Deltares

Analysis of track and soil behaviour at transition zones

Case study near Gouda Goverwelle

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Deltares

Title
Analysis of track and soil behaviour at transition zones

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Keywords
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Summary
At a transition zone at Gouda Goverwelle both long-term and short-term measurements are performed to analyse the performance and track degradation. At the measurement site, the track crosses a culvert founded on piles. The embankment at which the measurements are performed has a thickness of about 4 m. It was build about 15 years ago on a typical Dutch soft soil. The transition is created by an approach slab at both sides of the culvert. The length of the slab is 4 m. The transition requires a lot of position maintenance.

In this report, the measurements are analysed and formulated research questions are answered. Main observations are:

- Above the slab a void under the sleepers is present. It is expected that this hanging distance (height of the void) develops shortly after maintenance.
- The toe of the approach slab is found to settle two to three times as fast as the autonomous settlement of the subsoil.
- During train passage, the rail deflection at the approach slab is larger than on top of the culvert or the free embankment.
- The rail deflection at the approach side of the culvert differs significantly from the rail deflections at the depart side of the culvert.
- The rails show seesaw behaviour with the culvert as hinge when a train passes.
- The embankment moves vertically when trains pass on track 1 and rotates towards the old embankment when trains pass on track 2.

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1	Nov. 2009	dr. ir. P. Hölscher dr. ir P. Meijers		ir. A. Verweij ir. H. Brinkman		ing. M. Hutteman	

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1 Introduction

1.1 Background

The Dutch rail network is one of the busiest in the world. Structural, partly preventative, maintenance of the rail infrastructure is essential to ensure that such a busy network remains safe and free of faults. A substantial amount of position maintenance is currently necessary for the upkeep of the Dutch rail network and, in comparison with neighbouring countries, considerable wear and tear is apparent on the rails and rail joints. The soft subsoil provides a plausible explanation for this, particularly in the western part of The Netherlands. The consequences of this situation are relatively large amounts of position maintenance, especially on transitions between embankments and engineering structures, and a relatively large number position maintenance of related to faults, particularly where switches are located.

Delft Cluster investigates the impact of the dynamic behaviour of the subsurface on degradation and the associated position maintenance. The research mainly focuses on specific components of the rail network, namely transition zones and switches.

In the research plan ‘Impact of Dynamic Subsurface on Transitions and Switches’ dated 18 December 2006, the research was described in greater detail. Part of the research is to conduct field tests to analyze possible failure mechanisms in track and subsoil. A research site was selected near Gouda Goverwelle in the western part of the Netherlands. In 2008 and 2009 field measurements have been performed at a transition zone and at a switch.

The target of this report is the interpretation and conclusions from all field measurements at the Railway Transition Zone (RTZ) of a culvert near Gouda Goverwelle.

Three types of measurements are done: measurements for the long-term behaviour (period June 2008 – June 2009) and two measurements for the short-term behaviour (May 2008 and May 2009). Short-term refers to the period of one passing train. Long-term refers to the behaviour during the whole measurement campaign, which is about 1 year. The performed measurements are reported in the following four factual reports:

- Factual report field survey [Deltares, 2009a].
- Factual report short-term 2008 [Deltares, 2008].
- Factual report short-term 2009 [Deltares, 2009b].
- Factual report long-term [Deltares, 2009c].

In this report, the validity of the measurements is discussed and the originally posed research questions are answered.

1.2 Research questions

Based on the literature research (see [GeoDelft 2007b], [GeoDelft 2007c]), the field test of 2008 was carried out in May 2008 [Deltares, 2008]. During this short-term measurement the results showed a large influence of the hanging sleepers in front of the culvert [Coelho *et al*, 2009]. The field measurements of 2008-2009 were meant to elucidate the reason of this observation empirically.

The long-term measurement focuses on the mechanisms that might be responsible for the development of the hanging distance on the long-term, say a few days to a couple of weeks.

The following questions aroused:

- What is the development of hanging distance of the sleepers?
- What is the development of track level?
- What is the influence of the autonomous settlement of the embankment to the hanging distance?
- What is the contribution of the horizontal expansion of the ballast and the embankment to the hanging distance?
- What is the contribution of the motion of the approach slab to the hanging distance?
- What is the contribution of the water table in the embankment to the hanging distance?

The short-term measurement focuses on the possible contribution of the dynamic loading from train-passages to the development of the hanging distance on the long-term. The phrase short-term therefore refers to the passage of a single train.

The short-term measurement focussed on the answer on the following questions, that aroused from the results of the first short-term measurement in May 2008:

- Is the response of the system symmetric over the culvert?
- What is the background of the sharp upward peaks observed in the 2008 measurements?
- Does the embankment moves vertically as rigid body on the soft soil?
- Does the embankment rotate as a rigid body?

1.3 Measurements

To answer the questions on long-term behaviour the following parameters were measured [Deltares 2009b][1]:

- Horizontal motion of the ballast.
- Horizontal motion of the sand.
- Track geometry (unloaded track).
- Water pressure under the structure.
- Hanging distance of the sleepers.

These variables had been monitored during 1 year, only the hanging distance is monitored during 3 months (April-July 2009). Other data available are the results of the Eurailscout measurements, which are carried out regularly.

The measurement should give information on the magnitude each variable as a function of time. The hanging distance of the sleepers is considered as the source of the problem. The levelling of the sleepers should give information on the settlement of the embankment and the ballast. The last three variables are possible sources of the problem.

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1. It is strongly advised to have the report “Factual report long-term measurement” reference 1001069-000-GEO-0005 [Deltares 2009b] at hand while reading this report

To answer the questions on short-term behaviour the following parameters have been measured during train passages on May 4 2009 [Deltares 2009c]:

- Dynamic force on the track.
- Dynamic motion of the track.
- Dynamic motion of the ballast, embankment and subsoil.
- Pore water pressures.

Other data available are the axle load measurements by the Gotscha Quo Vadis system west of Gouda which are measured continuously.

1.4 Outline of the report

This report starts with a general description of the situation and geotechnical description of the site, including the water table from the pore water measurements in Chapter 0.

Before discussing the answers to the research questions, the results of the measurements are evaluated in general terms in Chapter 3. Here, a distinction between the short-term measurements and the long-term measurements is made. The validation of the BHM developed by Baas and ProRail is discussed in this Chapter 4. This refers to both the short-term and the long-term behaviour.

The questions related to the long-term behaviour are discussed in Chapter 5. These questions are mainly answered by the results of the long-term measurements, but sometimes the results of the short-term measurements are invoked to elucidate some aspects or to give a stronger support to the conclusions.

The questions related to the short-term behaviour are discussed in Chapter 6.

Further, we expect that the results of measurements in general will give additional information on mechanisms that are not expected beforehand. Therefore, some general judgement and discussion on the results of the measurements are required. These aspects are discussed in Chapter 5 and 6 as well. Conclusions are summarised in Chapter 7.

2 Geotechnical description of the site

2.1 General description

The test site is situated in the railway link Utrecht-Gouda, east of the railway station Goverwelle, a suburb of Gouda.

At the considered location, a watercourse crosses the railway though a culvert. The culvert is founded on piles and may be considered as a fixed point.

Figure 2.1 Location test site (Google maps)

Figure 2.2 Location test site (picture taken from the working road north of the track)

Figure 2.3 Location test site (picture taken from the south side of the track)

The original railway link Gouda-Utrecht was constructed in 1855. In (approximately) 1995, the section of the link near Gouda was widened from a two-track line to a four-track line by adding two tracks at the northern side of the existing railway embankment. The measurements are performed at the northernmost track of this most recent side of the embankment.

The construction of the culvert is shown in Figure 2.4, taken from the construction drawings by Romein Beton, 420/105/28.773/592/10, revision 31-8-94.

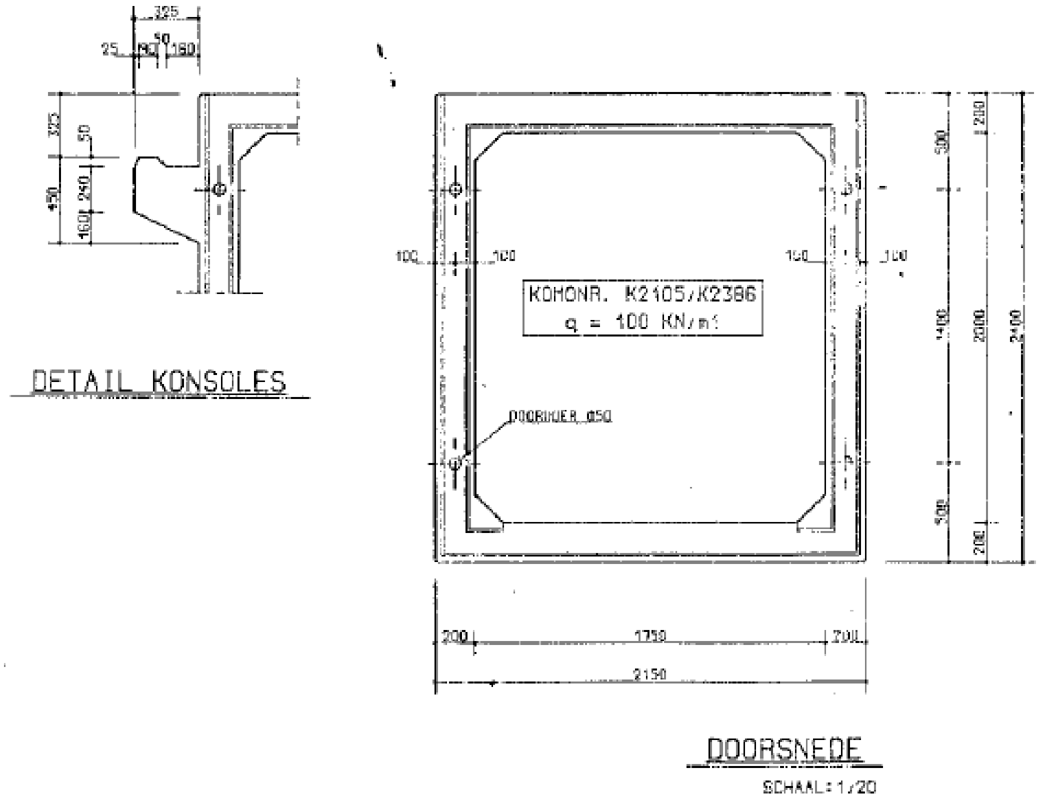

Figure 2.4 *Dimensions culvert*

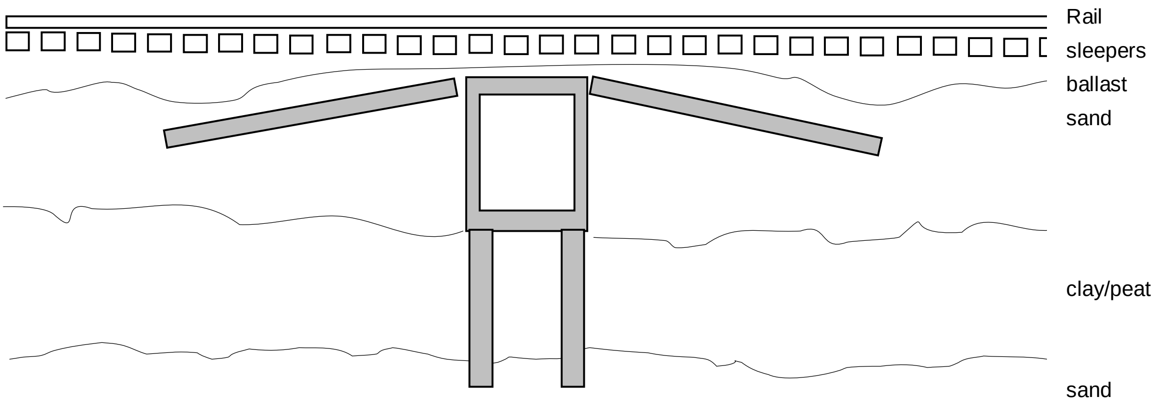

Figure 2.5 *Schematic view of culvert construction with approach slab*

The length of the approach slab is 4 m, the thickness 0,3 m and slope at which the slab is installed at construction was 1:40.

The designed top of the rail (B.S.) is at NAP + 0.33 m. The top of the ballast is at present at approximately NAP + 0 m. From the performed CPT's it is concluded that the thickness of the embankment (sand plus ballast) is 4 m thick (see section 3.2). The performed GRP (Ground

Penetrating Radar) and the inspection of the dug holes shows that the thickness of the ballast is 0.5 to 1.2 m.

2.2 Soil profile

Based on the CPT's, VSPT's and radar measurements the following description of the site is made. Figure 2.6 shows a in a longitudinal profile over the culvert the results of the performed CPT's.

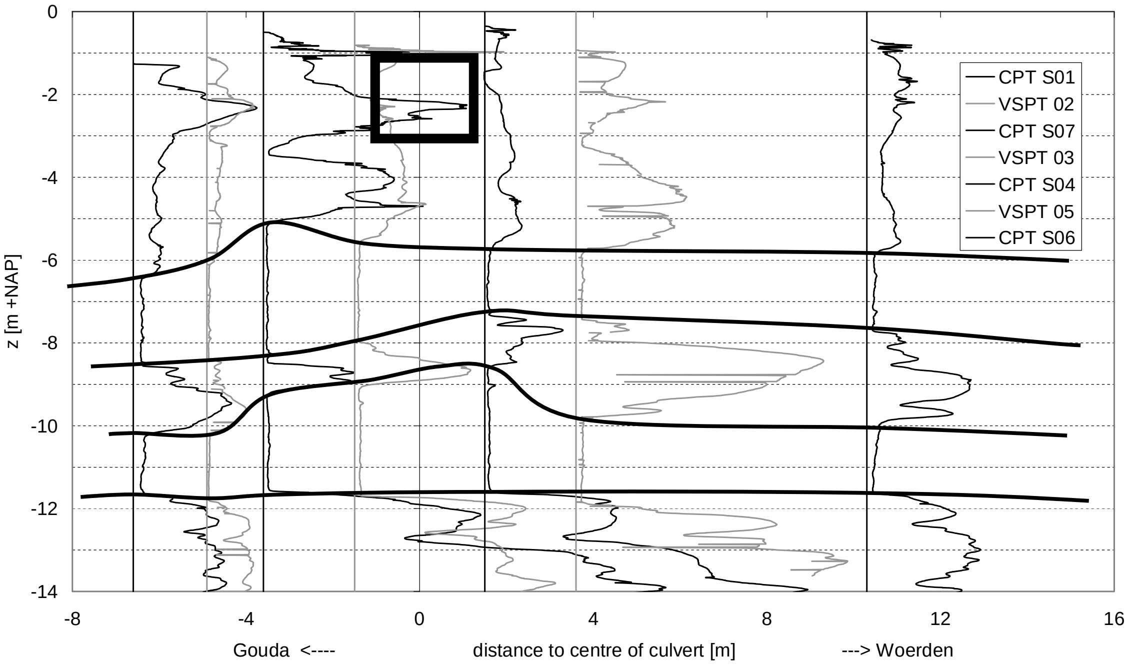

Figure 2.6 Soil profile at culvert, the position of the culvert is indicated with a rectangle

The top of the subsoil consists of a layer of sand, the embankment of the railway. At the east side (Woerden side) of the culvert the lower boundary of the embankment is at NAP – 5.5 m. At the switch the lower boundary is at approximately NAP – 4 m.
At the west side (the Gouda side) the lower boundary of the embankment varies. Just west of the culvert the lower boundary is locally at approximately NAP – 5 m. At 6 m distance the lower boundary is at approximately NAP – 6.5 m. At the dirt road the lower side of the embankment sand layer is encountered at about NAP – 3.5 m.
The cone resistance in the embankment sand varies considerably, indicating varying relative density of the sand in the embankment. It is noted that the absolute value of the cone resistance measured at VSP 02 is unreliable.

Locally, a thin clay layer is present in the embankment at about NAP – 2 m to NAP – 2.5 m. This clay layer is observed in VSP02, S07 and VSP05. It may be this thin clay layer that was detected in one of the hand dug holes (see section 2.3) at the Woerden (east) side of the culvert.

Near the culvert, the top of the pleistocene sand is at approximately NAP – 12 m. The depth increases a little in eastern direction. At the switch, the top of the Pleistocene sand is at NAP - 10 m. This indicates that the top of the Pleistocene first drops and than increases in the eastern direction.

Below the embankment, a soft soil layer is present, mainly consisting of peat. In this layer, a sand layer is present. The thickness of this sand layer varies greatly. At the culvert the thickness is 0.5 to 1 m. In the western (Gouda) direction, the thickness increases somewhat and in the eastern (Woerden) direction it increases strongly. The cone resistance of this layer varies between 10 and 20 MPa.

The thickness of the peat layer is about 5 m at the Gouda side and 3.5 m at the Woerden side of the culvert.

The VSPT tests of 2008 had to be repeated in 2009 due to a defect in the device. Therefore six new VSPT tests were performed in 2009, three in the dirt road just north of the track and three in the railway embankment itself. The three VSPT's in the railway embankment are processed and analysed in more detail. The three VSPT's at the dirt road served as double check of VSPT cone performance.

In the embankment, the shear wave velocity Cs of the sand could not be reliably measured. In the peat layer, the shear wave velocity is about 50 m/s for the peat above the intermediate sand layer and 80 m/s for the peat below this sand layer. In the intermediate sand layer the shear wave velocity is about 150 m/s.

2.3 Embankment profile

Both at the east and at the west side of the culvert three holes have been dug through the ballast for inspecting the construction of the embankment. The thickness of the ballast, with respect to BS, varied from 0.7 m close to the culvert to 1.4 m near the toe of the slab.

The mixing of ballast and sand was not studied in detail. The excavations suggested that some mixing takes places, but due to the application of 'small' holes, the observations are inconclusive. During the excavation continuously, ballast rolled from the edges into the pit. However, a mixed zone of about 20 cm seems possible.

3 General evaluation of the measurements

3.1 Introduction

In this chapter the validity of the data obtained in the field measurements is discussed. First the long-term measurements are discussed, secondly the short-term measurements. The calibration of the BHM (TLMS) is discussed in Chapter 4.

3.2 Long-term measurements

The long-term measurements consist of:

- Levelling of the position of the rail.
- Levelling of overhead line pylons.
- Levelling top of slab.
- Measurement of the hanging distance.
- Ground penetrating radar measurements (GPR).
- Track level measurement system.
- Inclinometer measurements.
- Water table measurements.

3.2.1 Levelling data

Comparing the different levelling data did not yield any remarks on these data.

3.2.2 Hanging distance

The hanging distance of 15 sleepers is measured for a limited period of 2 months (from April 21 2009 till June 30 2009). The reported data do not indicate any severe error in these measurements. Within the period of measurements, no time dependent behaviour of the hanging distance could be observed. However, as will be shown in Section 5.4, the accuracy of these transducers is limited.

3.2.3 Ground Penetrating Radar

For the time – depth conversion in the GPR measurements, a dielectric constant is needed. For this use is made of data on the depth of the slab as provided by Deltares. The following data are used.

Position with respect to centre of culvert [m]	Lower side ballast [m – BS*]	Top of slab [m – BS*]
-4.8	1.1	
-2.4	1	1.4
-1.2		
0		
1.2		
1.8	0.7	1.2
3.7	1.3	1.55
5.6	1.4	
BS = Bovenkant Spoor = top of rail		

Table 3.1 Data from hand-dug holes used for time-depth conversion of GPR measurements

For track 147, a comparison is made between the reported level of the slab from the GPR measurements and from the dug holes. The horizontal axis is the coordinate system used for the GPR measurements. The centre of the culvert is at about x = -7m.
It is assumed that the difference between BS (top of rail) and top of ballast is 0.15 m.

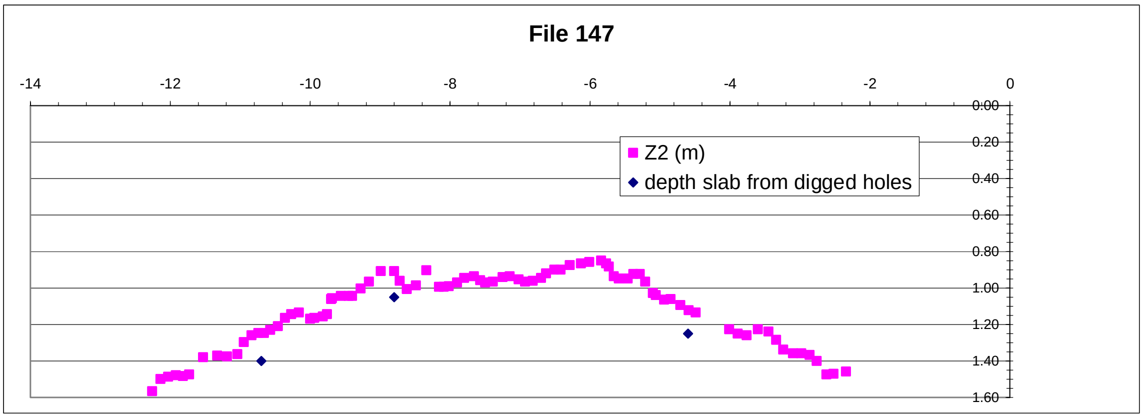

Figure 3.1 Check used time-depth conversion GPR measurement

This comparison suggests that the depth of the slab according to the hand dug holes is about 0.05 m to 0.1 m as follows from the GPR results. This may be interpreted also that the depths of the GPR may have to be multiplied with a factor of 1.05 to 1.1.
When using an offset (height of rail) of 0.2 m the agreement is satisfactorily and no further corrections are needed.

Finally it is mentioned that the annexes in the report by Geofox-Lexmond on the GPR measurement (version 1, dated 14 April 2008) are incorrect. The correct profiles are provided contained in a spreadsheet.

3.2.4 Baan Hoogte Meetsysteem (BHM) - Track level measurement system

The long-term measurements of the BHM are discussed separately in Chapter 4.

3.2.5 Horizontal motions from inclinometers

At seven locations, inclinometer tubes were installed to investigate horizontal movement of embankment and track. The inclinometers have been read monthly. The readings turned out to be too low to give reliable numbers. After half a year the monthly reading is stopped. One year after installation a final reading is made.

Figure 3.2 shows the position of the inclinometers.

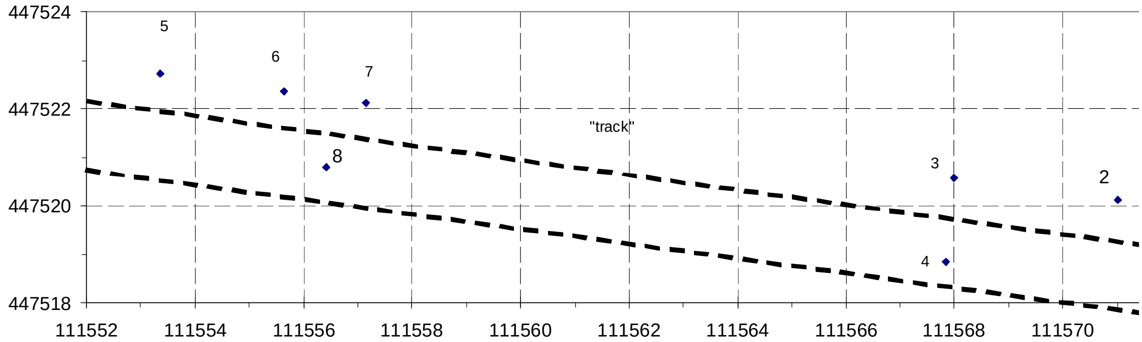

Figure 3.2 Position of the inclinometers

During an inclinometer reading, the deviation from the vertical at all depths is measured. Assuming that the deviation is valid for the interval around the reading, it is possible to determine the horizontal motion. The displacement is found by integration of the measured angles of the inclinometer tube.

