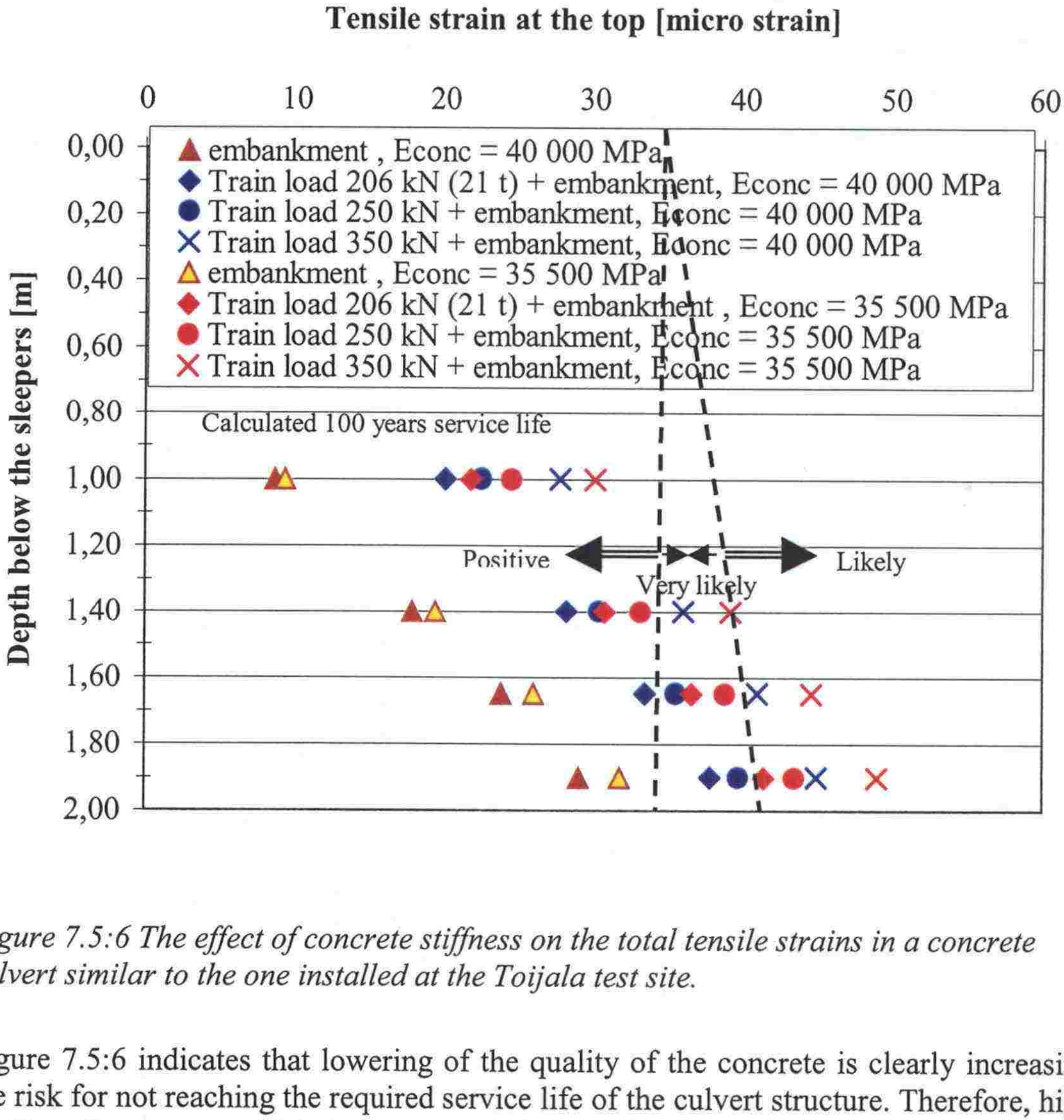


Figure 7.5:6 The effect of concrete stiffness on the total tensile strains in a concrete culvert similar to the one installed at the Toijala test site.