The reliability of the measurements for the depth used here; it is about 2.5 mm at the top. All readings are were too small in comparison with the reliability of the device. During the one-year period, no specific trend in horizontal deformations could be seen.

Figure 3.3 shows the results of two inclinometers. Inclinometer 4 (the one with the largest measured value; right hand side in Figure 3.3) seems to move reasonably steady to the north direction. However, inclinometer 3 (left hand side in Figure 3.3) shows no steady motion in north direction. The expected horizontal motion of either embankment or track was not found in the inclinometer measurements.

The final conclusion is that the horizontal motions in the embankment are smaller then the accuracy limit of the inclinometer, thus smaller then a 2.5 mm per year.

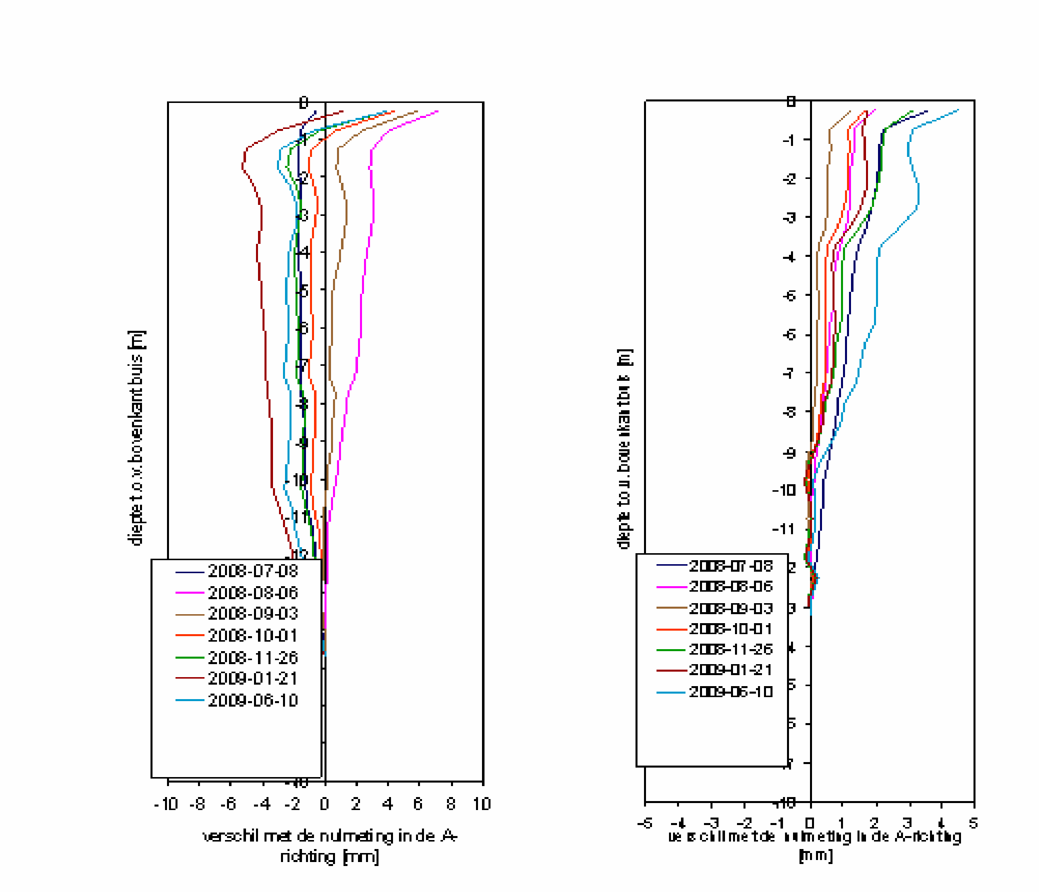

Figure 3.3 *Results of inclinometer measurements*
Left: Inclinometer number 3, motion in North direction
Right: Inclinometer number 4, motion in North direction

3.2.6 Water table

The long-term pore water pressure is measured during almost 1 year at two locations near the culvert (the first one just before the approach slab and the second one at the other side directly behind the approach slab). The first three months, only a few readings are available, later on four readings a day are available. The level of the two transducers is at NAP – 3 m. WSM1 is located at the eastern (Woerden) side of the culvert and WSM2 at the Gouda side.

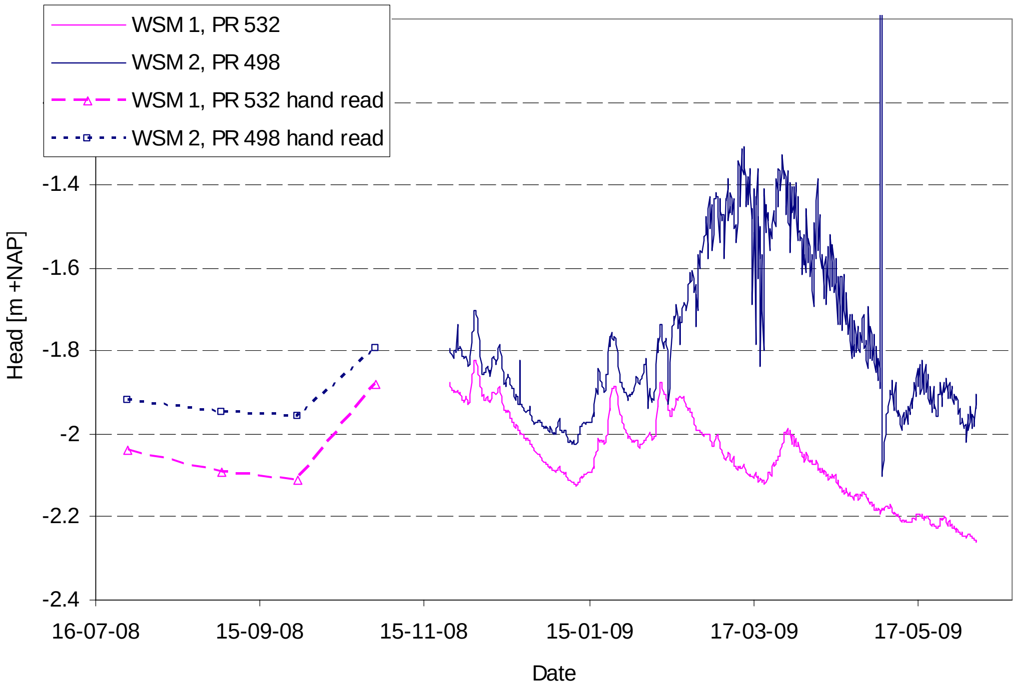

Figure 3.4 Piezometric head in the embankment near the culvert

Figure 3.4 shows the piezometric head, based on the measured pore water pressure and the depth of the transducers. Three periods can be distinguished:

1 The hand readings from July to November.
2 The automated readings from November till February showing similar behaviour.
3 The automated readings from February till June showing dissimilar behaviour.

In the first two periods there is a small and consistent difference in the piezometric head of 0.1 m. This may be due to small errors in the zero levelling of the transducers.

Figure 3.5 shows the precipitation measured by the Royal Netherlands Meteorological Institute (KNMI) in the station Rotterdam. The peaks in the water table reasonably coincide with days of heavy rains. The relation is not unique, maybe because heavy rain can be very local.

There is no physical explanation for a large difference in piezometric head between WSM1 and WSM2 in the third period. The precipitation data do not indicate any reason for a much higher water table in the third period, compared to the remaining part of the measurement period.
The level of the dirt road north of the railway link is at NAP – 1.4 m, the ground level of the polder will be even lower. A piezometric head of NAP – 1.4 m in the embankment suggests flooding of the area adjacent to the railway link, which is not reported. Therefore, it is expected that pore water pressure transducer 498 did malfunction in the third period.

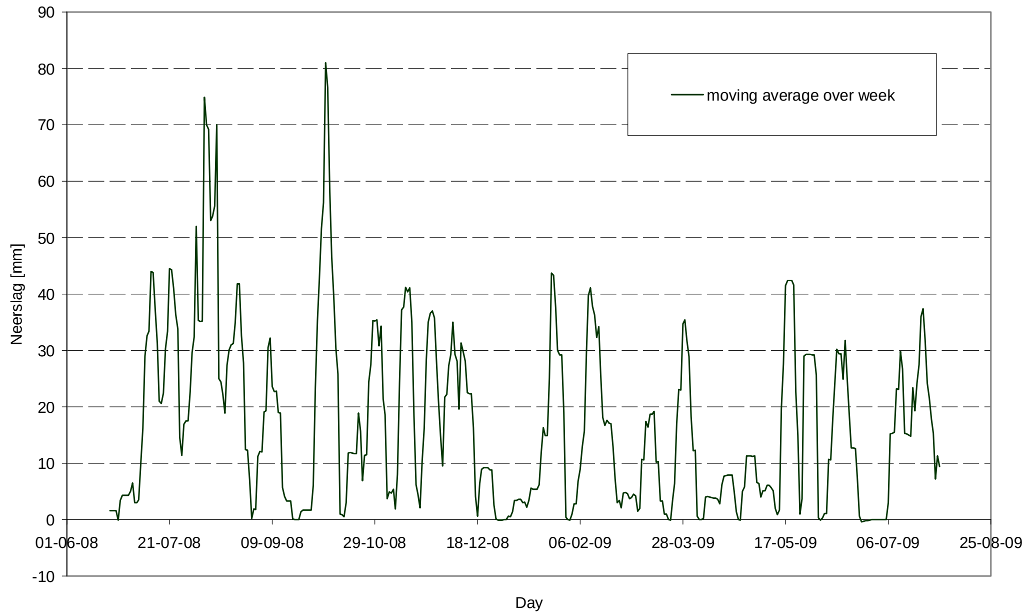

Figure 3.5 Precipitation in measurement period [source: Royal Netherlands Meteorological Institute]

Five CPT's (1, 3, 4, 6 and 7) are performed as piezocone soundings. These CPT's are performed at 2008-01-07. From this, it is concluded that the water table at the time of the soil investigation is at about NAP - 2 m. The results of the piezocone measurements do not indicate any difference in piezometric head between the railway embankment, the intermediate sand layer and the Pleistocene sand.

3.3 Short-term measurements

During the 2009 short-term measurements the following instruments were used [Deltares, 2009c]:

- Ten accelerometers at surface (in the ballast) and four sets of three accelerometers at depth (in the embankment and the soft soil) (data recorded by Deltares).
- Nine geophones on the sleepers (data recorded by University of Southampton)
- Nine accelerometers on the rails (data recorded by Baas).
- Two pore water pressure transducers in the embankment (data recorded by Deltares).
- Strain-gauges at the rails (data recorded by DUT).

Appendix A offers an overview of the position of the devices.

The evaluation of the data files in this section is based on a visual inspection of the appendices in factual report on the short-term measurements [Deltares, 2009c]. The identification of these appendices starts with a capital D.

3.3.1 Accelerometers

The following integration of the Deltares acceleration measurements Appendix D.1 and Appendix D.2 at the surface may be not reliable:

- Train_1: channel 22.
- Train_36: channel 9.
- Train_47: all channels.
- Train_62: channel 6.
- Train_68: all channels.

All other channels give good signals. For the deep accelerometers, the measured horizontal displacements are small, and therefore in general less reliable. For many signals, the influence of the filtering is in similar order as the measured signals. The horizontal motions at depth should be treated with care.

3.3.2 Pore water pressure measurements

The pore water pressure measurements (Appendix D.3) give suspected results. For Train_1, the static pressure measured at P01 seems a factor 10 to high. Since the dynamic pressure in P01 is much higher than the dynamic pressure in P02, it is reasonable to assume that the pressure at P01 (channel 30) is a factor 10 to high. For all other trains the factor is about 2.5. The pressure is maybe not reliable. The measured value is order 0.5 kPa.

In P02, the value is lower than the noise. This is a small value, which might not make sense: if one axle load of 100 kN spreads over a square of 2*2 m^2, the vertical stress is 25 kPa. At 3 m depth the stress is spread over $(2+2*3)^2 = 64\ m^2$, leading to a vertical stress of 1.6 kPa. The observed value in P02 is a factor 10 smaller, which might be not realistic.

The Trigger at the bottom of each page of Appendix D.3 shows that for the trains numbered 33, 40, 47, 50 and 56 no downward line is available; this means that exact synchronisation is not possible for these trains.

3.3.3 Geophone / high speed camera measurements on sleepers

The high speed camera observes the displacement of the target directly. The geophones measure the velocity of the target, so the displacements must be calculate from integration with respect to time.

The geophone measurements (Appendix D.4) lead to realistic displacements. Sometimes, the displacements show some prior vibrations, which are not physically. Especially, Geophone 2 on point G9 and sometimes Geophone 3 on point G8 suffers this behaviour. Based on the small magnitude of the prior vibrations it is concluded that the from the geophone measurements by integration derived displacements during train passage are not strongly influenced by these vibrations.

Comparison of the results of the geophones and the camera (most right figure on row number 2 in Appendix D.4.9) shows that for Train 43 the relation is poor. For the trains numbered 47, 50, 56 and 68, the relation is very poor. Further study shows that during the passing of these trains, the camera is filming the targets behind the culvert (at the Gouda side of the culvert). This means that the time integrated signals for the geophones behind the culvert are less reliable. This is explained from the fact that the velocity has large peaks, which influences the time integration. These peaks are presumably caused by the ‘slapping’ of the track against the ballast before (at the Woerden side) of the culvert [Priest, 2009].

3.3.4 Strain measurements on rail

The strain measurements give reasonable results. However, not always all axles are measured, e.g. Train_1, Train_14, Train_36 (first set of gauges), Train_50 and Train 56 some axles are missing.

3.3.5 Accelerometers from BHM (TLMS)

The results of the BHM (Appendix D.6) seems to be less reliable. The passage of the axles is not always clearly visible. The channels 8 (8.4 m in front of the culvert) and 1 (8.4 m behind the culvert) are always giving strong differences between the passing axles; the deformation pattern differs strongly of the expected pattern. The channels 5 (1.2 m in front of the culvert) and 2 (6.0 m behind the culvert) have similar problems, but these are less systematic. It might be explained from the fact that the deviating accelerometers were not fixed accurately to the rail.

3.3.6 Accelerometers meant for interpretation with trains on track 2 (south track)

The vertical displacements of the surface and deep transducers which are meant to give information for trains passing on track 2 (counted from the north) is given in Appendix D.7. In general, these look reliable. However, some train passages have relatively large vibrations from the integration routines, which might play a role, since the displacements are relatively small. E.g., Train 4 has this problem.

The results of the following trains should not be used, since these are not properly integrated, or should be handled with care, since these have other types of errors or differ otherwise:

- Train 7 (too much noise).
- Train 12 (vibrations form integration, beat).
- Train 15 (Channel 22 erroneous).
- Train 17 (result differs from readings for passages of other trains).
- Train 23 and Train 25 (measurement started too late).
- Train 30, Train 32, Train 35, Train 39 and Train 44 (measurement started too late).
- Train 48 (measurement started too early).
- Train 51 (signal much smaller, order of noise).
- Train 53 (small signal, very noisy).
- Train 54 (maybe beat[2]).
- Train 55 (some beat).
- Train 60 (measurement started too late).
- Train 66 (unknown problem).
- Train 67 (maybe beat).

It is noted that not all these trains are erroneous, e.g. Train 32 and Train 39 might have a correct signal, and might be an interesting result.

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2. beat is the signal which is obtained when two signals with slightly different frequency are summed

4 Validation of the Baan Hoogte Meetsysteem (Track Level Measurement System)

4.1 Introduction

Part of the 2009 field test was the validation of the Baan Hoogte Meetsysteem (BHM), a track level measurement system [Baas, 2008]. The track level measurement system (BHM) is mounted on the culvert, in order to validate the results with the other levelling measurements.

The BHM measures:

- The long-term displacement of each fourth sleeper (9 sleepers in total) by forces in measurement wires and.
- The dynamic behaviour by nine accelerometers in between.

Both results will be evaluated in this chapter.

It is noted that the BHM installed at Goverwelle is different from the one presented in [Baas, 2008] which was used before by ProRail before (e.g. the measurement in Breukelen [Baas, 2006]). At that location 18 long-term devices were installed and no accelerometers were used. This means that the working distance of the wires is doubled from originally 2 sleeper-distances (1.2 m) to 4 sleeper-distances (2.4 m).

4.2 Long-term behaviour

The report of the BHM [Baas, 2009] contains plots of the development of the amplitude as function of time (date) and train velocity.

The reported track level compares well with the data from the manual levelling of the rails at 2009-06-12. Figure 4.1 shows the results of the levelling of the rails. In the BHM measurement not the actual level of the track but the relative level is given. The levels according to the BHM are corrected such that the first and last values match the values according to the levelling of the North (right) rail.

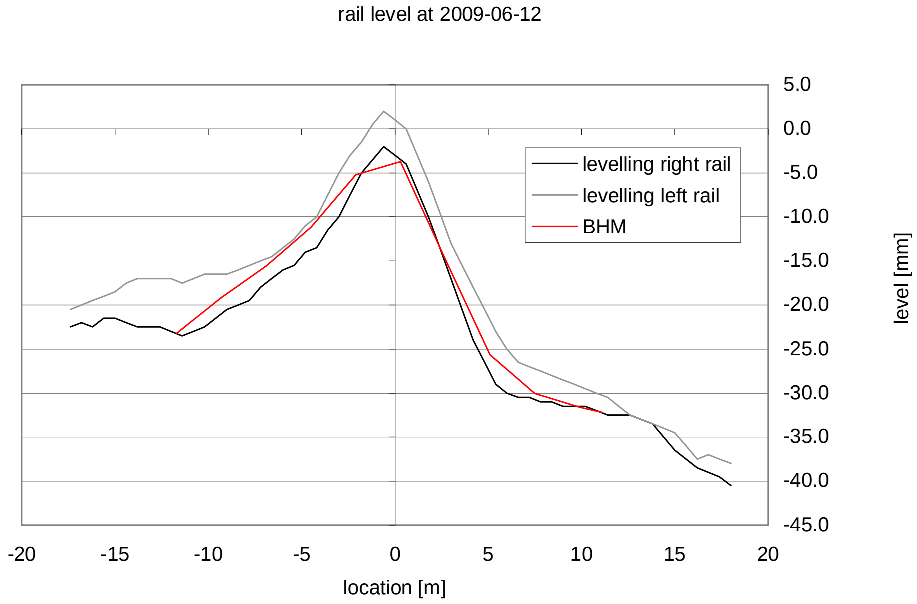

Figure 4.1 *Height of rail according to levelling data*

The shape of the BHM track level matches well with the shape from the manual track levelling. The bulge at the culvert appears a little wider in the BHM measurements as according in the levelling data. In practice, these differences are not significant.

The curve of the BHM measurement, as shown in Figure 4.1, is based on the measurements during the period 22 April – 8 May. Within this period, only during the first 6 days and last 2 days measurements were provided by Baas. This means that this measurement does not offer the possibility to judge the system on the real long-term (3-6 months).

Besides the actual level, results of the BHM are presented as maximum deflection from a straight line over 4.8 m at the centre of the culvert. The levelling data are analysed in the same way for comparison.
The levelling data in the measurement period shows a difference in level over 4.8 m at the centre of the culvert of 7.5 mm, while the BHM measures 6.5 mm. This is a reasonable match. The development observed in the BHM of 0.5 mm per month is not observed in the levelling data. These show a constant deflection value over 4.8 m in that period, but it might be outside the accuracy of the levelling (provided levelling results are at 0.5 mm interval).

4.3 Short-term behaviour

The version of the BHM installed at the Gouda Goverwelle site has nine static displacement transducers (at each fourth sleeper) and nine accelerometers in between. This Section compares the displacements obtained form the accelerometers of the BHM with the results of the geophones. In order to get displacements, the accelerations from the accelerometers were integrated twice with respect to time, the velocities of the geophones were integrated once with respect to time.

Two methods for comparison are adapted:

- For each geophone the nearest accelerometer is selected and the signals are compared.
- For both devices a seismogram is drawn and compared globally.

The first method compares two signals very accurately, but has as disadvantage that these two signals are not identical. The second method offers the possibility of a more global comparison.

It should be kept in mind that the positions of the BHM transducers do not coincide with geophone positions due to installation restrictions. Table 4.1 shows the position of the transducers relative to sleeper 30 (located at the centre of the culvert) and the distances between the transducers shown in the third column. It is expected that in the centre large differences occur, since the geophone is on the culvert and the accelerometers of the BHM are beside the culvert.

Geophone number	Geophone position (m)	Acelerometer Number	Accelerometer Position (m)	Inter-distance (m)
		9	-10.68	
8	-7.94	8	-8.27	0.33
7	-5.49	7	-5.84	0.34
5	-3.12	6	-3.40	0.28
		5	-1.02	
4	0.00			
		4	1.57	
3	3.07	3	3.96	0.89
2	5.38	2	6.41	1.02
1	8.49	1	8.83	0.33

Table 4.1 Distances between geophones and accelerometers BHM

First, one displacement is compared using the camera measurement, the geophone and the accelerometer result from the BHM. Train 40 is selected, where a proper camera measurement is available. The camera measured the displacement on the sleeper at 5.46 m (before the culvert). This displacement can be compared with the displacement from the accelerometer at 5.84 m (device 7) and from the geophone (location G05, device 7).

Figure 4.2 and Figure 4.3 show the results for the three devices. These Figures shows similar curves. The measurements are shifted in time, to synchronize the axle passages, and moved vertically, to have similar vertical zero-displacement during train passage. The agreement between the camera measurement and the geophone is good. Some maximum values are different, order 10%. During the passage of the fifth carriage, the upward spike is too high.

The differences between the displacement of the BHM and the camera measurement are larger. The peak values differ 20%, the details in the signals are more or less similar.

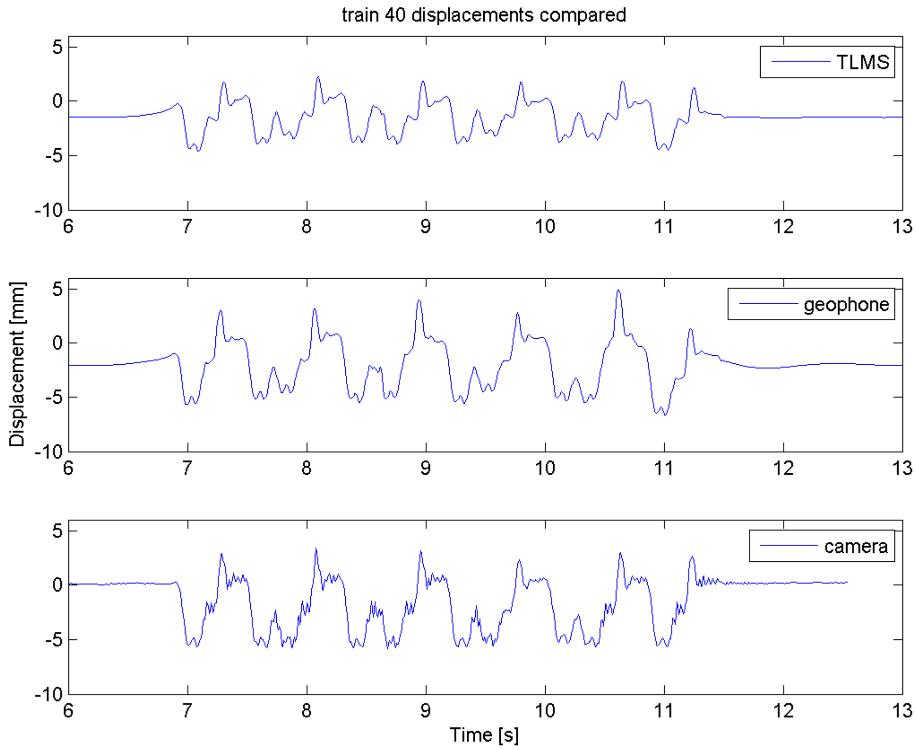

Figure 4.2 *Displacement form three systems 5-6 m before the culvert, passage Train 40*

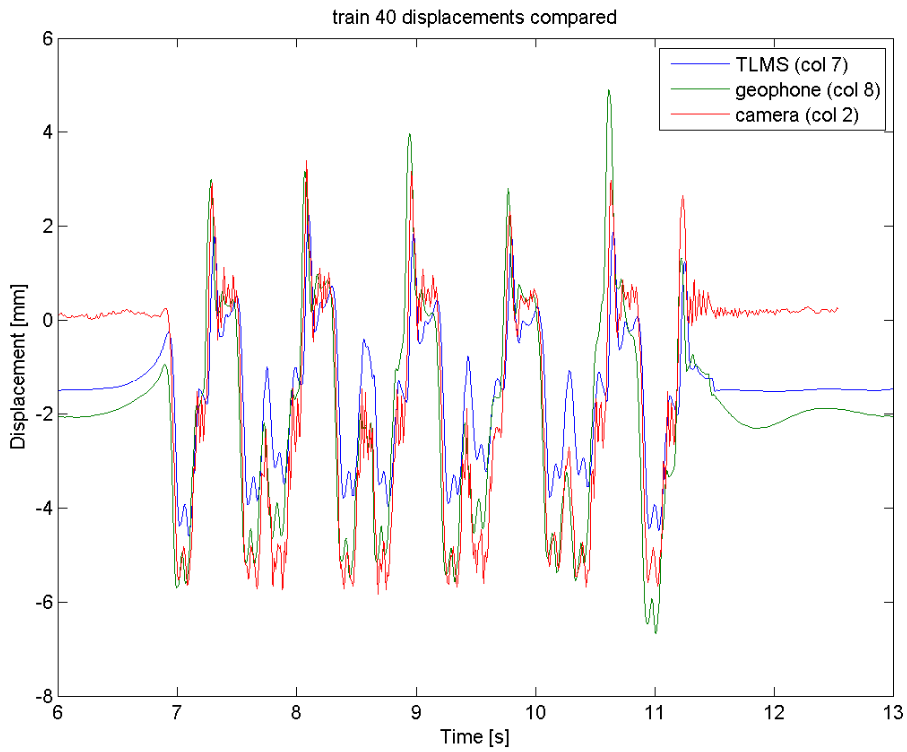

Figure 4.3 *Displacements of Figure 4.2 in one figure, passage Train 40*

A similar post processing is done for Train 20, for which also a proper camera measurement is available for Geophone number 5 (column 6), see Figure 4.4 and Figure 4.5. Accelerometer 6 of the BHM is selected; the distance between these devices is 0.28 m. Here, the geophone signal is missing the upward spikes and the displacements during the passage of the second carriages are relatively small. It is noted that this train is a Sprinter with three carriages (SGM-3). The global view of the BHM is in this case better than from the Geophones.

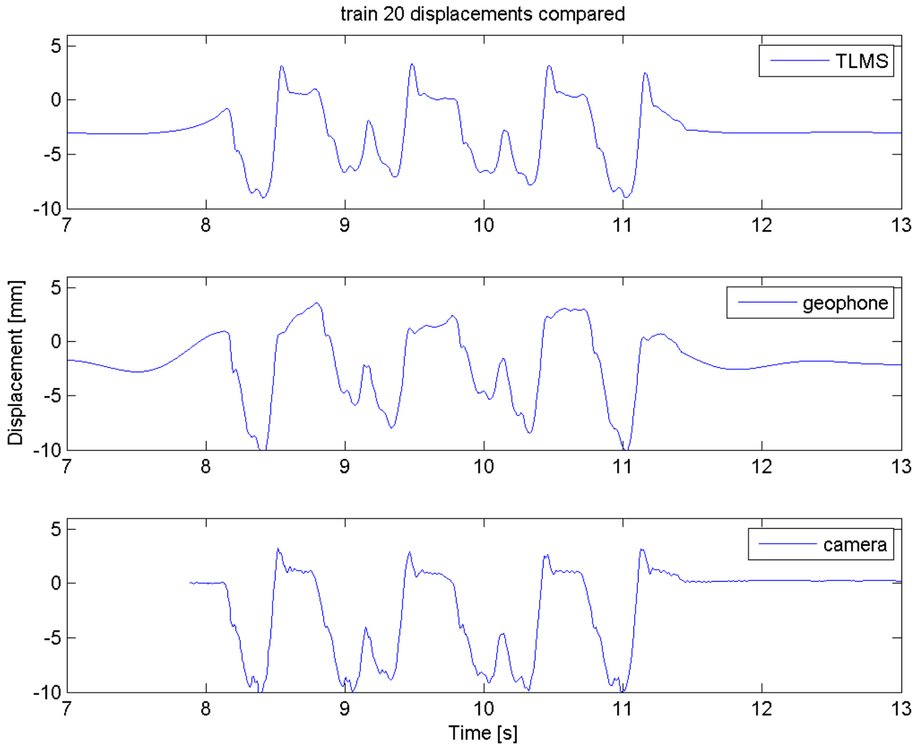

Figure 4.4 *Displacement form three systems 5-6 m before the culvert, passage Train 20*

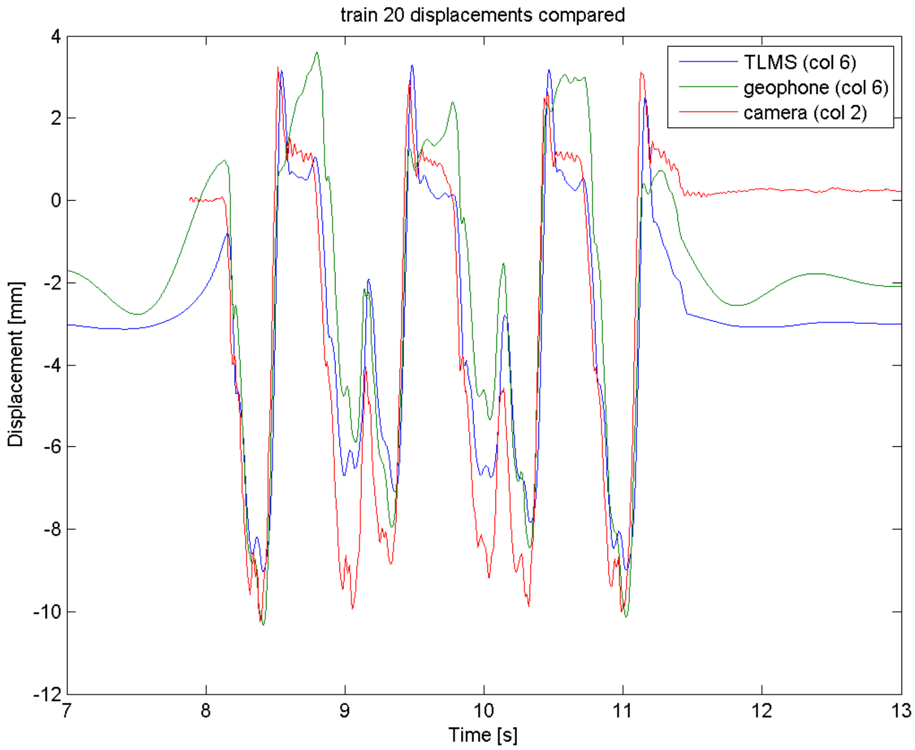

Figure 4.5 *Displacements of Figure 4.4in one figure, passage Train 20*

Figure 4.6 shows the comparison of three measurements for Train 50. The green lines show the Southampton Geophone results, the blue lines show the results of the BHM and the red line the camera results. The differences are significant.

The camera seems to deliver a reliable result. Clearly, the passage of the axles can be observed. Just before the passage of the next boogie, an upward peak is observed. This is symmetric with the signal before the culvert (at the Woerden side), which seems a realistic behaviour of the track as cantilever.

None of the other systems that use time integration gives reliable results.

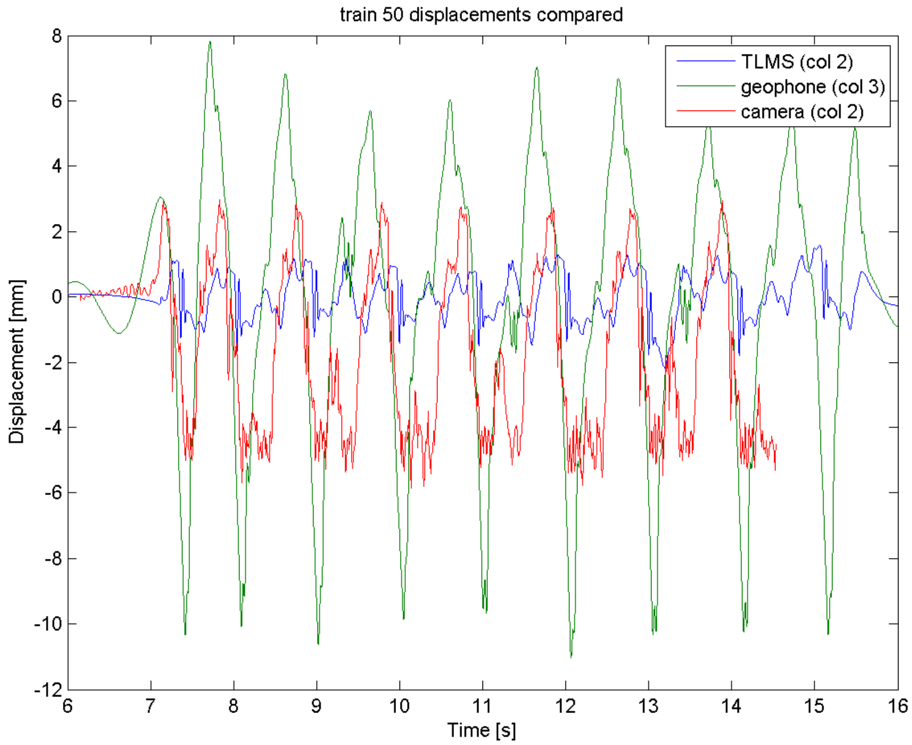

Figure 4.6 Comparison nearby displacements from geophones and accelerometers BHM

Figure 4.7 and Figure 4.8 show the seismograms of the track displacement measurements by geophones and accelerometers. Significant differences are observed. Since only one high speed camera was used, it is impossible to draw a seismogram of high speed camera results.

The signals of the BHM and geophones are not always reliable. It is not always clear beforehand, which signal is reliable. For Train 40 the signals before the culvert (the Woerden side) of the BHM seems to be better than the geophones, but behind the culvert (at the Gouda side) the opposite holds.

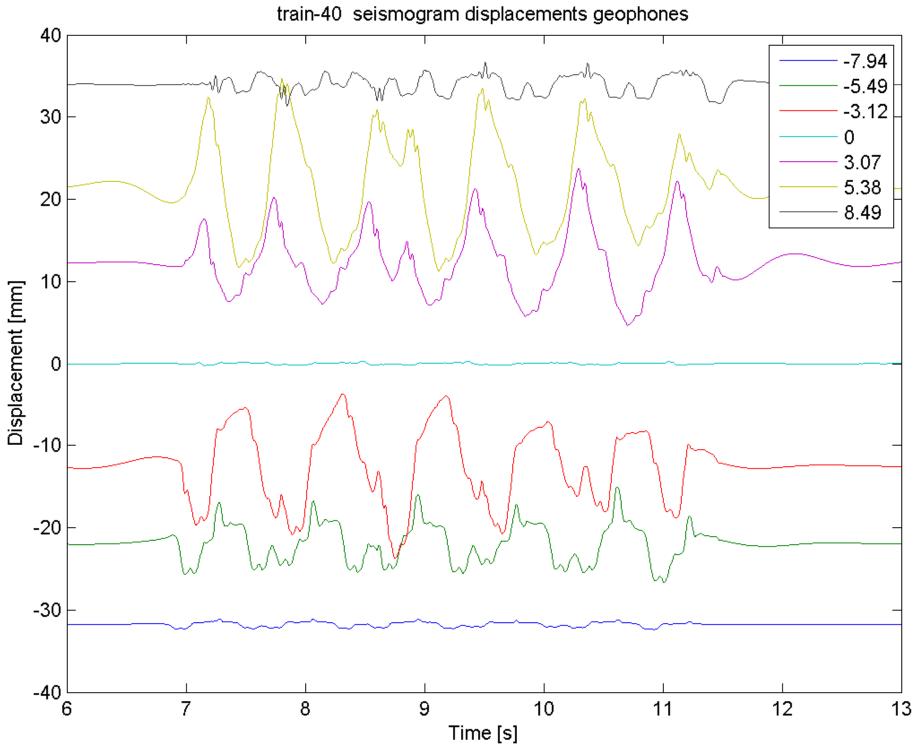

Figure 4.7 Displacement track under Train 40 from Geophones

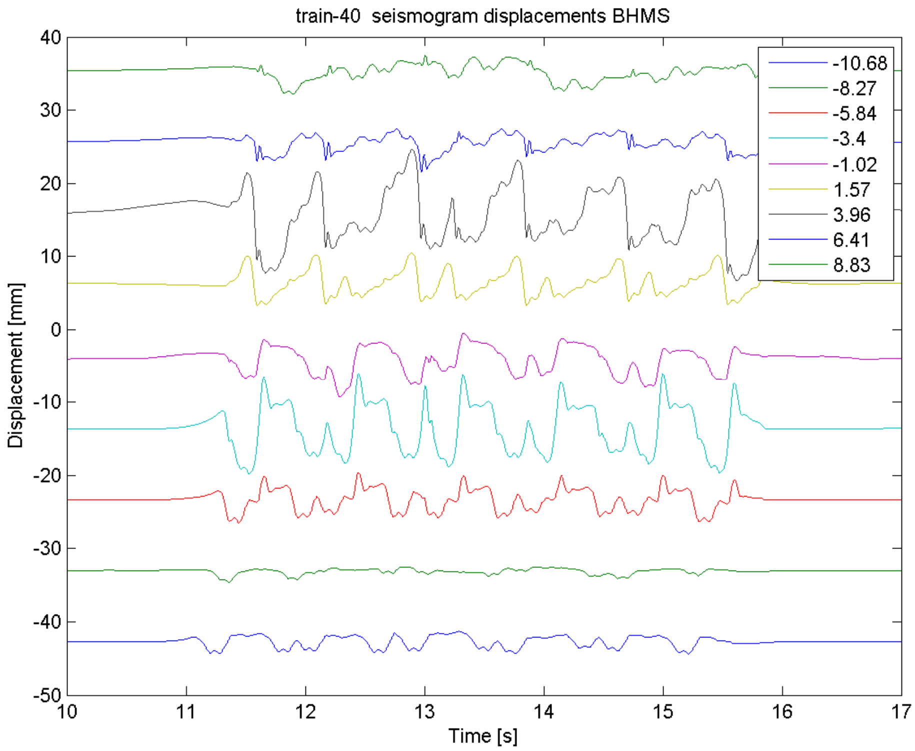

Figure 4.8 Displacement track under Train 40 from BHM

4.4 Development of short-term behaviour with time

The BHM did measurements for a period of 1.5 month. This offers the possibility to judge the development of the dynamic behaviour in time.

The plots in Section 5.2 of the BHM report show the development of track level as a function of time at transducer 6, located next to the culvert. This Figure suggests that in the first month after BHM installation the amplitude of the rail at passing trains increases. During the last two weeks, the amplitude becomes constant. The BHM report suggest a day-night dependancy in the long-term behaviour of the system. This might be related with temperature. Therefore, the temperature (average day value) during the period of the measurements was checked. In the beginning of the measurement period, the temperature gradually increased from 13 degrees to 19 degrees, which coincide with the increase of track level. For the last days, the temperature dropped to 13 degrees again, while no decrease of level is observed. Therefore, it is expected that the observed development is not related to temperature.

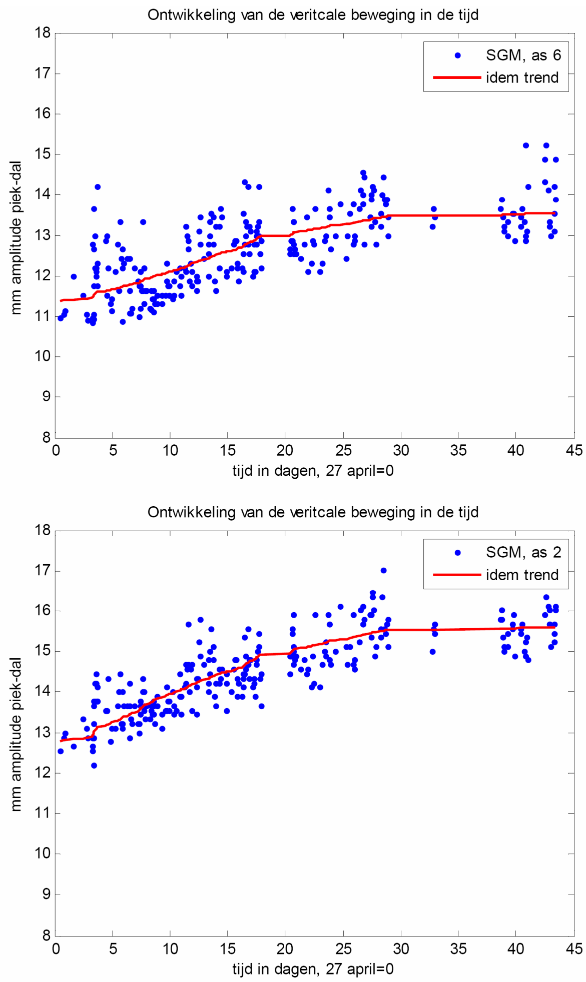

Figure 4.9 Development amplitude rail at train passage according to BHM

The measured response suggests a continuous degradation of the subsoil (increase in hanging distance). This however is not observed in the measurements of the hanging distance. Noted is that the change observed with BHM is out of the accuracy range of the Vortok devices. It should be remarked that the BHM does not directly measure the hanging distance of the track, but the displacement of the track during passage. If the measured value is ‘large’, it is called ‘*blinde vering*’ (hanging sleeper).

The BHM results also show a relation of the track amplitude with train velocity. The amplitude increases with increasing train speed, suggesting a decreasing apparent stiffness of the transition zone. This observation must be compared with the results of the other dynamic measurements. This will be discussed in Chapter 5; *e.g.,* Figure 6.8 confirm this finding.

4.5 Final evaluation of the *Baan Hoogte Meetsysteem*

On installation
From the experience at the Gouda Goverwelle test site can be concluded that the practical workability (installation, calibration) of the system is questionable. The long time needed for installation (more than two nights) and the limited freedom for positioning the accelerometers (each fourth sleeper) are drawbacks of the system.

The calibration of the system takes 5 minutes, which is quite long for the current timetable (the probability of a train passing during the calibration period of 5 min. is not small). It might be a suggestion to limit the calibration to the night only.

An advantage of the system is that it is well prepared to stay for a longer time on a track measurement site and therefore offers good possibility to determine long-term behaviour.

On long-term behaviour
The results for the long-term behaviour are satisfactory.

On short-term behaviour
The results of the BHM short-term measurements by the accelerometers are quite reasonable. It appears from the results that not all accelerometers were fixed accurately to the track. Time integration of accelerations to displacement shows similar problems as the Deltares (and Southampton) accelerometer and geophone measurements (see chapter 3).

On Baas' report of the BHM measurements [Baas, 2009]
Many results are removed as 'outliers', which might give arbitrary choices. The results are based on the measurements of a few days; it is not known why on other days the data are completely or almost completely removed. In fact, the system did function well only a few days. If it functions well, it gives several measurement results per day, which is an advantage.

5 Analysis of long-term behaviour

5.1 Settlement of embankment

The settlement of the free embankment can be derived from the settlement of the pylons and from the settlement of the top of the rail.

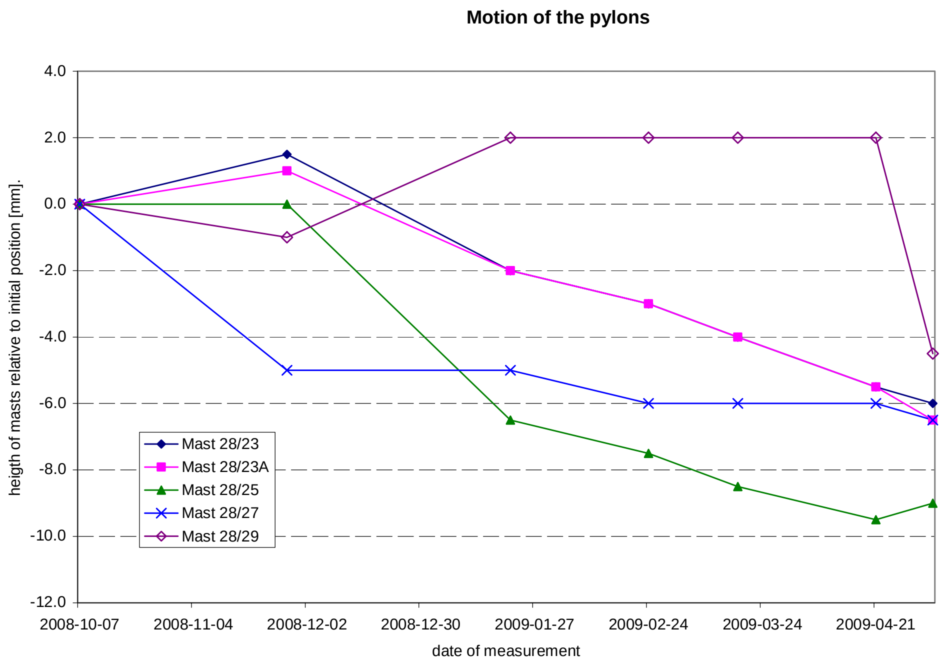

Figure 5.1 Measured settlement of the pylons with respect to culvert

The settlement of the pylons, with reference to the culvert, is about 1 mm/month. This settlement may be considered as an indication of the autonomous settlement of the subsoil. Pylon 28/29 shows a dissimilar behaviour. Pylon 29/29 is situated at the Gouda side of the culvert, whereas the others are located at the Woerden side. The reason for the dissimilar behaviour is unknown. The results for this pylon are considered unreliable.