Figure 7.5:6 indicates that lowering of the quality of the concrete is clearly increasing the risk for not reaching the required service life of the culvert structure. Therefore, high quality of concrete, which in this connection can be understood as high compressive strength and thus high stiffness of the concrete, is essential in guaranteeing the expected 100 years service life of the concrete culvert.

Another example of the results of the performed calculations confirming the above mentioned conclusion is presented in Figure 7.5:7, in which the tensile strains due to both the weight of the embankment and the train load at the top of a 800 mm diameter concrete culvert installed at a depth of 1,9 m are presented. Again, the figure shows clearly that lowering of the quality of the concrete is increasing the experienced tensile strains and thus also the risk for shortening of the service life.

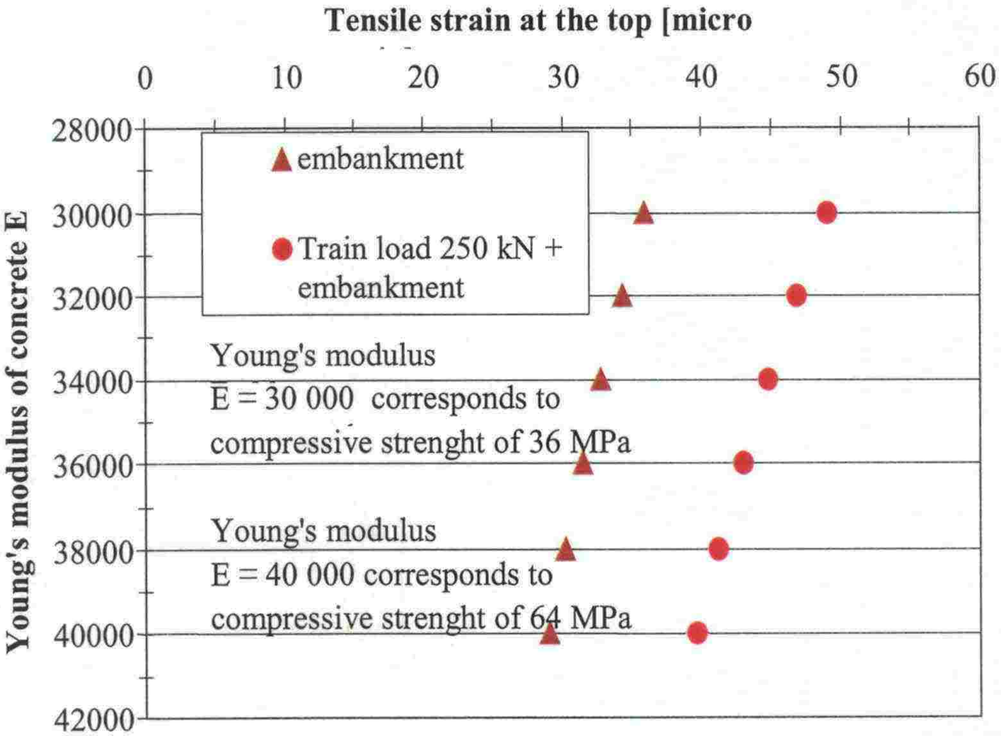


Figure 7.5:7 The effect of concrete stiffness on the tensile strains at the top of the culvert inner wall.

7.5.4 The effect of culvert diameter and shape

Investigations with regard to the diameter and shape of the culvert are summarised in Figures 7.5:8 and 7.5:9. In these figures the tensile strains at the top of the culvert are again presented at two different installation depths, 1,4 m and 1,9 m, as a function of the culvert diameter. The two shape variations to be considered were culverts which include a footing with a rectangular base and circular culverts without a footing.