The settlement rate for the autonomous settlement is confirmed by the measurements of the track level. Figure 5.2 shows the settlement of the top of the rail with respect to the situation at 2008-10-07 (first measurement after tamping).

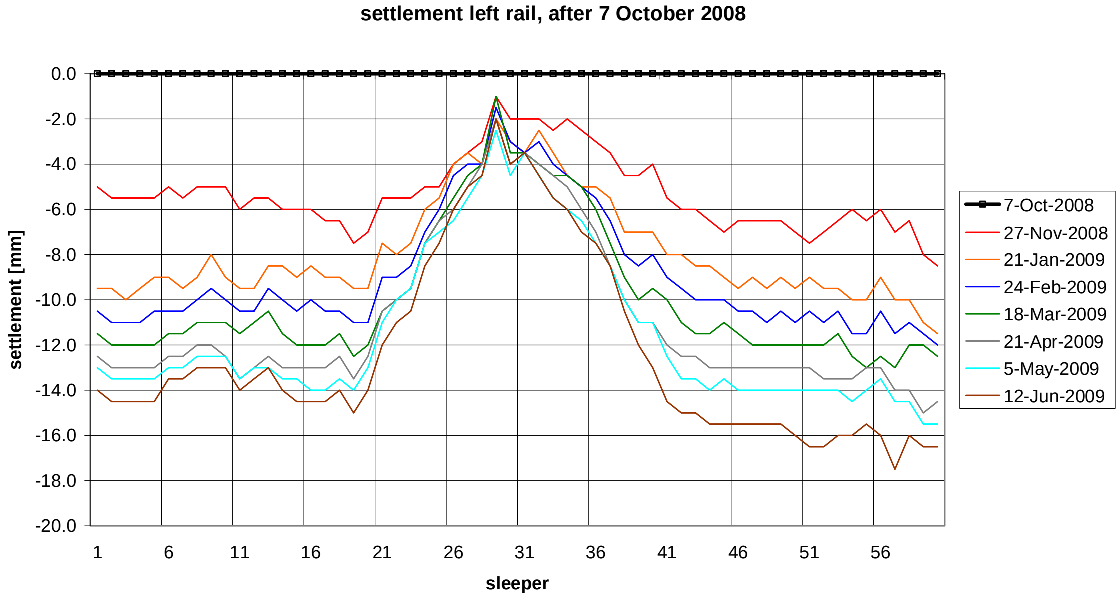

Table 5.1 Settlement top of left rail after tamping

At top of the culvert, the settlement is limited to 2 to 4 mm. At the free embankment, the settlement is almost independent of the location. The Gouda side however appears to settle more as the Woerden side. It is not clear whether this is due to the subsoil, the driving direction of the trains or the fact that at 2008-08-07 only the Woerden side was tamped.

From the measured top level of the settlement rate after maintenance is derived. Figure 5.2 shows the development of sleeper 1, 11, 16, 46, 51 and 60 compared to the level at 7 October 2008. For the considered points at the Woerden side, a straight line is used and for the points at the Gouda side a dashed line. The selected sleepers are outside the areas of culvert and approach slab and are therefore considered to represent the behaviour of the free embankment.

In the graph, two regimes can be observed. For the period after December 2008, a more or less constant settlement rate of about 1 mm/month is observed. This agrees well with the observed settlement rate of the pylons. This is called the autonomous settlement of the subsoil. The rate is equal for the Woerden and for the Gouda side of the culvert. In the first 1 to 2 months, the settlement rate is larger. This larger settlement rate is attributed to densification of the tamped ballast and is further discussed in section 5.3.

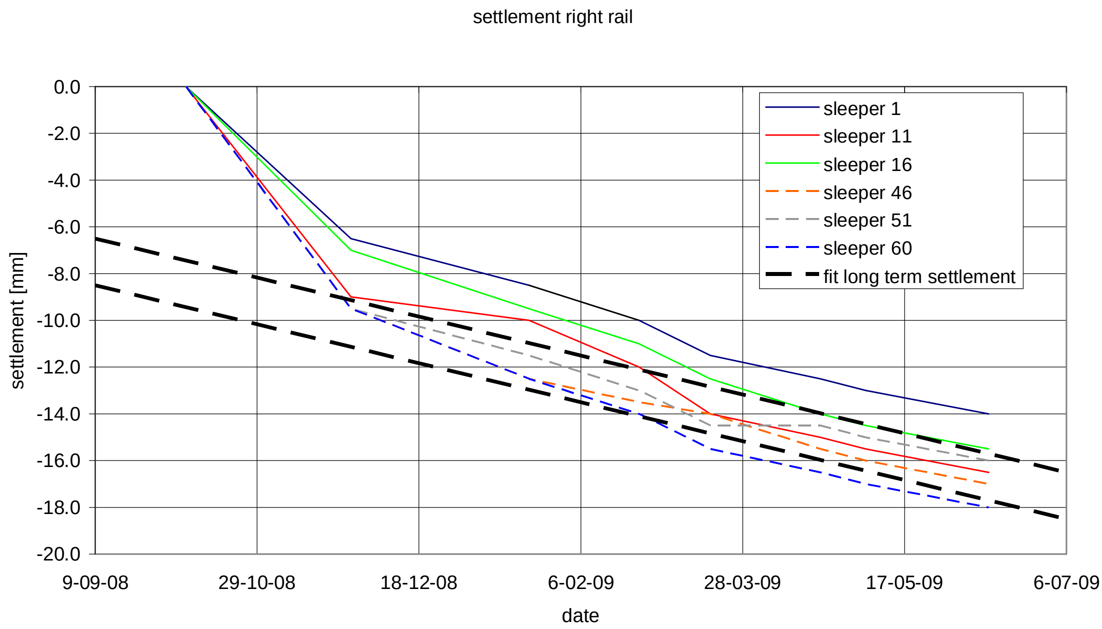

Figure 5.2 *Settlement right rail at free embankment after tamping*

Figure 5.3 shows the difference in settlement of the rails at 12-09-2009 with respect to the measured level at 7-10-2008 (the first measurement after maintenance). A negative value indicates that the right rails settles more as the left rail. The difference varies between 0 mm and 4 mm. The difference is already present 1 month after tamping and does not change much after this period. This indicates some larger densification at the right rail as at the left rail. Another reason for the larger settlement may be a sideward flow of ballast from below the sleeper.

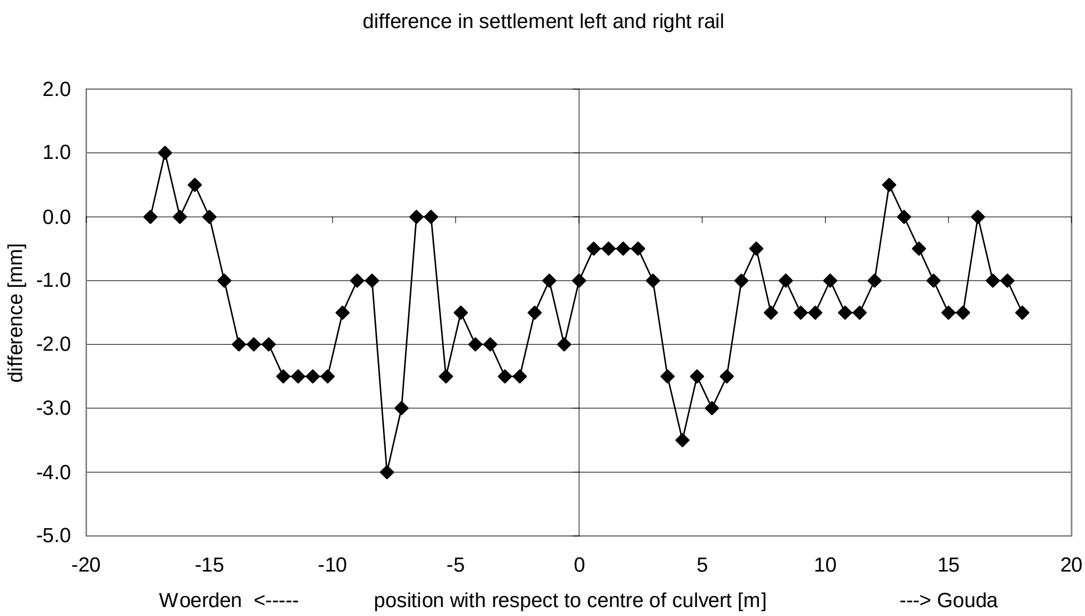

Figure 5.3 *Difference in settlement left and right rail between 7-10-2008 and 12-06-2009*

5.2 Settlement top of ballast at culvert

For assessing the deformation pattern, the settlement of the ballast at some points is investigated. Considered points and results are summarised in Table 5.2. For the settlement of the sleeper the settlement in the period 7 October 2008 to 12 June 2009 is used, so an 8 months period. For the hanging distance, the average of the available measurements in April and May 2009 is used (see section 5.4 for the hanging distance). The total settlement of the ballast is the sum of these two numbers.

Point	Sleeper	Δz, top of track [mm]	Hanging distance [mm]	Total settlement [mm]
Top of culvert	30	2	0	2
	28	4	n.a.	
Top of slab	27	5.5	8.9	14.5
	25	7	8	15
	24	8.5	5.8	14.3
	23	10.5	5.5	16
Toe of slab	22	11	6.3	17.3
Embankment	20	14	2.9	17
Embankment	15	14.5	1.2	15.7

Table 5.2 Settlement of top of ballast at slab

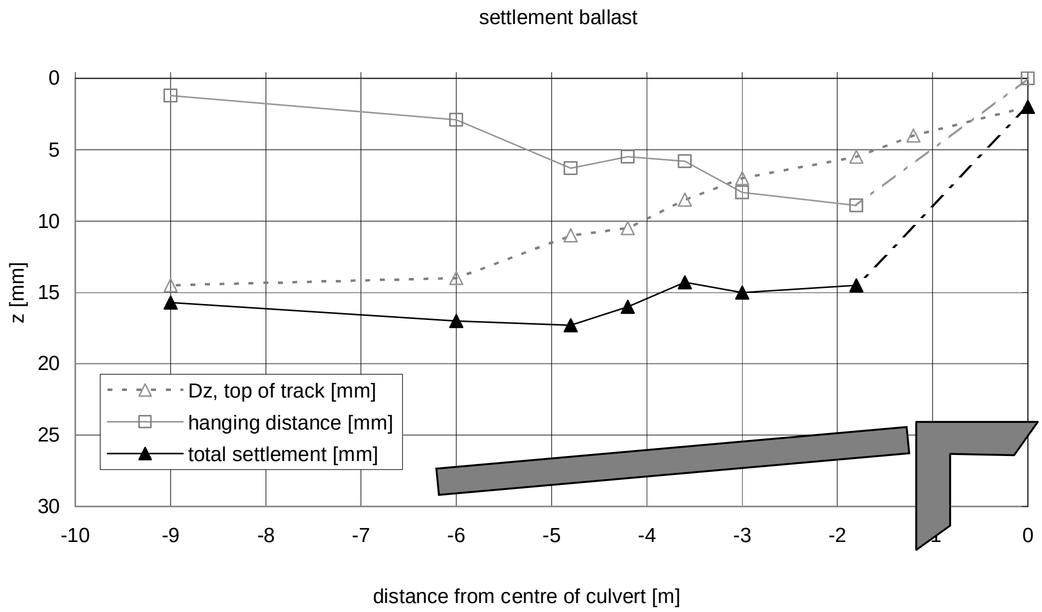

Figure 5.4 Settlement of top of ballast at slab

At the culvert (x=0, sleeper 30) a small settlement is found (sleeper 28, 29 and 30 are on the culvert). At x = -5 m toe of the slab) the largest settlement of the top of the ballast is found and a few millimetres more as at the free embankment and the upper part of the slab.

5.3 Densification of ballast

The densification of the ballast after tamping is obtained from the difference between the settlement of the top of the ballast and the autonomous settlement.

On top of the culvert, the autonomous settlement is zero. For observing the development of the settlement in time the average of the settlement of sleeper 29 to 31(both left and right side) is used.

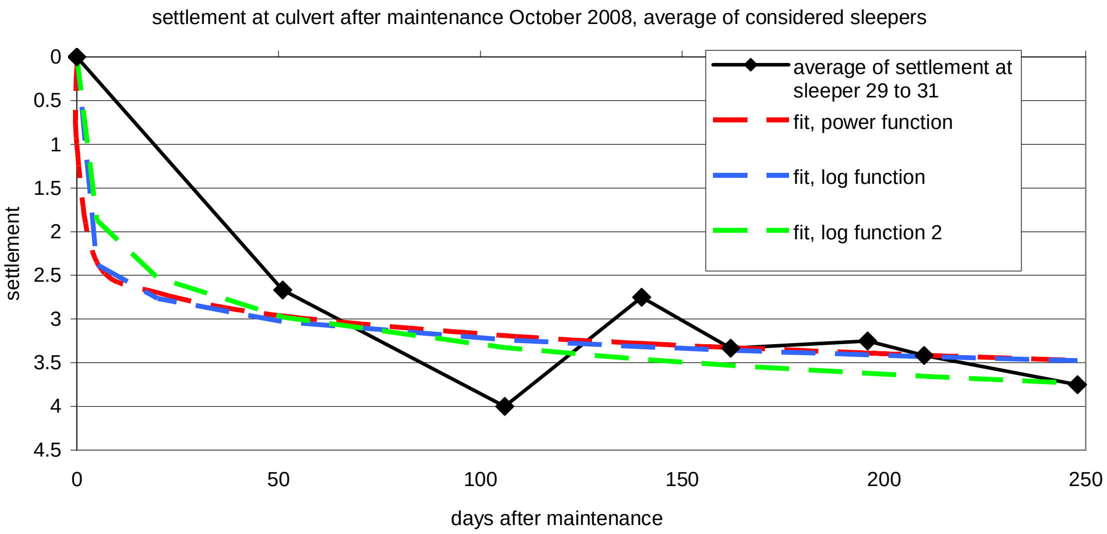

Figure 5.5 Densification ballast at culvert

The average settlement is about 3.5 mm. In Figure 5.5 three lines are added that may be used as fit of the observed settlement. The expressions are:

- $\Delta z = aN^b$.
- $\Delta z = a + b \log N$.
- $\Delta z = a \log(1 + bN^2)$.

These expressions are commonly used in the literature to describe the time dependency of densification of granular materials. The values for the parameters *a* and *b* used to draw these lines are arbitrarily selected such that a reasonable fit with the observed settlement is obtained. The lines serve only as indication of the settlement behaviour.

For the free embankment, the densification of the ballast is obtained from the difference in measured total settlement and the autonomous settlement. Figure 5.6 shows the estimated densification of the ballast at the free embankment. Again, the theoretical curves are plotted, the used empirical parameters differ from the parameters used to draw the lines in Figure 5.4.

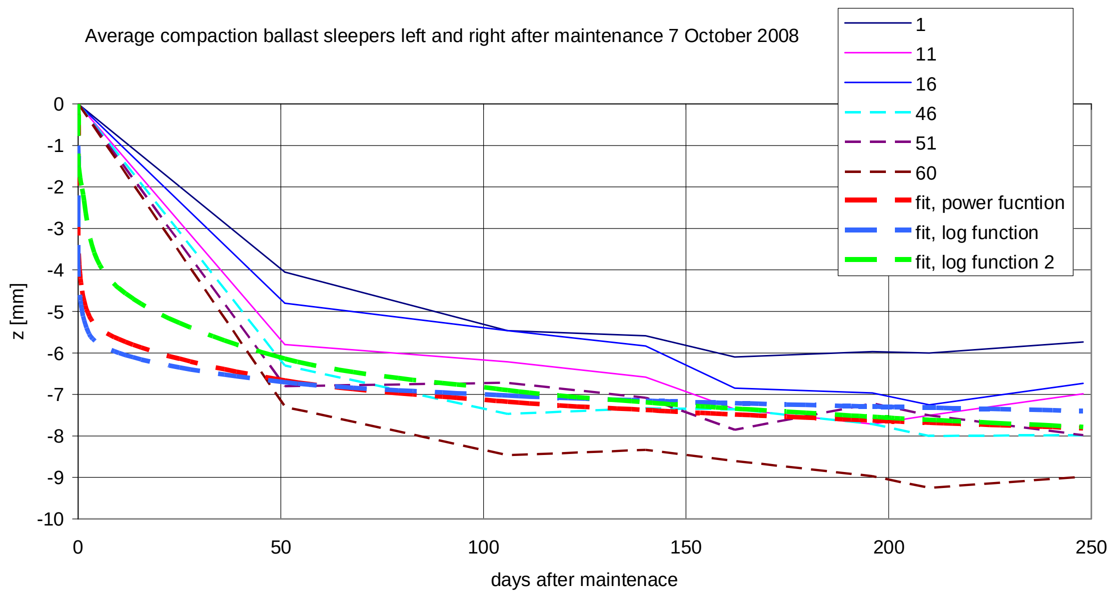

Figure 5.6 *Densification ballast at free embankment*

After 3 months (100 days), the mean settlement of the ballast above the culvert is 3.5 mm, at the free embankment 7 mm. The differential settlement is 3.5 mm. The autonomous settlement of the embankment in this period is about 3 mm, so less than the settlement of the ballast. After 1 month, the autonomous settlement is only 1 mm, while the differential settlement due to ballast compaction is 3 mm. After about 6 months, the autonomous settlement clearly dominates the differential settlement (is 70% of the total differential settlement).

The densification of the ballast at the free embankment is much larger as at the culvert. The reason for this difference is presumably the difference in soundboard. On the culvert, the concrete of the culvert is a good soundboard. On the free embankment, the soundboard is much softer. From compaction research, it is known that this strongly influences the quality of compaction.

The strong change in level shortly after maintenance, as suggested by the theoretical curves, cannot be confirmed or rejected from the measured data, since the development of the settlement shortly after maintenance is not measured.

5.4 Hanging distances

The hanging distance of 15 sleepers was measured directly using the Vortok hanging sleeper devices. Figure 5.7 shows the results of these measurements. The measurements started some time after the maintenance. Above the culvert, sleeper 30, no hanging distance is observed. A hanging distance of about 10 mm is measured above the approach slabs. The hanging distance decreases slowly with increasing distance from the culvert. At about 12 to 15 sleepers (thus 7-8 m), the hanging distance decreases to zero.

Figure 5.8 shows that these measurements do not show a significant increase during two months. This observation confirms the result of the previous section that this phenomenon occurs in a relatively short period after maintenance.

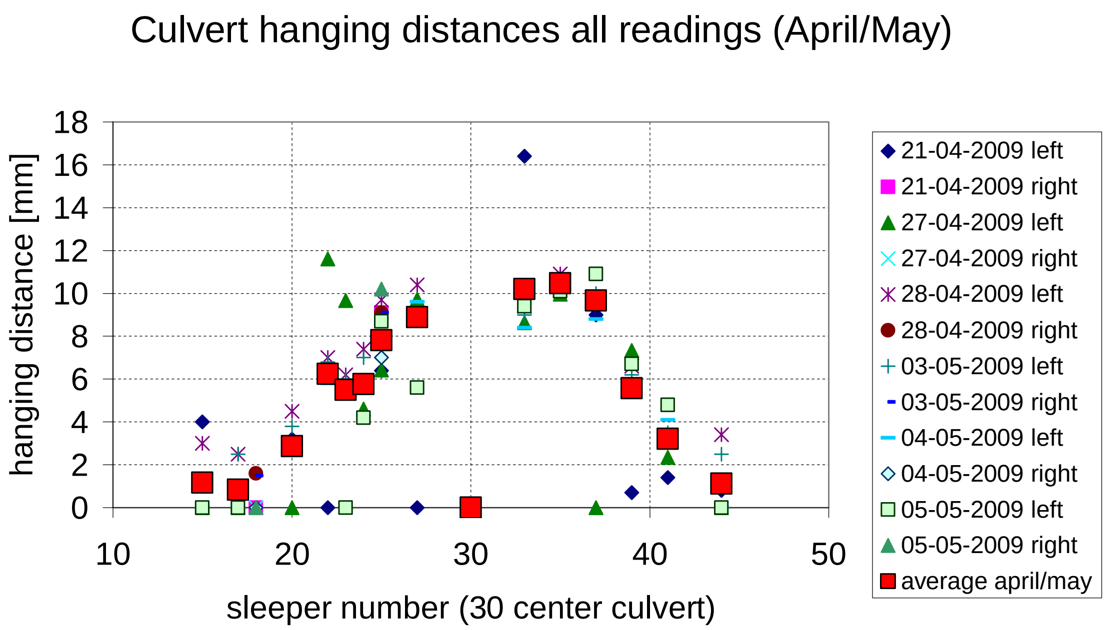

Figure 5.7 Hanging sleeper distances measured May/April 2008

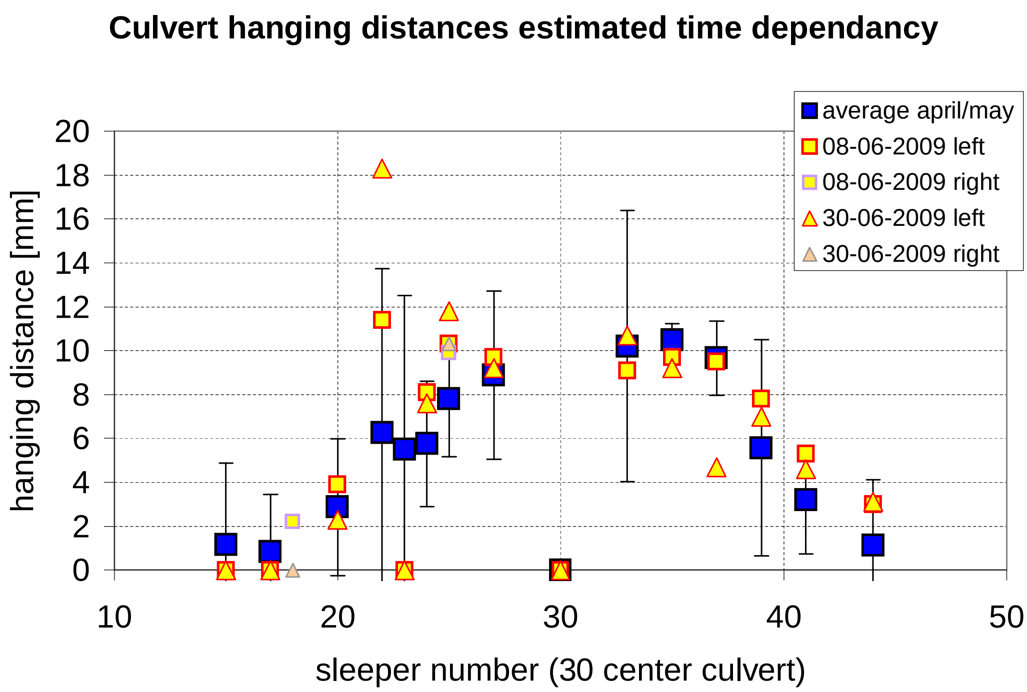

Figure 5.8 Changes in hanging distances after 4 and 7 weeks

The hanging distance can also be determined by comparison the motion of a sleeper (generally measured with a geophone) and the ballast around it (generally measured by a accelerometer). At some places, both are measured, close to each other. Figure 5.9 shows the results of this comparison. The geophones (with code G) are positioned at the top of the sleeper; the accelerometers (with code A) are installed at the top of the ballast.