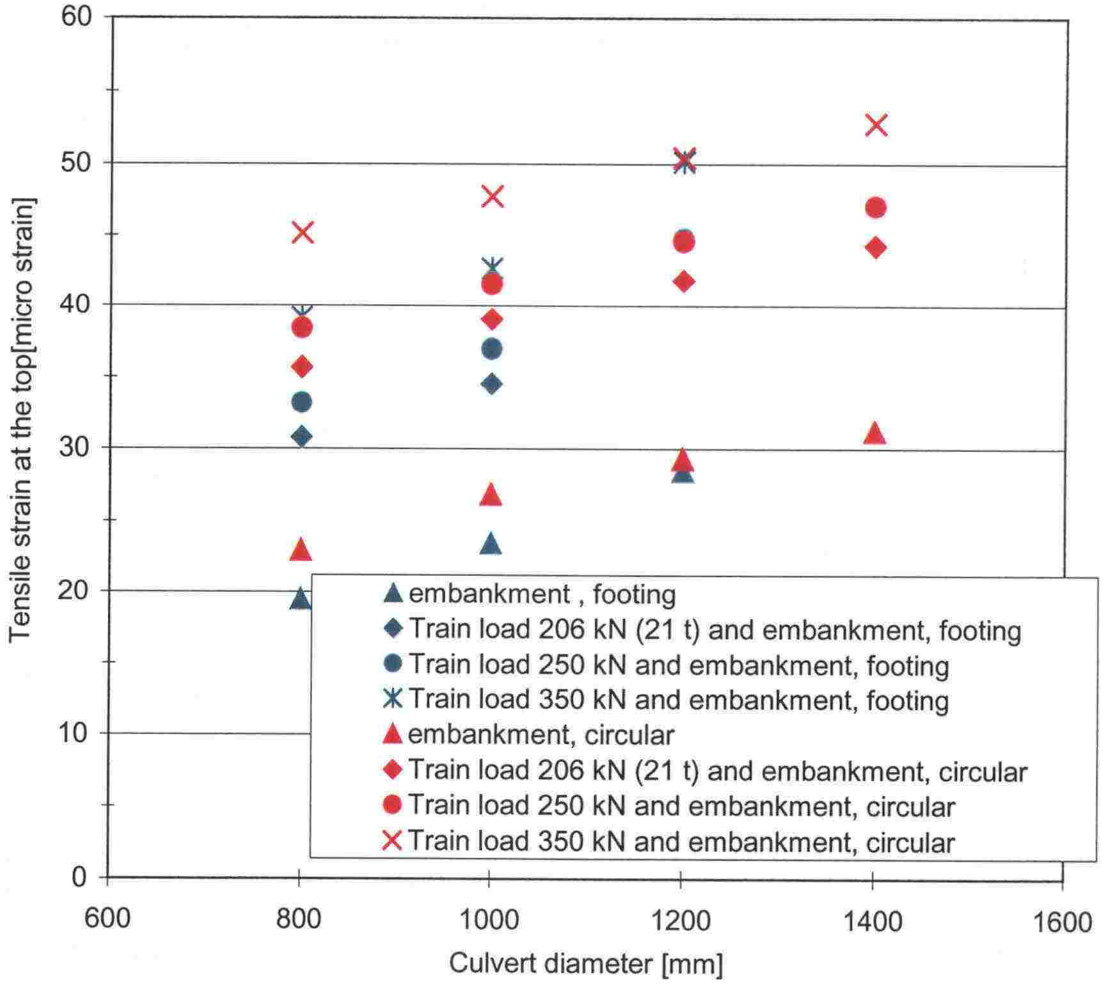


Figure 7.5:8 Tensile strain at the top of the culvert installed at a depth of 1,4 m as a function of the culvert shape and diameter.

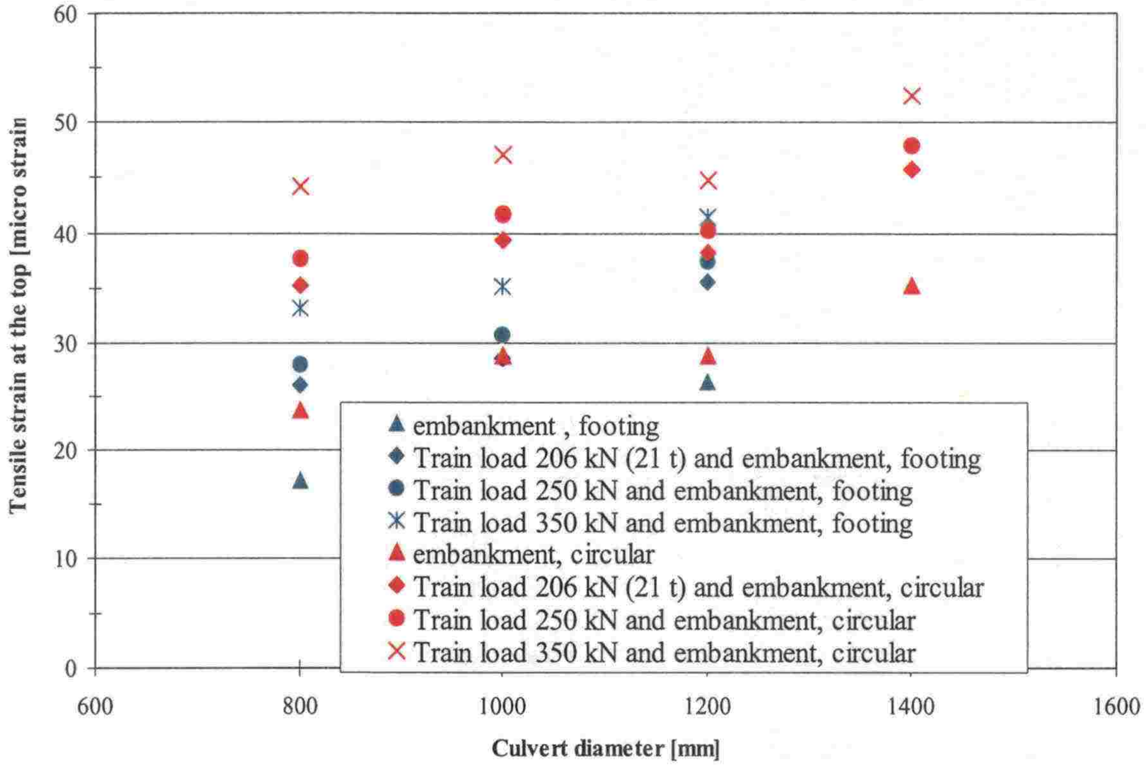


Figure 7.5:9 Tensile strain at the top of the culvert installed at a depth of 1,9 m as a function of the culvert shape and diameter.

Both of the figures above indicate that according to the performed calculations the relative proportion of the weight of the embankment in the total tensile strains is increasing alongside with the diameter of the culvert. Meantime, the tensile strains induced by the train load within the investigated types of culverts (see Chapter 7.5.1) are mainly depending only on the magnitude of the train load but not that much on the diameter of the culvert. However, when the two different culvert shapes are compared, it is quite obvious that tensile stresses are somewhat higher in the circular culverts than in those which have a footing that is supporting the culvert structure.

7.5.5 The effect of embankment material

The effect of the embankment material was studied by decreasing the values of Young's modulus in each of the embankment layer at first by 25 % and then by 50 % in comparison to the values presented above in Figure 4.2:1. The type of culvert structure was again corresponding to that of the Toijala test site. The results in terms of the tensile strain at the top of the culvert are presented in Figure 7.5:10.