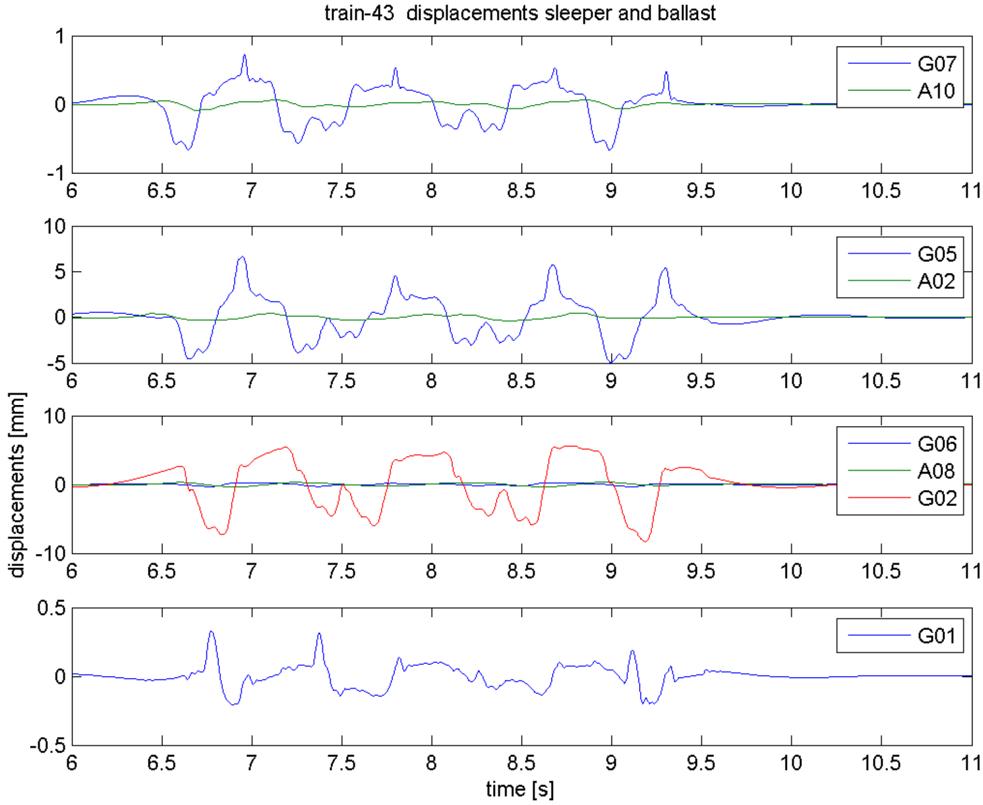

Figure 5.9 *Comparison motion sleeper (G) and ballast (A)*
note: Geophone G06 is placed on ballast

The geophone G01 above the culvert shows a small displacement. Accelerometer A10 and geophone G07 show a small displacement, these are placed at about 7 m in front of the culvert. No large difference between movement of sleeper and ballast is observed, which indicates a negligible hanging distance. Geophones G02 and G05 on the sleepers show a much larger displacement than the displacement measured with the accelerometers A08 and A02 and the geophone G06 (which was placed on ballast). Therefore, almost all motion of the track is due to hanging sleepers. The value is approximately 10 mm. This confirms the results of the Vortok hanging sleeper devices. It also indicates that most likely the sleeper touches the ballast when a train is passing.

5.5 Development of hanging distance

In order to evaluate the development of the hanging distance an analytical model has been used. The results of the levelling suggest that rail can be considered as a cantilever beam. Figure 5.10 shows the model. Above the culvert, the track is rigidly supported. This is modelled by a clamped support, based on assumed symmetry. Over a certain length, the track is free, loaded by weight of the two rails and the sleepers only. Further away, the track is supported by an elastic stiffness. This part settles in time; here, the settlement is chosen as the independent variable. The criterion for determination of the free hanging length is the fact that in the elastic foundation no tension is possible. The stiffness of the foundation is estimated, taking into account the measured track displacement under the passing axle load. The track properties are based on two rails UIC 54 supported by a sleeper each 0.6 m.

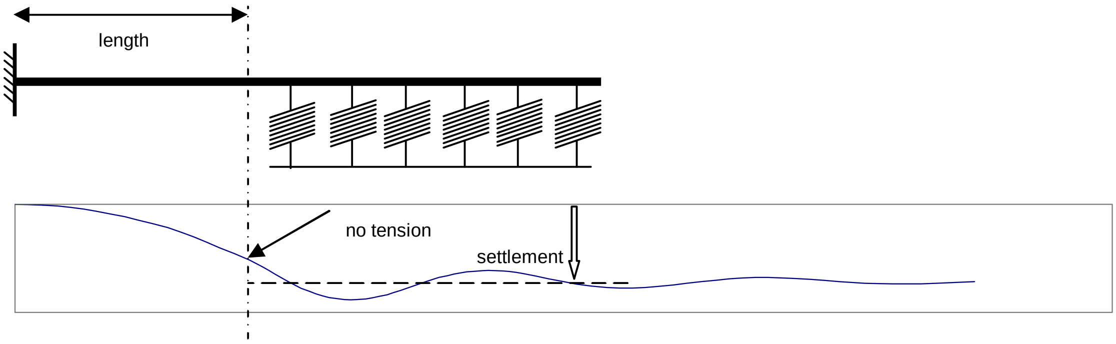

Figure 5.10 *Analytical model for development of free hanging sleepers*

Parameter	Symbol	Value	Unit
Stiffness track support	k	2.20E + 08	N/m
Bending stiffness track	EI	9.85E + 06	Nm2
Weight structure	q	3678	N/m

Table 5.3 *Track properties used for calculation free hanging distance*

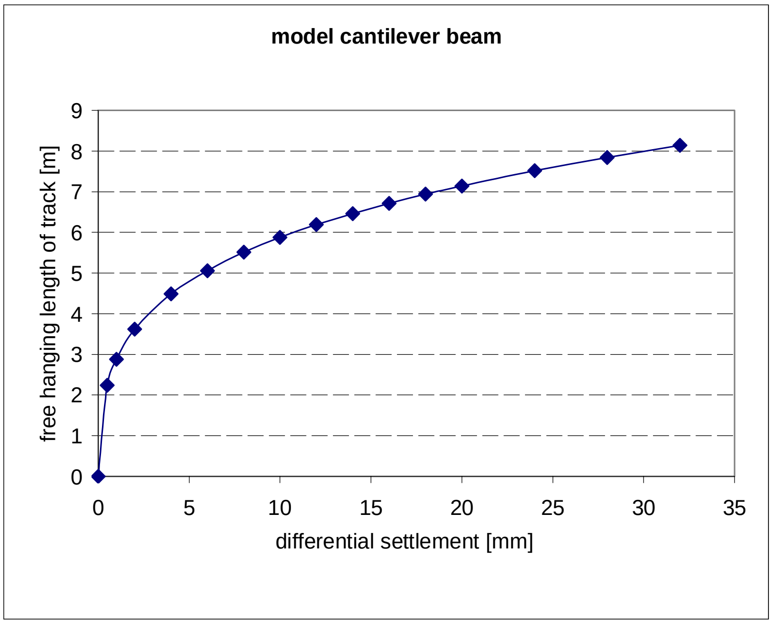

Figure 5.11 *Free hanging distance of the track as function of track settlement (parameters see Table 5.3)*

Figure 5.11 shows the results. It is seen that (for the parameters shown in Table 5.3) for a settlement of 2.5 mm the free hanging distance is 4 m (plate length) and for a settlement of 6 mm the free hanging distance is 5 m (plate length plus half culvert width). Obviously, a small settlement leads almost directly to hanging sleepers.

From the levelling data, we observed that directly after maintenance a relatively large settlement occurs (see also Section 5.3). E.g., after the maintenance of 7 October 2008 the track above the culvert settled 3 mm, above the toe of the approach slab 10 mm, within a period of 50 days. This means that after 50 days differential settlement is 7 mm. Using Figure 5.11, it is concluded that all sleepers above the approach slab are hanging.

This phenomenon is indirectly related to the subsoil. From compaction research, it is known that compaction is only possible if a good soundboard is available. Above the concrete culvert the soundboard is almost perfect, above the toe of the approach slab it is poor. Therefore, compaction of the ballast at the embankment during maintenance is expected to be less.

5.6 Behaviour approach slab

5.6.1 Present position approach slab

The position of the approach slab at the beginning of the long-term measurements can be derived from the following measurements:

- Hand-dug holes above the plates.
- GPR measurement.

The development of the level of slab in time, is measured at one point at each slab.
The hand-dug holes provide the level of one slab (at Woerden side) at two points. Processing this data gives the position of the slab.

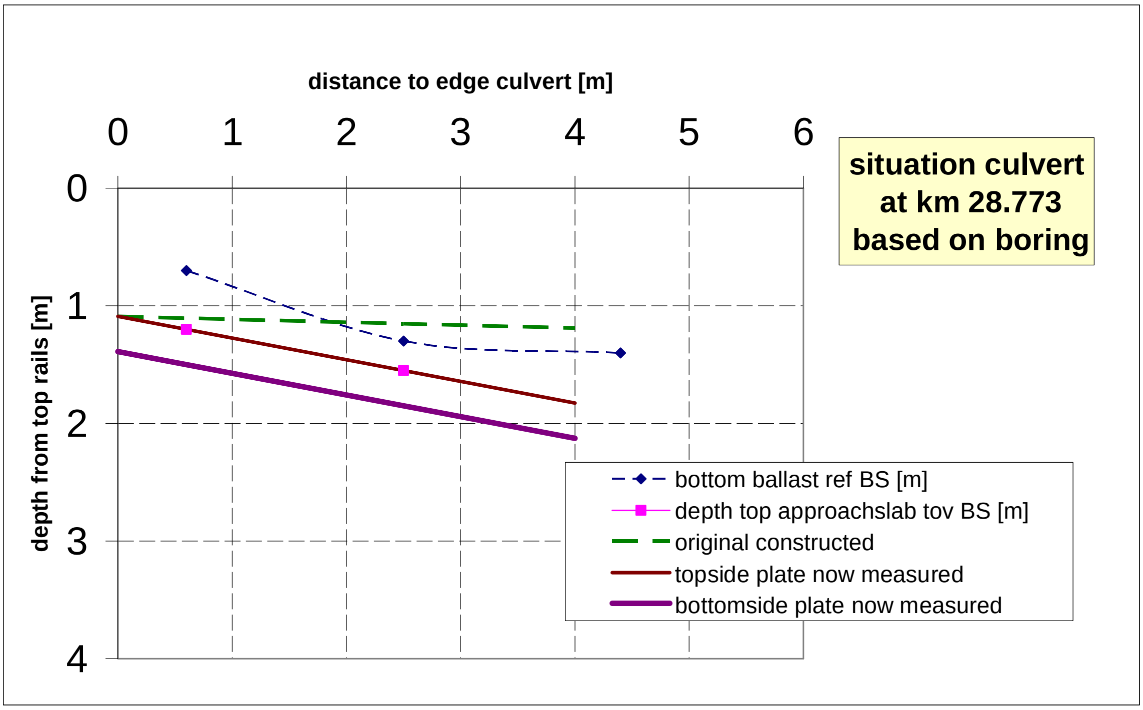

Figure 5.12 Result measurement settlement approach slab from dug holes

From extrapolation of the slope of the slab the end of the slab is expected to be at 1.8 m below top of rail (BS). The part of the slab resting at the culvert is at about 1.1 m below BS. This implies a settlement of the slab of about 0.7 m. The exact difference in height between the two ends of the plate is 0.74 m. When the plate is originally installed at a slope 1:40 the initial height difference is 0.1m, so the settlement is 0.64 m.

On 22 and 23 January 2008 a ground penetration radar measurement was performed. A total of 20 tracks are mentioned in the report of Geofox. Results of 18 tracks are reported. From these reported tracks the length of the slab and culvert and the position of the toe of the slab with respect to the top of the culvert are derived. An overview of the data derived from the radar tracks is summarised in Table 5.4. For the analysis the data in the more recent sheets and not the ones in the report of Geofox are used.

Radar track	Direction measurement	Length slab Gouda side [m]	Length culvert [m]	Length slab Woerden side [m]	Dz toe of slab Gouda [m]	Dz toe of slab Woerden [m]	Remarks
135	to Woerden	2.5	2.9	2.45	0.45	0.6	dirt road
134	to Woerden	2.7	2.4	2.7	0.55	0.6	
133	to Woerden	2.35	2.65	2.7	0.5	0.55	
15	to Gouda	--					foot path, not reported
14	to Woerden	--					
149	to Woerden	3.65	2.8	4.0	0.55	0.5	railway track 4 (north track)
148	to Woerden	n.a.	>2.4	3.7	n.a.	0.65	
144	to Woerden	3.4	2.7	3.85	0.55	0.5	
145	to Gouda	3.3	3.6	3.3	0.6	0.55	
147	to Woerden	3.45	3.2	3.25	0.65	0.55	
146	to Woerden	n.a.	2.7	n.a.	n.a.	n.a.	
13	to Woerden	3.8	3.45	3.9	0.6	0.6	between railway track 3 and 4
143	to Woerden	3.1	3.2	3.3	0.45	0.45	railway track 3
142	to Woerden	3.8	2.75	3.3	0.6	0.5	
138	to Woerden	3.8	3.5	3.8	0.6	0.55	
139	to Gouda	3.75	2.9	3.5	0.55	0.4	
141	to Woerden	3.65	3.5	2.9	0.5	0.45	
140	to Woerden	n.a.	1.85	n.a.	n.a.	n.a.	
136	to south						dirt road, perpendicular
137	to south						

Table 5.4 Dimension and depth culvert and slab, as derived from excel sheets Geofox

The settlement of the toe of the slab with respect to the top of the culvert is further analysed. First the derived values for the depth of the toe of the slab are corrected for the varying length of the slab as derived from the radar tracks. A net slab length of 3.9 m is used. The results are shown in Figure 5.13. The uncorrected values are the data from Table 5.4.

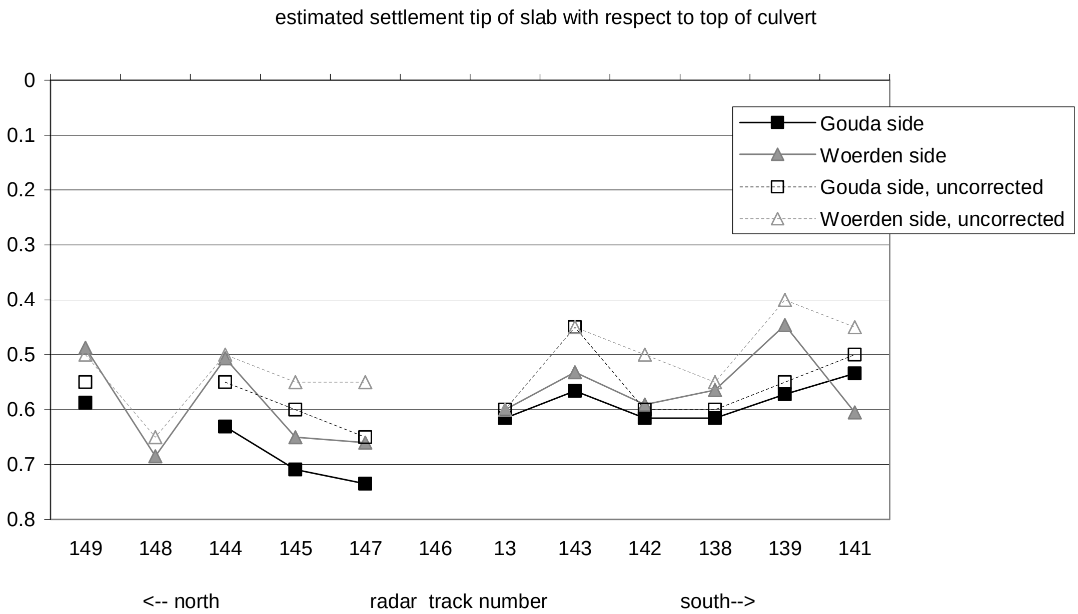

Figure 5.13 *Height difference toe of slab with respect to top of culvert, as derived from reported results GPR measurements*

From the radar tracks 140 to 149 the following is concluded:

- Height difference of toe of slab is at Gouda side about 0.62 m and at Woerden side 0.58 m.
- Settlement at rail track 4 (radar track 149 to 146) seems a little more as at rail track 3 (radar track 140 to 143).

The data suggest that at the Gouda side the settlement is a little more as at the Woerden side. Difference is small (on average 0.05 m) and not consistent for all radar tracks.
The average settlement of the toe of the slab is about 0.60 – 4/40 = 0.50 m. This is comparable to the settlement at the dirt road. The settlement is less as derived from the dug holes. The same value was expected as the radar measurements are calibrated using the data from the dug holes. However, in section 3.2.3 it was already concluded that the time depth conversion might be a factor 1.05 to 1.1 wrong. This factor however is insufficient to fully explain the difference in level.

The third dataset (the level of the two settlement points used for measuring the settlement of the slab in time) will not be used for determining the toe level of the slab. Reason for this is that there is some uncertainty regarding the exact position of these points with respect to the centre of rotation of the slab (see the next paragraph). The results of the analysis would be less reliable as the presented analysis in this section.

5.6.2 Settlement rate toe of slab

At two approach slabs (one at the Woerden and one at the Gouda side of the culvert) a settlement point was installed. The development of the settlement during time is shown in Figure 5.14.

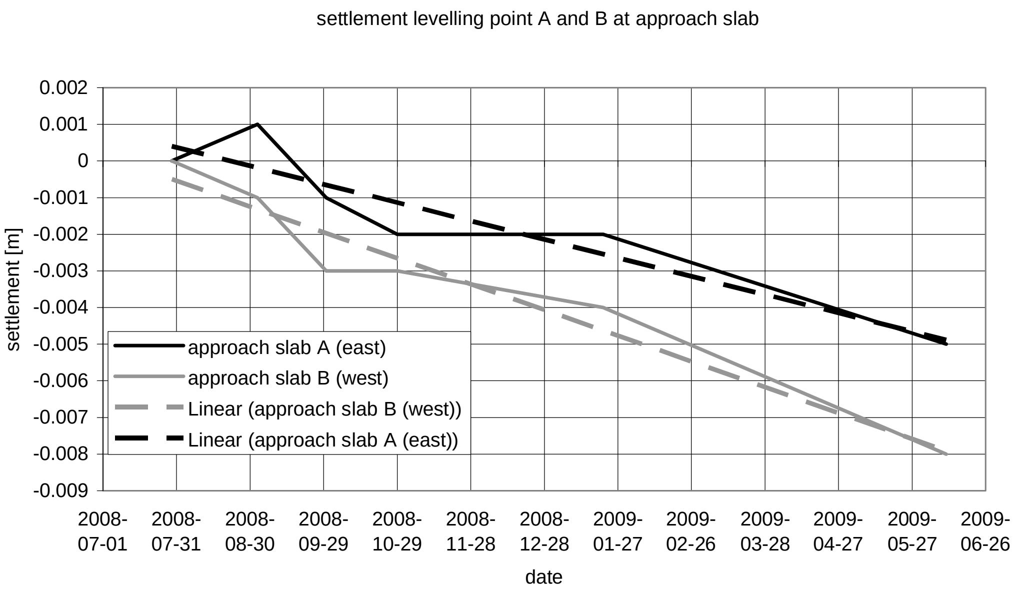

Figure 5.14 Development settlement slab in time

The distance of the levelling points to the point of rotation of the slab is not clear. According to the position of the levelling points with respect to the sleeper number, the points are located 8 sleepers apart (point A is between sleeper 34 and 35, point B is between sleeper 26 and 27). This results in a distance of 8*0.6 = 4.8 m. The width of the culvert is 2.15 m. The width of the support ridges is 0.325 m. This results in a distance between the rotation points of 2.8 m. The average distance of the levelling point to the point of rotation is thus 1 m.

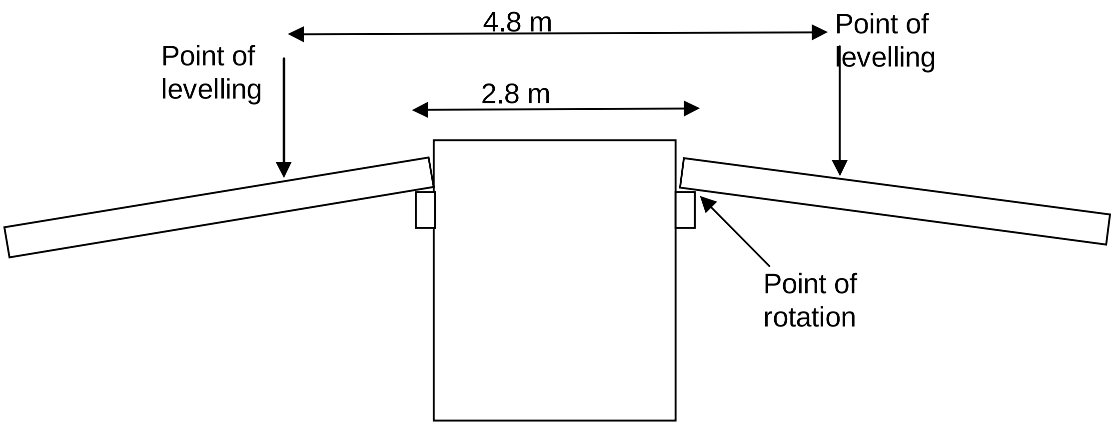

Figure 5.15 Illustration method for assessing rotation of slab and settlement of end of slab

Extrapolating the measured settlement to the settlement at the end of the slab results in a settlement of about 2.5 cm in 10 months. This is about 2.5 times the autonomous settlement of the subsoil. This suggests that part of the settlement near the transition zone originates from mechanisms below the approach slab.

The toe of the slab is thus found to settle more as the autonomous settlement of the subsoil. This is confirmed by the measured thickness of the ballast in the radar measurements. For three radar tracks the thickness of the ballast is reported. Main results are summarised in Table 5.5. At these tracks the 400 MHz radar is used. At the other tracks the 900 MHz radar is used. It is not mentioned why at these tracks no boundary ballast-sand is reported.