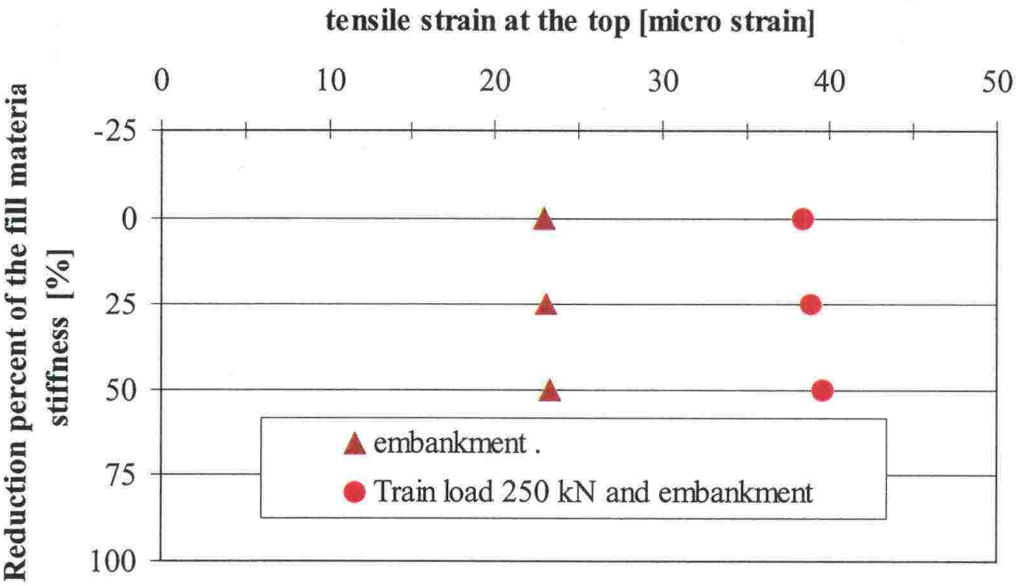


Figure 7.5.10 The effect of stiffness of the embankment materials on the tensile strains at the top of the 800 mm diameter concrete culvert installed at a depth of 1,4 m.

Based on Figure 7.5:10 it is quite evident that the stiffness of the embankment material does not have a primary effect on the tensile strains that are to be experienced by the culvert.

7.6 Comparison of the FE modelling and the hand calculations

The differences in the tensile strains at the top of a concrete culvert corresponding to the Toijala test site predicted by the Finite Element modelling calculations and the hand calculation method presented in the existing design code for concrete culverts 'Betoniputkinormit 2001' are compared to the measured ones in Figure 7.6:1.