Track	Thickness ballast [m]				
	Embankment Gouda	End slab Gouda	Culvert	End slab Woerden	Embankment Woerden
145	0.6	0.75	n.a.	0.75	0.55
13	0.6	0.8	0.45	0.8	0.6
138	0.75	0.85	0.45	0.85	0.6
14	not reported				

Table 5.5 Thickness ballast in radar measurements

Note: thickness is as reported in excel sheets by Geofox

The thickness of the ballast at the end of the slab is about 0.1 m to 0.2 m more as at the adjacent embankment. This indicates that the settlement of the toe of the slab is more as the settlement of the embankment.

Assuming that the thickness of the ballast at the culvert is representative for the original thickness of the ballast an estimate of the ballast settlement can be made by subtracting this value from the measured values.

Track	Settlement ballast [m]				
	Embankment Gouda	End slab Gouda	Culvert	End slab Woerden	Embankment Woerden
145 [1])	0.15	0.3		0.3	0.1
13	0.15	0.35	0.0	0.35	0.15
138	0.3	0.4	0.0	0.4	0.15
14	not reported				
average	0.20	0.35	0.0	0.35	0.13

Table 5.6 Settlement ballast from radar measurements

[1]): for the thickness of the original ballast d = 0.45 m is used

From this follows that the settlement at the toe of the slab is on average 2.1 times the autonomous settlement of the embankment.

The vertical deformation of the sand and the ballast on top of the approach slab will be discussed. For the period October 2008 to June 2009 the following measured data are available:

- Top of ballast from hanging sleeper devices and levelling of the track (see Section 5.2).
- Settlement toe of slab (for this the assessed 25 mm in 11 months is used, this Section).

For the period October 2008 to June 2009 the best estimates of the vertical deformation of the ballast is sketched in Figure 5.16. The estimated settlements are indicated with an arrow. The dashed figure shows the deformed shape of the ballast on top of the culvert (deformations are exaggerated). The settlement of the toe of the slab during 8 months is estimated from the assessed settlement of 25 mm during 11 months. At the point of rotation the vertical displacement of the lower side is of course zero.

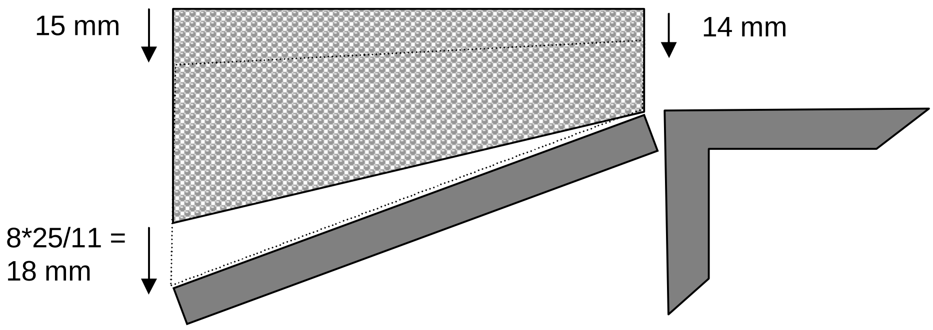

Figure 5.16 Vertical deformation of sand/ballast body on approach slab, position of culvert and slab is indicated (figure not to scale)

Near the culvert the net vertical loss of thickness is 14 mm. At the other end of the slab the top of the ballast settles 15 mm while the toe of the slab settles 18 mm. This indicates that the thickness of the sand and ballast here increases with 3 mm. As no maintenance was performed in the considered period, this increase in thickness cannot be explained from adding additional ballast material.
The average settlement over the area of the slab is about 0.5*(14 – 3) = 5.5 mm. This coincides well with the average of the compaction of the ballast of 3 mm at the culvert and 8 mm at the free embankment (see Section 5.3). This however may be coincidentally.

This deformation pattern suggests that the soil (sand and ballast) above the slab compacts or is transported to another area. Part of it may flow around the side edges of the slab to the void below the slab. The increase in thickness near the toe suggests a possible downward flow of material over the slab.

5.6.3 Possible explanation settlement toe of slab

In this section two aspects are discussed:

- A check on volume.
- A possible model for predicting the settlement of toe as function of the autonomous settlement.

*** Check of volume**
Here a check on the volume balance is made, for checking if the observed settlement rate of the toe of the slab is possible from a volumetric point of view. After so many years it is reasonable to assume that the sand under the approach slab does not densify anymore, so the volume of sand under the slab the may be considered as constant. As concluded above the best estimate of the settlement rate of the toe is 2.5 times the autonomous settlement.

A mass of sand below the slab is considered. The main components of flow of the sand in and out of this control volume are shown in Figure 5.17. This consideration is done for total volumes, so is the combination of sand and void volume is considered.

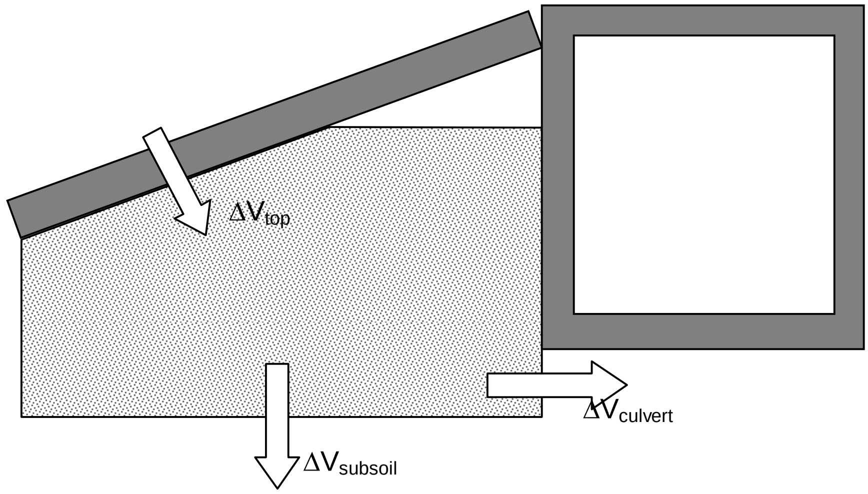

Figure 5.17 Flow of sand at settlement of subsoil

Settling of the clay/peat layers with an amount of Δz results in a loss of sand through the original sand-clay interface of $\Delta V_{subsoil} = \Delta z*L$, where L is the (horizontal) length of the approach slab.

Since the toe of the approach slab settles 2.5 times the autonomous settlement and the slab is hinged at one side (so zero settlement), the average settlement is $1.25*\Delta z$. The volume change (decrease) at the top side is $\Delta V_{top} =1.25*\Delta z*L$.

Another source for volume loss is the possible void below the culvert. The autonomous settlement of the soil below the culvert is not measured. A first assumption is that the settlement of the soil directly below the culvert is comparable to the autonomous settlement of the embankment. The width of the culvert is B. A void below the culvert will be filled from two sides, so only 0.5B is available for storing sand from one side. In this void a volume of $0.5B*\Delta z$ may be stored. With L = 4 m and B = 2 m this component amounts $\Delta V_{culvert} = 0.25*L*\Delta z$. So the net volume change without densification is
$\Delta V = \Delta V_{top} - \Delta V_{culvert} - \Delta V_{subsoil} = 1.25*\Delta z*L - 0.25*\Delta z*L - 1.00*\Delta z*L = 0$

This evaluation of the volume changes shows that a settlement rate of the toe of 2.5 times the autonomous settlement is possible. The volume that flows at the top into the control volume, can flow out of the control volume at the bottom.

*** Modelling settlement of approach slab**
A model has been developed to describe the mechanism described above. The inclination of the interface between the slab and the sand below the slab must change during settlement of the subsoil: In case the toe of the slab settles as much as the subsoil the contact length between slab and subsoil decreases. In that case the slab would rest on its toe only.

For transferring the load of the ballast and the train on the slab to the subsoil a certain minimum contact length is required. For heavy trains passing the transition zone the slab will settle in order to create enough contact length. It is assumed that after some time the minimum contact length will be present. This implies that the slab is at the verge of stability. This additional settlement requires that sand moves away from the toe of the slab. This will result in some heave of the sand elsewhere in the considered length section and/or sideward displacement of soil.

For the model the following assumptions are made:

- The horizontal length of the area where the slab is resting on the sand is constant;
- The net volume change of the sand is zero.
- A void may be present below the upper part of the slab, in this void the level of the sand is horizontal.
- A change of the height of the void under the slab has no influence on the contact length, this means that the heave of the soil in the void does not play a role in the support of the slab.
- The autonomous settlement of the soil below the culvert is equal to the autonomous settlement of the soil below the embankment.
- Sand may flow into the void below the culvert.
- The situation is modelled as a 2-dimensional situation, sideward displacement of sand is neglected.

In Figure 5.18 the approach is illustrated.

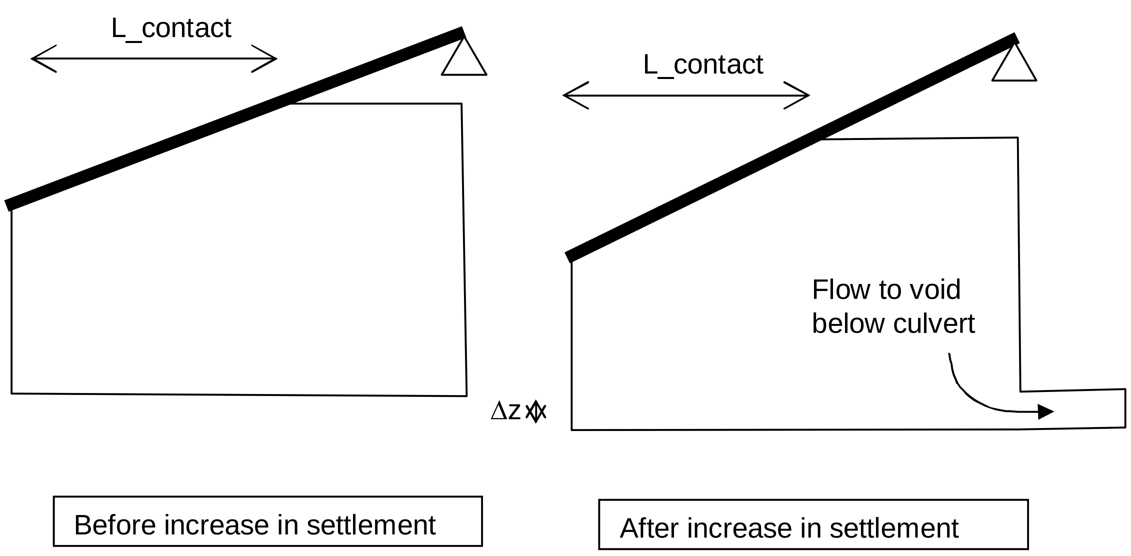

Figure 5.18 Illustration model settlement of plate

With this model an assessment of the development of the settlement of the subsoil, the toe of the slab and the void below the slab was made. Two situations are considered as the two extremes for the actual situation are presented here:

- Contact length L_contact = 1 m, sand may flow under 1 m of the culvert, this is the minimum case.

- Contact length L_contact = 3 m, underneath the culvert and plate sand may flow in sideward direction as well (this increases the available space for storing sand in the void below the culvert). In the model this is described by a doubling of the width of the culvert, here mentioned the effective width. This is the maximum case.

The results of the calculation for these two situations are shown in Figure 5.19 and Figure 5.20. The graphs show the settlement of the toe of the slab and the change in height of the void near the point of rotation as function of the autonomous settlement of the subsoil.

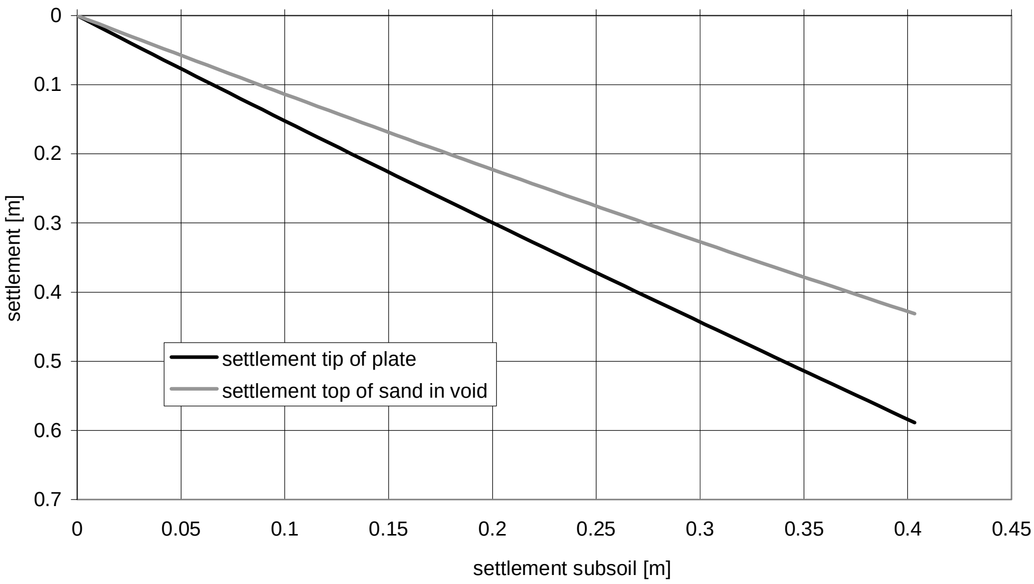

Figure 5.19 Development settlement, L_contact 1 m, B_eff = 1 m

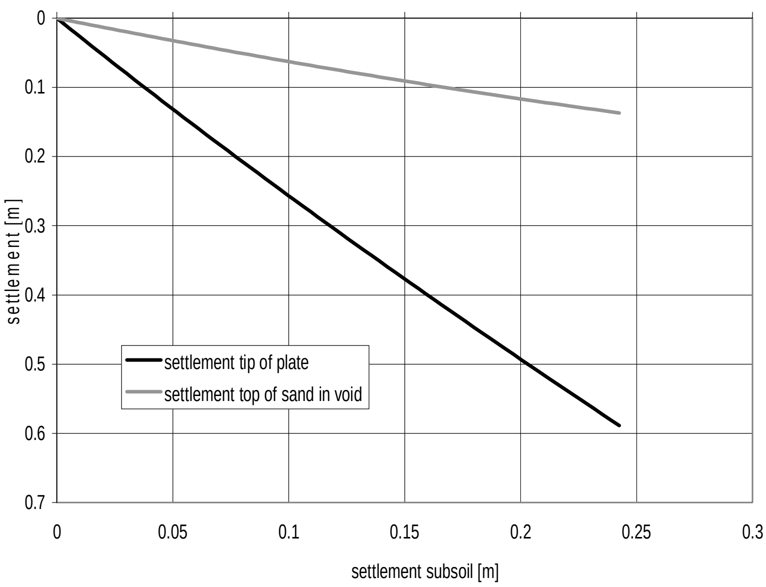

Figure 5.20 Development settlement, L_contact 3 m, B_eff = 2 m

According to this model the toe settles 1.5 times (minimum case) to 2.5 times (maximum case) as fast as the autonomous settlement of the subsoil. In the minimum case the surface of the sand in the void settles a little bit faster than the subsoil. In the maximum case the surface of the sand in the void settles about 2/3 of the settlement of the subsoil. This means that in both cases the height of the void underneath the slab increases

According to the model, a relatively long contact length is needed for obtaining this ratio. A static solution acc. to *e.g.* Brinch-Hansen shows that a contact length of about 1-2 m is enough to carry the load. The cyclic and dynamic load of the passing trains may increase the required contact length. Due to the vertical motion of the embankment during train passage (see Chapter 6), a continuous shear friction along the slab surface is generated. Although it cannot be excluded that other, not identified, mechanisms are present, the model developed here gives a reasonable explanation for the difference in settlement of the toe compared to the autonomous settlement.

5.7 Settlement of slab compared to settlement of embankment

From the preceding it is concluded that the settlement of the toe of the slab is about 2.5 mm/month. This settlement rate may be compared to the settlement of the embankment after maintenance. Figure 5.21 shows the development of the two points in time.

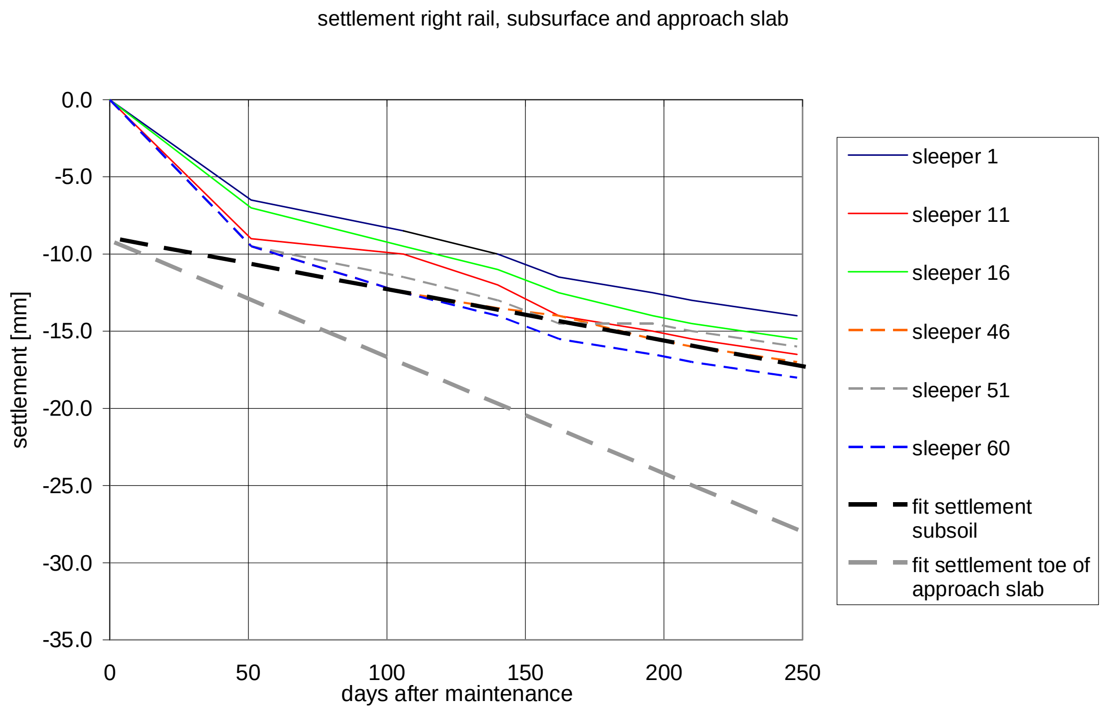

Figure 5.21 Comparison settlement of embankment and of toe of slab

5.8 Horizontal motions of ballast and embankment

In Section 3.2.5 it was concluded that the horizontal displacements as measured with the inclinometers are within the accuracy range of the equipment. Therefore, the only conclusion that can be drawn from these measurements is that the horizontal displacements are less than 2.5 mm per year and may be close to zero.

6 Analysis of short-term behaviour

6.1 Introduction

In this chapter the results of the short-term measurements of 2008 and 2009 field measurement campaigns are discussed. The 2008 measurements were reported in [Deltares, 2008], the 2009 measurements were reported in [Deltares, 2009c]. Section 3.3 offers a global overview of the devices installed during the 2009 measurement. Appendix A offers an overview of the position of all devices. The 2008 measurement was more limited, only some geophones and accelerometers were installed in front of the culvert (at the approach side) and the high-speed camera measurement was used.

6.2 Available trains

The following trains did pass the measurements devices at 4 May 2009.

Time	Numerical train id	Train type, composition	Speed [km/h] (App D.3)	Remark
10:59	01	mat V, 6	103	composition from measurement
11:27	08	SGM, 3	99	
11:57	14	SGM,2+3	98	
12:28	20	SGM, 3	100	
12:57	26	SGM, 3+2	111	
13:27	33	mat V, 2+2+2	113	composition from measurement
13:57	36	SGM, 3	106	
14:26	40	SGM 2+3	114	
14:57	43	SGM, 3	109	
15:30	47	SGM, 3+2	73	
15:58	50	mat V, 2+2+2+2	99	composition from measurement
16:29	56	SGM, 3+3	102	
16:59	62	SGM, 3+3	104	
17:29	68	SGM, 3	69	

Table 6.1 Trains passed over culvert on 4 May 2009

Two trains with lower speed (47 and 68) offers the possibility to consider the behaviour at lower train speed. Train 43 has similar composition as train 68, but passes with a higher speed. The same holds for Train 47 and Train 40. Finally, Train 33 and Train 50 are of a different type. These six trains are selected for analysis. The other trains might be useful for further analysis, e.g. to see whether results are repeatable.

6.3 Track deformations

The following pages shows the deformations of the track. measured with geophones. The vertical axis shows the displacement in mm. The position of the curve depends on the position of the transducers, where one meter in the field leads to an offset of 6 mm in the vertical axis of the graph. In these figures, the trains “go from bottom to top”. The transducer at the bottom are passed as first.

On each page two sets are shown:

- Train 43 and train 68: SGM with 3 cars, speed 106 and 66 km/h.
- Train 40 and train 47: SGM with 5 cars, speed 110 and 67.
- Train 33 and train 50: mat V with 6 cars (speed 106) and 4 cars (speed 93 km/h).