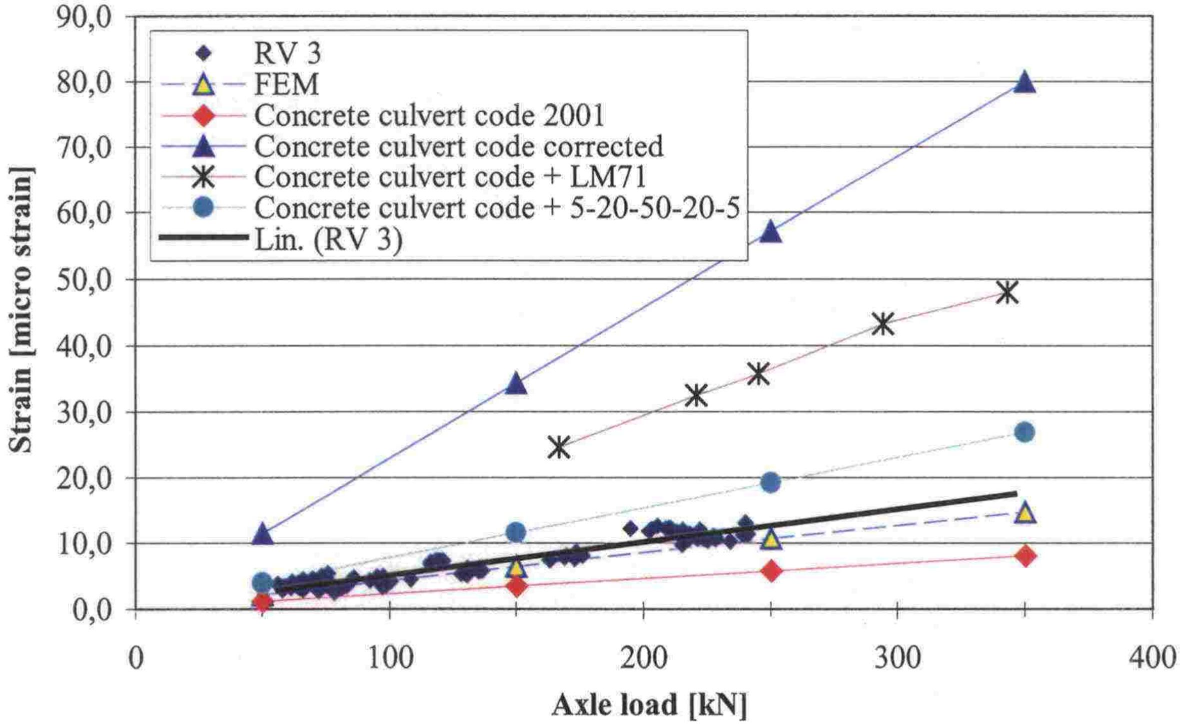


Figure 7.6:1 Comparison of the predicted tensile strains at the top of the culvert to those measured at the Toijala test site.

First of all it must be noted that the vast differences in the predictions obtained by the various hand calculation approaches are explained partly by an error in the formulas presented for the calculation of bending moment and normal force in the 2001 version of the design code for concrete culverts. Thus, the lowest estimates based on the wrong formulas are only 10 % of the predictions that are obtained when correct formulas for the bending moment and normal force are used.

As Figure 7.6:1 indicates the correct version of the calculation method presented in the design code for concrete culverts overestimates the strains several times. The reason for this is, however, more due to the loading assumptions made in the design code than due to the calculation method as such. This is visualised in Figure 7.6:1 by the hand calculation result indicated with round symbols. In that case the nominal axle load is assumed to be transmitted to the embankment exactly in the same manner as in connection with the FE calculations (see Figure 7.6:2). As a result, the predictions obtained by the hand calculations are only 50 % higher than the average trendline of the actual measurement results from the Toijala test site.

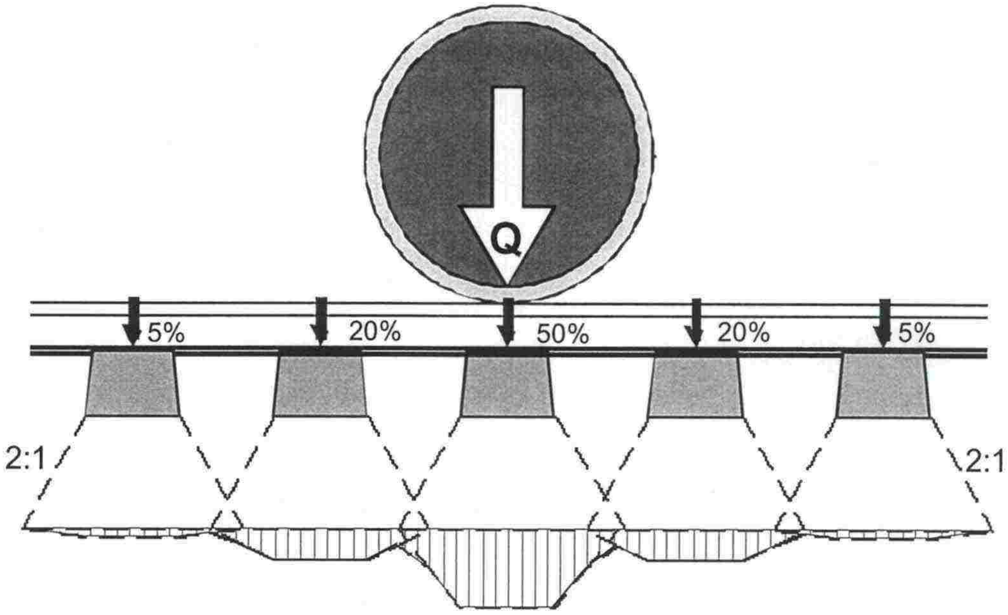


Figure 7.6:2 Assumed distribution of a single axle load in the calculation indicated by round symbols in Figure 7.6:1.

One more conclusion from the Figure 7.6:1 is that with regard to the stresses and strains experienced by a concrete culvert in the railway embankment the loading assumption of the Eurocode, LM-71, is also fairly much on the conservative side.

As a final conclusion regarding the various calculation methods it can be concluded that the accuracy of the predictions obtained from the performed Finite Element calculations are superior to any of the available hand calculation methods.

8 CONCLUSIONS

8.1 Instrumentation of the Tampere test site

- Instrumentation of the Tampere test site in summer 2001 succeeded well and an abundant amount of measurement data to be used in verification of the results of the Finite Element modelling was managed to be acquired.

- The measurement data included strain measurements at eight different points on the inner wall of the 1200 mm diameter culvert and changes of the culvert diameter in horizontal and vertical directions both at two different cross sections. All these were recorded as a function of the vertical rail forces in both of the rails.

8.2 Temperature measurements at the Toijala test site

- Temperature measurements were performed at the Toijala test site during the winter period 2000–2001 and the early autumn 2001 at altogether 19 measurement points both below the concrete culvert installed across the railway embankment and inside the embankment surrounding the culvert.

- The measurement results indicated that in the vicinity of the culvert the embankment material was freezing clearly quicker than the embankment without a culvert. Near to the culvert the freezing front was also penetrating clearly deeper and thus leading to the risk of frost heave in the frost susceptible subsoil even during a relatively mild winter like that in between years 2000–2001.

- The most efficient ways to avoid excessive freezing of the neighbourhood of the open ended culvert would be some sort of measures to prevent air flow trough the culvert. If these prove out to be too complicated to realise, another alternative might be the use of XPS type of frost insulation boards installed below and on the sides of the culvert.

8.3 Finite Element modelling calculations

- The Finite Element model was successful in prediction of the actual responses of the concrete culverts both at the Toijala and at the Tampere test sites with an accuracy of +/-15 % when material parameters determined based on the performed laboratory measurements were used. Taking into account the simplifications made for instance in selection of the material model used for the unbound embankment materials this can be considered as a very good result indeed.

- The prediction of the mechanical behaviour of the Toijala test site, where also the embankment was instrumented, can also be considered as successful with regard to the vertical stresses and strains of the embankment. However, in horizontal direction the predictions were much poorer mainly due to the anisotropic behavior of the embankment materials.

- Because some of the measured responses indicate clearly non-linear behaviour towards increasing deformations as the axle load is approaching the value of 250 kN, extrapolation of the application area of the presented calculation model much beyond that limit may be risky and clearly on the unsafe side.

8.4 Service life of the concrete culverts

- According to the suggested classification system to estimate the service life of concrete culverts based on the Wöhler curves the critical distress is the tensile strain experienced at the top of the inner wall of the culvert.

- All of the investigated culvert installation conditions could be classified to meet the expected service life of 100 years at least with the grade *likely*. Furthermore, it must be noted that the classification deals with the likelihood of the appearance of cracking into the culvert, after which a reinforced concrete culvert may of course still survive for many years.

- There is not any reason to reduce the currently applied minimum installation depth of 1,4 m for concrete culverts due to a number of factors that may turn the loading conditions to more unfavourable ones in comparison to the performed modelling calculations. These include for instance unhomogeneities in the embankment material, poor compaction of the fill around the culvert, temporary high peak loads e.g. due to flat wheels etc.

- An efficient way of guaranteeing the long service life of concrete culverts is to keep the quality of concrete high enough. Another way of prolonging the service life would be to increase the wall thickness and thus to reduce the tensile strains experienced by the culvert at the critical points. However, the effect of the later mentioned action was not studied in this research.

8.5 Comparisons between the hand calculations and the FE model

- In the year 2001 version of the design codes for concrete culverts there is an error in the formulas that are used to calculate the bending moment and normal force in the wall of the culvert. Thus the calculations made according to that procedure are underestimating the distresses experienced by the culvert.

- If correct forms of the above mentioned formulas as used, the calculated distresses are clearly over-estimated. This is, however, mainly resulting from the load assumptions made in the code rather than due to the calculation method as such.

- If the load assumption in the hand calculations is made comparable to the Finite Element Model and correct form of the formulas for bending moment and normal force are used, the over-prediction of the distresses in the hand calculations is on a fairly reasonable level, of the order of 50 %.

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