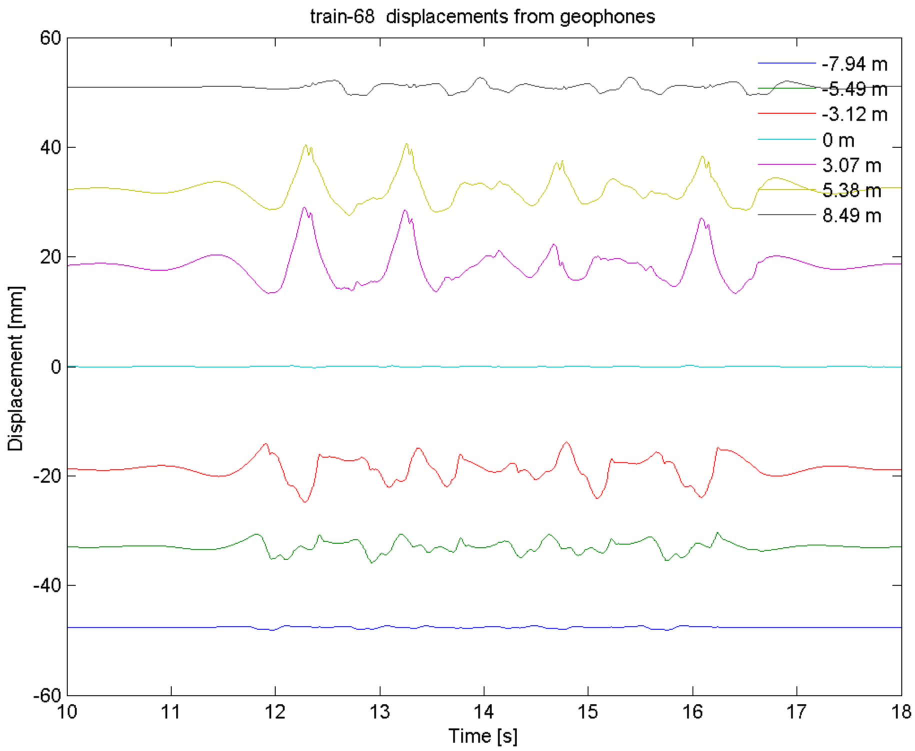

Figure 6.1 *Track displacements seismogram Train 68, SGM 3 cars, 66 km/h*

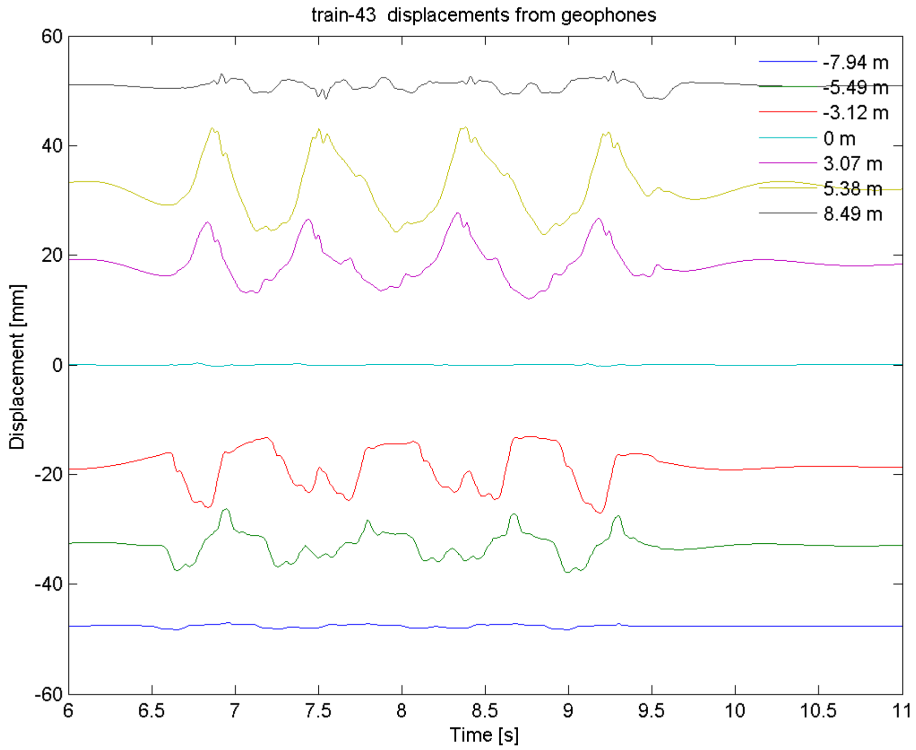

Figure 6.2 Track displacements seismogram Train 43, M 3 cars, 106 km/h

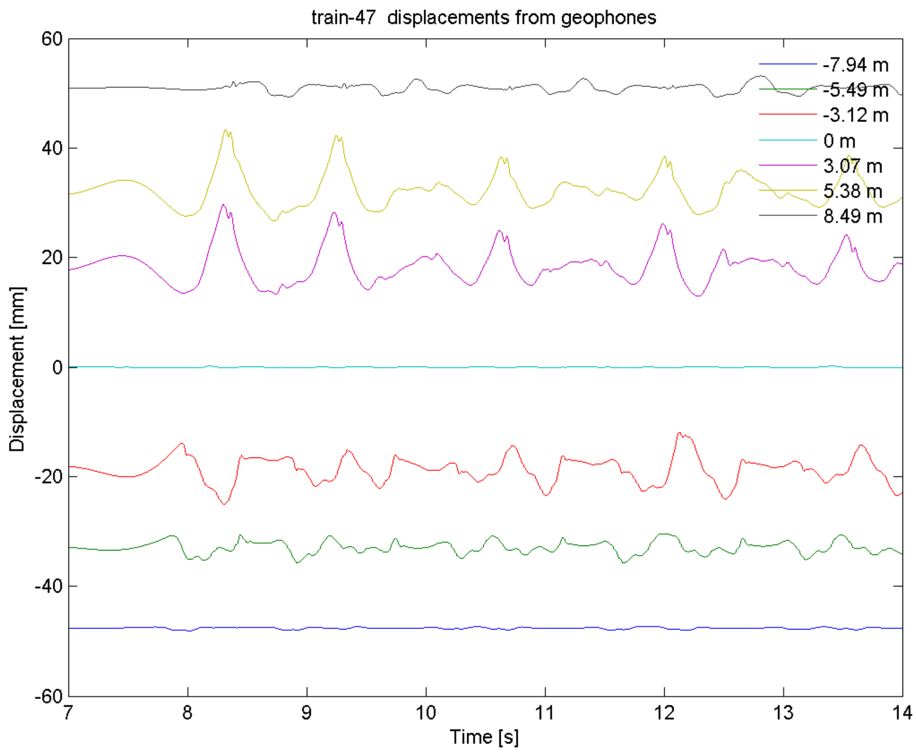

Figure 6.3 Track displacements seismogram Train 47,SGM 3+2 cars, 67 km/h

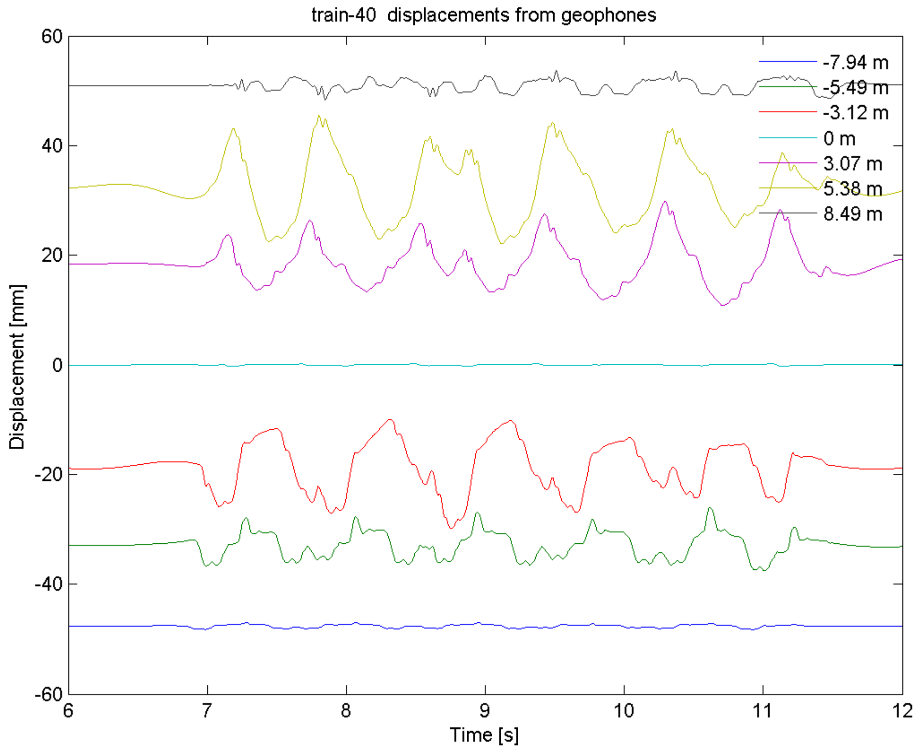

Figure 6.4 Track displacements seismogram Train 40, SGM 3+2 cars, 110 km/h

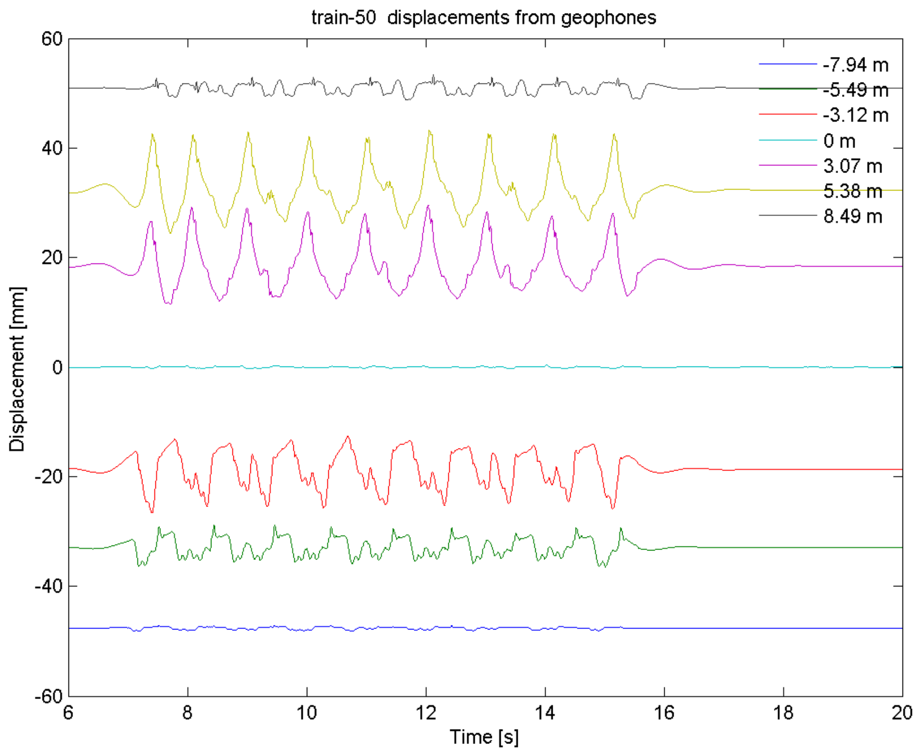

Figure 6.5 Track displacements seismogram Train 50, Mat V 2+2+2+2 cars, 93 km/h

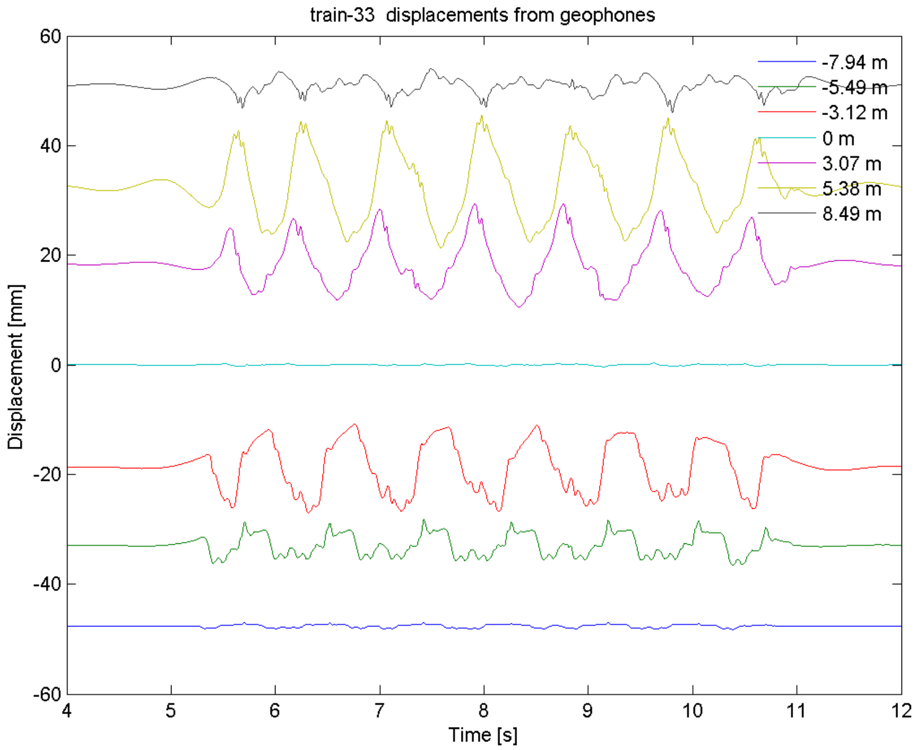

Figure 6.6 Track displacements seismogram Train 33, Mat V 2+2+2 cars,106 km/h

The difference between the motion of the track in front of the culvert (positions with negative coordinate in the legend) and behind the culvert (seen in the driving direction; positions with negative coordinate in the legend) are large. These aspects are speed dependant. Figure 6.7 shows the motion of the (sixth) transducer about 5.4 m from the centre of the culvert. The time (on the horizontal axis) has been shifted over 0.5 s, in order to get the axle-passage on the same position in the graph.

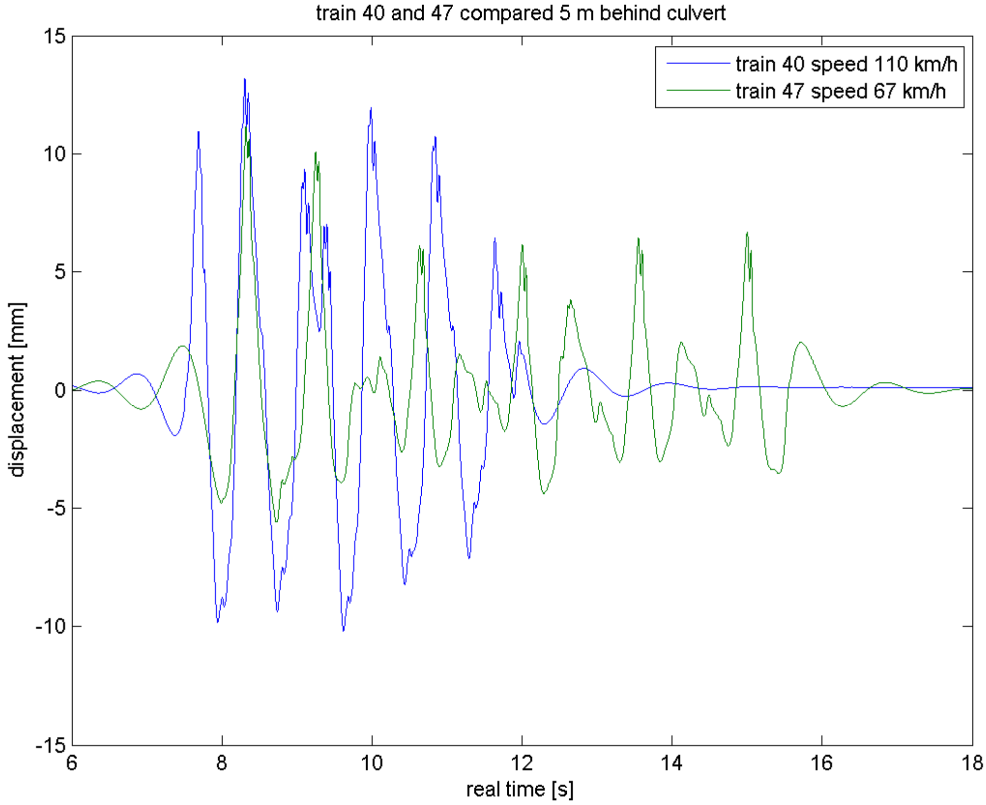

Figure 6.7 Displacement at 5.4 m behind culvert compared for Sprinter (SGM) 5 cars

The influence of the speed is seen. The observations seem to show resonance behaviour of the track:

- Train 47 with half of the speed of Train 40, shows a double number of vibrations.
- The passage of Train 40 with 110 km/h excitates the lever behaviour of the track almost optimal.

Obviously, track resonance occurs, the resonance frequency is estimated from the carriage length (24.4 m) and the speed (110 km/h = 30.6 m/s), leading to a loading frequency of 1.25 Hz.

The passage of the trains 40 and 47 will be inspected in more detail, to get information on the background of the peaks in the measured signals. Figure 6.8 shows the track displacements in front of the culvert, Figure 6.9 shows the track displacements behind the culvert. It should be noted that the geophone above the culvert is shown twice. In these Figures the train passes “from top to bottom”. The position of the geophones is shown in Table 4.1.

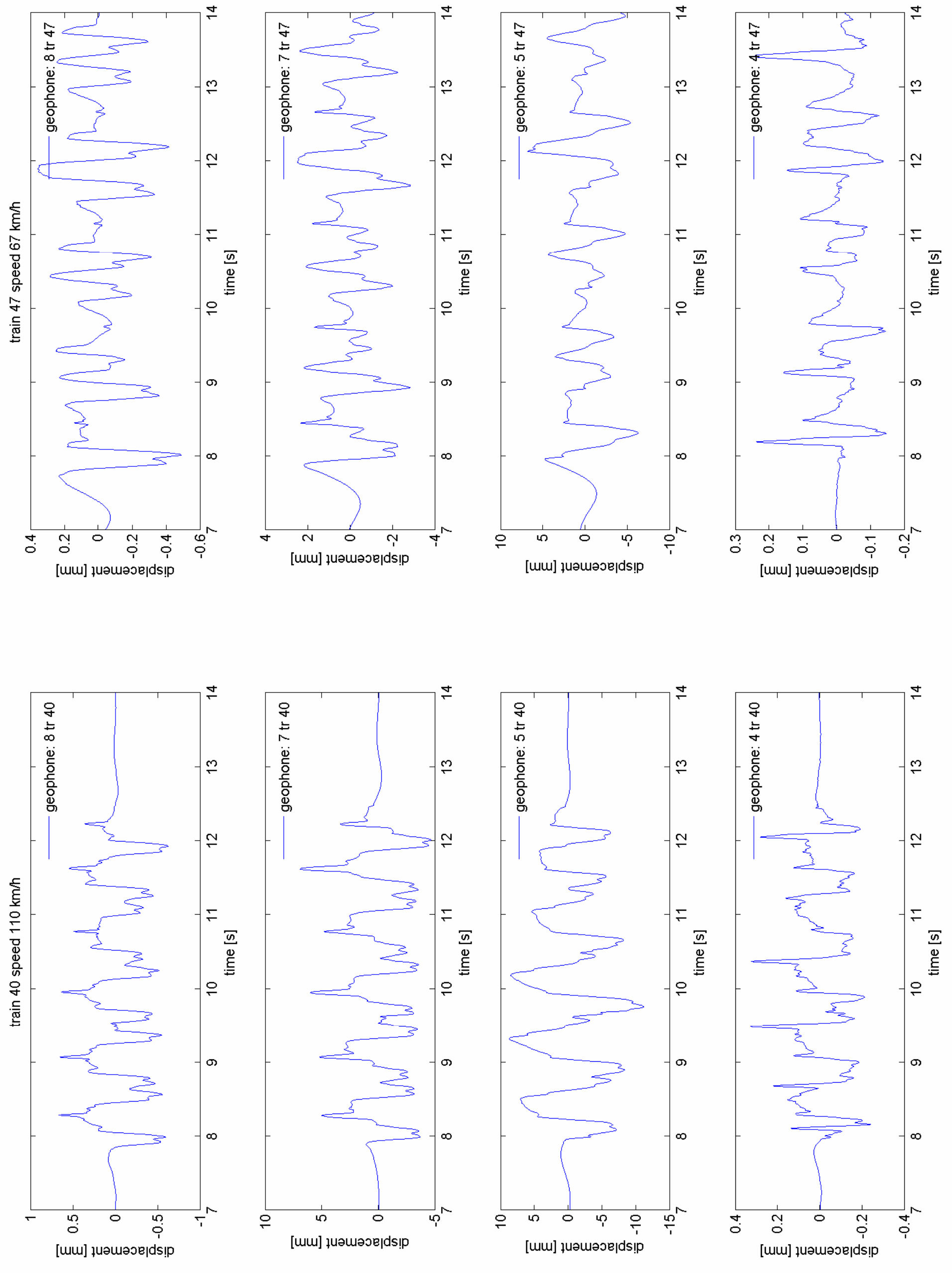

Figure 6.8 *Motion of the track in front of culvert for Train 40 and Train 47*

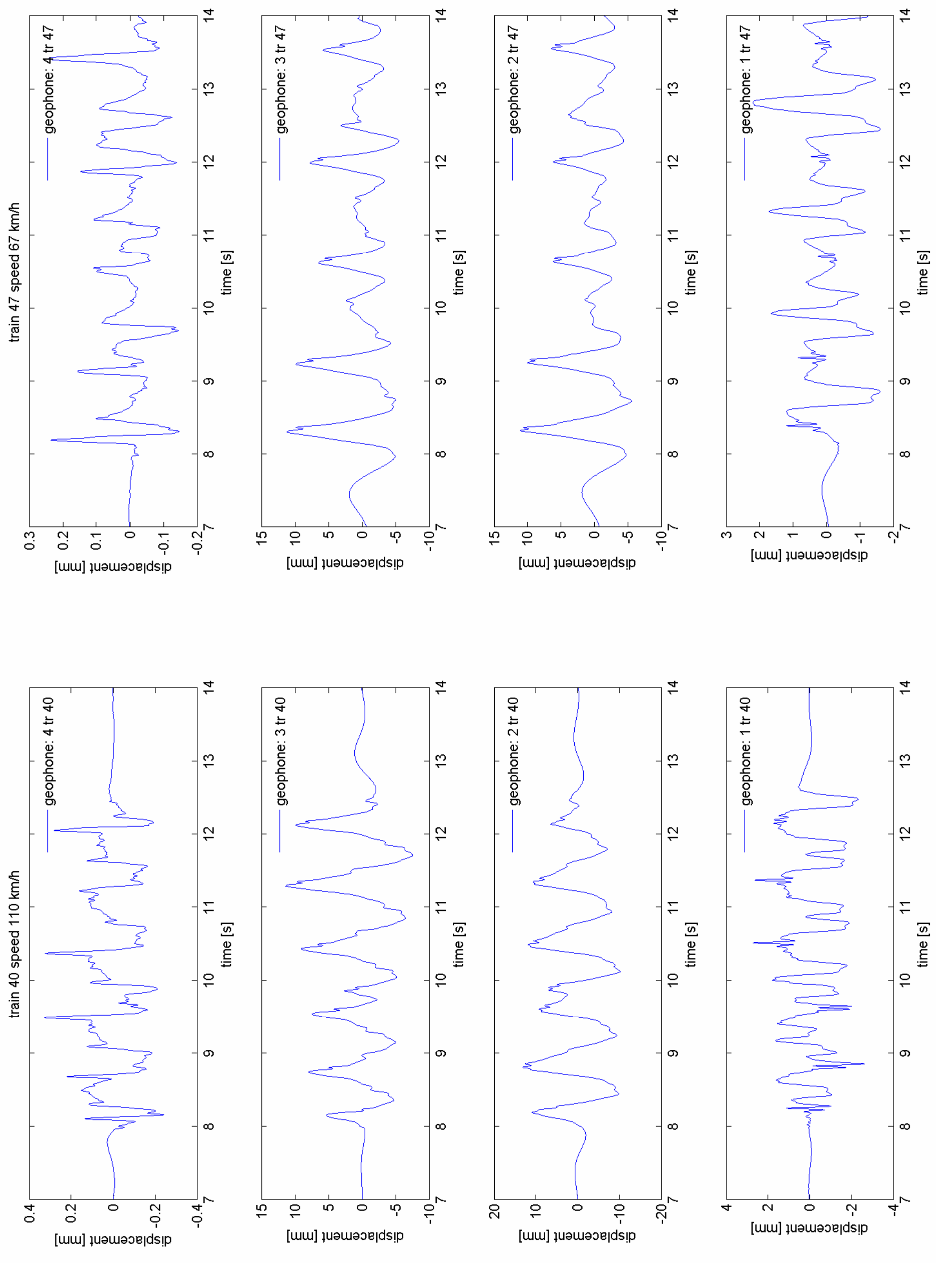

Figure 6.9 Motion of the track behind the culvert for Train 40 and Train 47

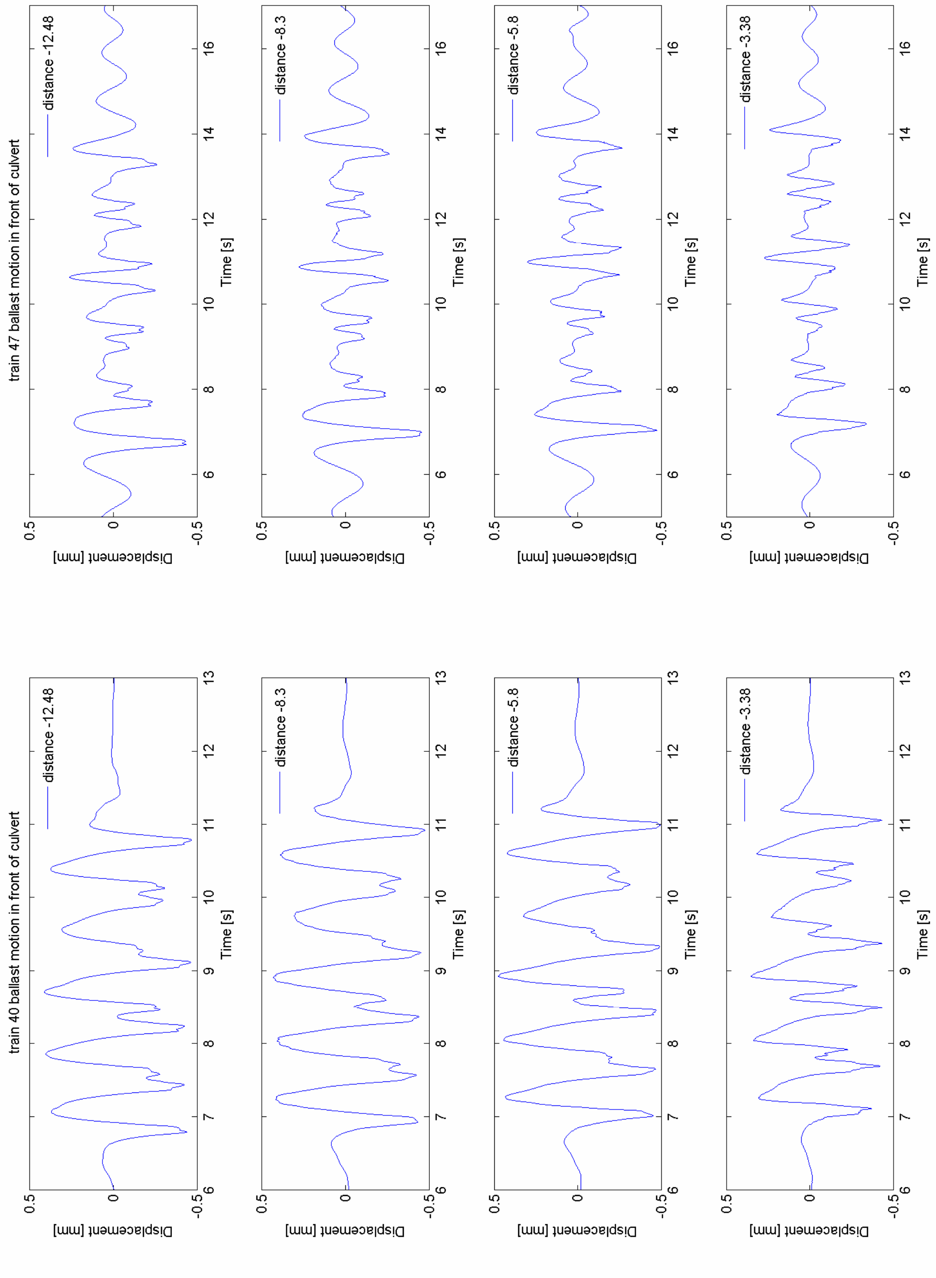

Figure 6.10 Motion of the ballast in front of the culvert for Train 40 and Train 47

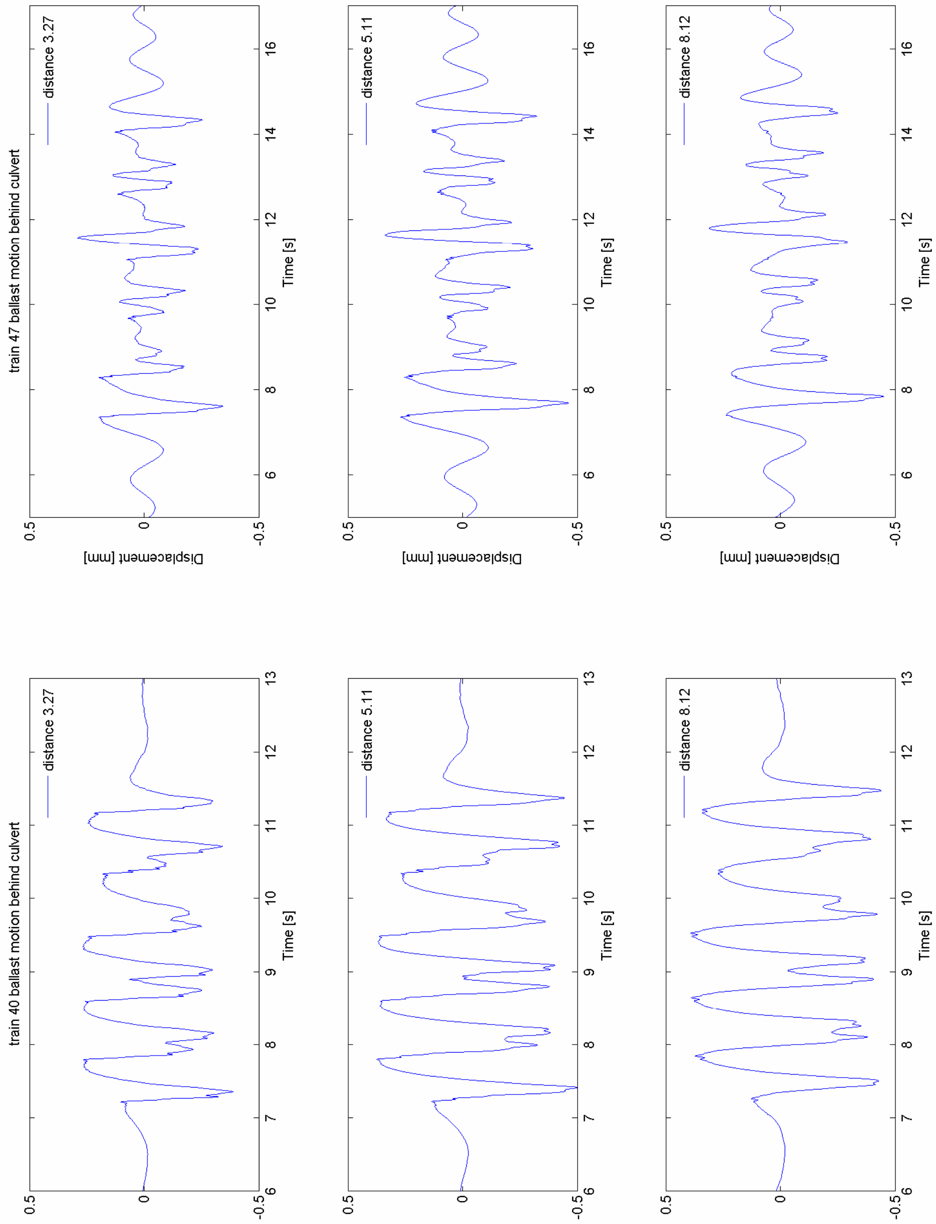

Figure 6.11 Motion of the behind the culvert for Train 40 and Train 47

First, the motion of the track is studied. In Figure 6.8 (in front of the culvert) and Figure 6.9 (behind the culvert), the left column holds for Train 40 with 110 km/h, the right column holds for Train 47 with speed 67 km/h.

Some remarkable differences are observed:

- For both speeds the behaviour is not symmetric.
- For the higher speed (train 40), the sharp peaks ('spikes') are clearly observed in front of the culvert.
- The height of the spikes depends on the strength of the signals (note that the scales in the figures are different!).
- The duration of the spikes is almost constant 0.12 s for the higher speed (Train 40).
- For the lower speed (Train 47) the track moves fully upward between two boogies, for the higher speed (Train 40) this does not happen anymore.
- The spikes in front of the culvert are related to the spike at the sleeper before the boogie passage, the spikes behind the culvert are related to the spikes after the boogie passage.

Figure 6.12 and Figure 6.13 show the time position of the spikes for each geophone. In train 40 six spikes are seen, so the phenomenon depends on the axle groups, where one or two nearby boogies are considered as an axle group. In Train 47 the spike in front of the culvert cannot be clearly distinguished, there are too many maxima.

The lines for the spikes are almost horizontal, this means that the spikes occur almost instantaneously and the speed of the spikes is much higher than the train speed (the train speed is marked by a dashed line).

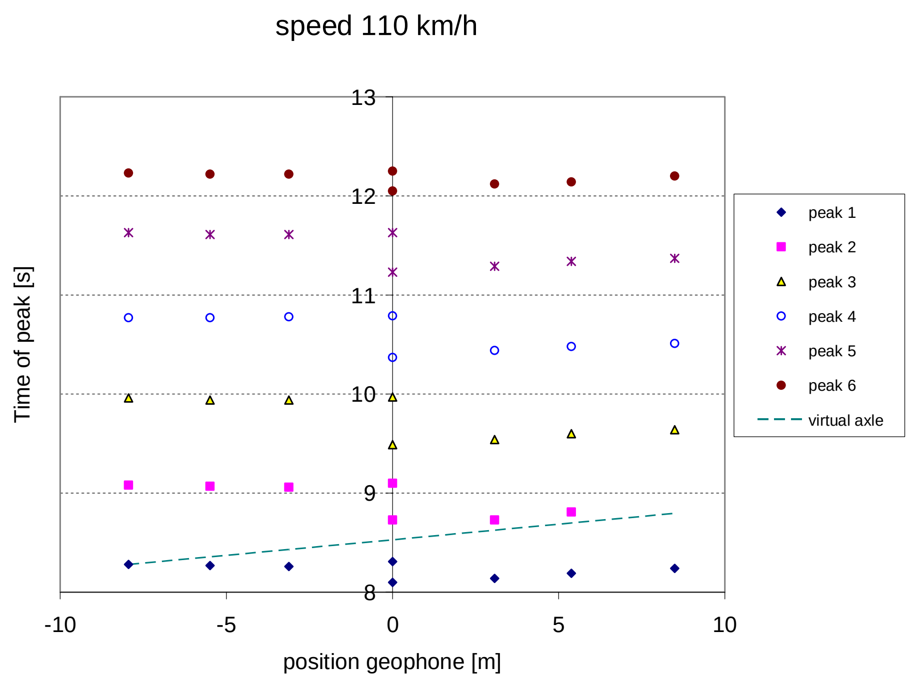

Figure 6.12 Position of spikes for Train 40 (110 km/h)

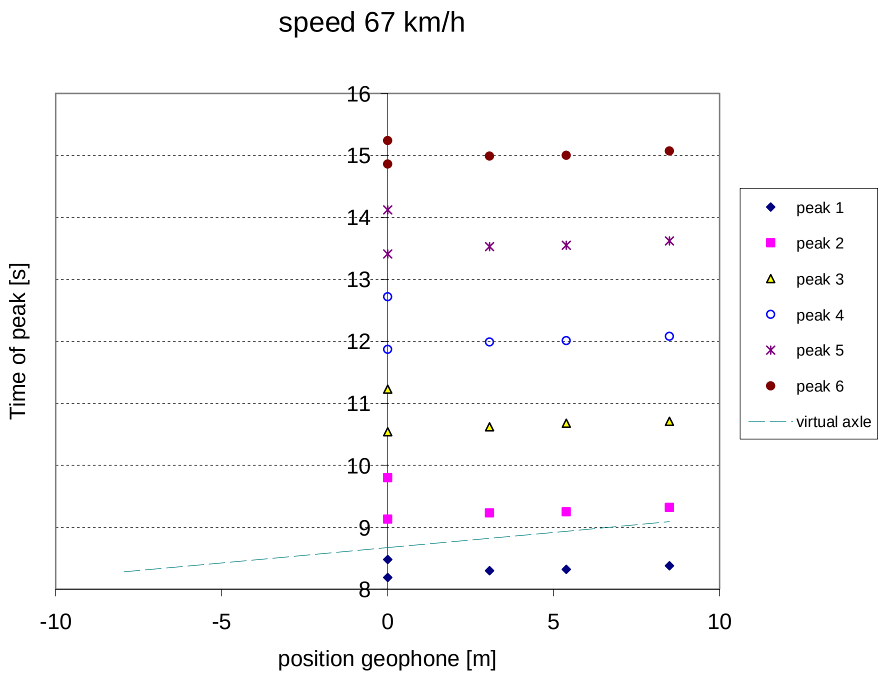

Figure 6.13 *Position of spikes for Train 47 (67 km/h)*
In front of the culvert (negative positions) the position of the spikes cannot be determined exactly

The spikes seems to be linked with the passage of an axle group on the edge of the culvert.

Figure 6.14 shows the distance related to the jump in these lines at position 0 m in Figure 6.12 and Figure 6.13. This distance is calculated from the (time) jump multiplied with the train speed. For the first and the last axle group the related distance is about 6 m, the axles in between are 14 m.

Figure 6.15 shows similar information for Train 33 and Train 50, existing of both Mat V trains. The results are identical as the results in Figure 6.14. This suggests that the phenomenon is related with the structure and not the train type.

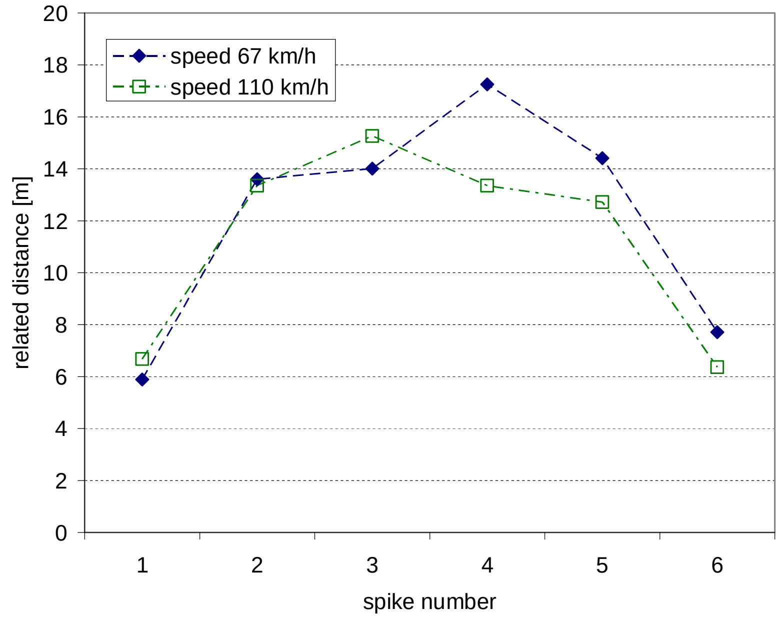

Figure 6.14 *Distance related to the jump in the lines in Figure 6.12 and Figure 6.13*

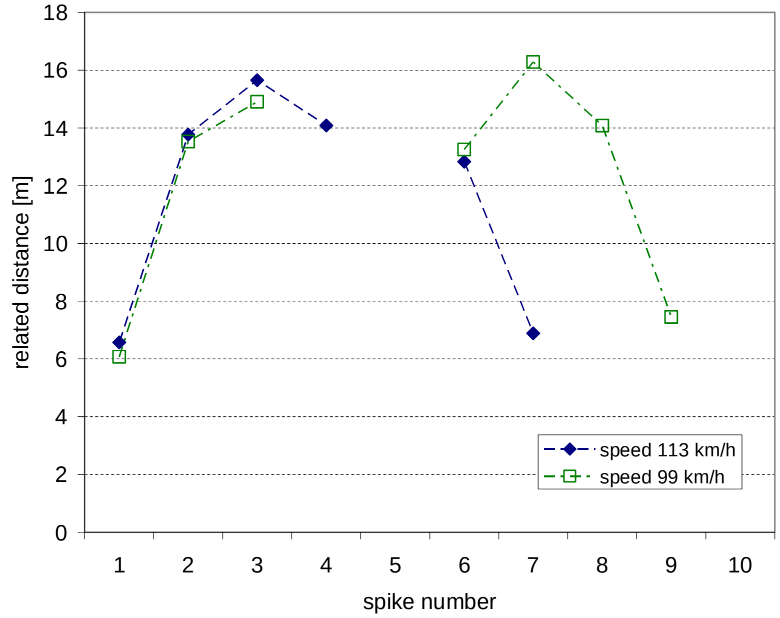

Figure 6.15 *Distance related to the jump in the lines for Mat V passages (Train 33 and Train 50)*

6.4 Motion of the ballast

Now, we focus on the measurement of the embankment. For Train 40 and Train 47 (Sprinter with 5 carriages) the results are shown in Figure 6.10 (in front of the culvert) and Figure 6.11 (behind the culvert). The motion of the ballast above the culvert is not measured. In these Figures the train passes “from top to bottom”.

The first observation is the amplitude of the displacement, which is order 1 mm, independent of the position. This is almost identical with the track displacement at Geophone 8 (the first one met by the train), but much smaller than the displacement of the track. Near by the culvert the displacement decreases somewhat.

The second observation is the dependency on train speed. The displacement under the first boogie is almost independent of the train speed, but for the consecutive boogies the higher speed gives a much higher displacement. It can be seen that train 40 (speed 114 km/h) has a 2+3 composition, while Train 47 has a 3+2 composition. Since the second carriage of the 3-carriage train has a lower axle load (about 90 kN versus 135 kN for the others), a lower displacement is expected for that carriage. That is observed for Train 40 at time 10.5 s and for Train 47 at time 8.5 s.
Train 40 shows a displacement that is twice the displacement found for Train 47. The passage of each second boogie (the odd numbers) are not able to put the ballast back to the position reached during the passage of the boogie before (the even number). It is expected that this is due to some type of resonance in the embankment.

6.5 Motion of the embankment

The motion of the embankment is studied in this Section. From the 2008 field-test, we observed that the embankment behaves as a ‘rigid’ mass. The lack of support at the edge of the embankment was considered as a mechanism that might lead to additional deformations. These two aspects are evaluated in this Section.

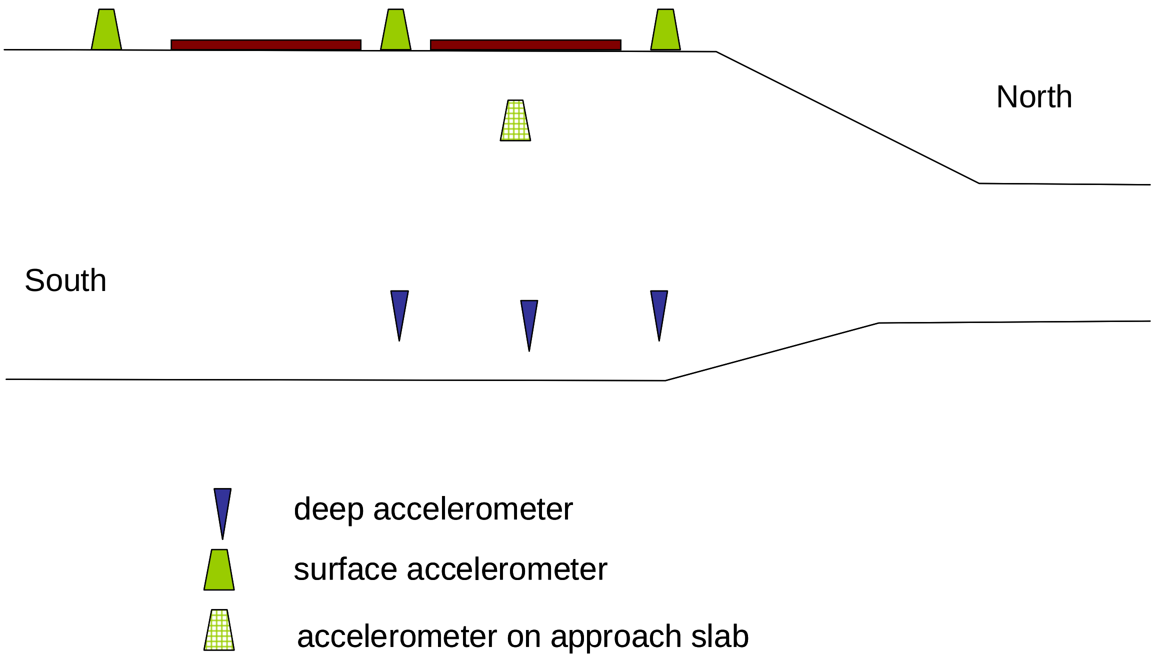

Figure 6.16 Cross-section of transducers

In order to evaluate the motion of the embankment three deep accelerometers and six surface accelerometers were installed, see Figure 6.16.

The deep accelerometers were installed at 8 m in front of the centre of the culvert (her called line 2), about 3 m below the track, just in the embankment. These are called 'south': south of track 1, 'north': north of track 1 and 'middle' right under track 1. A fourth accelerometer, called 'deep' was installed in the soft soil, at about 7 m right under track 1.
Two sets of three surface transducers are installed on the ballast:

- Line 1: A06, A04, A05, about 12 m in front of the culvert.
- Line 2: A03, A01 and A02, about 8 m in front of the culvert.

Four train passages are evaluated, see Table 6.2:

Train number	Train type	Speed [km/h]	Track	Number of cars
40	SGM	110	1 (north)	2+3
41	ICM	123	2 (south)	3+3
42	DDM	93	2 (south)	6
43	SGM	106	1 (north)	3

Table 6.2 Trains selected for behaviour of embankment

Figure 6.17 to Figure 6.20 show the vertical motion of the three sets of three transducers in the embankment for all four trains. Each figure has three plots: the top for the results in ray (line) 1, the second for Ray 2 and the third for the deep transducers.
During train passage over track 1 (the track most north, trains 40 and 43), the signals in middle and north have almost identical amplitude, while south is lower. This means that the embankment moves without rotation in vertical direction. During train passage over track 2 (the track closer to the centre of the embankment, trains 41 and 42), the signals are higher and south and middle do not the same amplitude. These results suggest a rotation towards the middle of the embankment during train passage at the south track, whereas a rotation towards the edge of the embankment was foreseen during passage on the north track.

The history of this embankment might give an explanation of this behaviour. The observed rotation suggests that the support in the middle of the embankment is less than the support at the north side of the embankment. At the north side the working road has been build, giving good support. In the middle, the support must be given from the old embankment, which might be much thinner and looser than the new embankment. However, this theory is speculative, since it is not supported by field data showing the thickness of the old embankment. Old measurements in the embankment nearby shows a thickness of the embankment between 1 and 4 meters. No results are available, at exactly the location of the culvert.

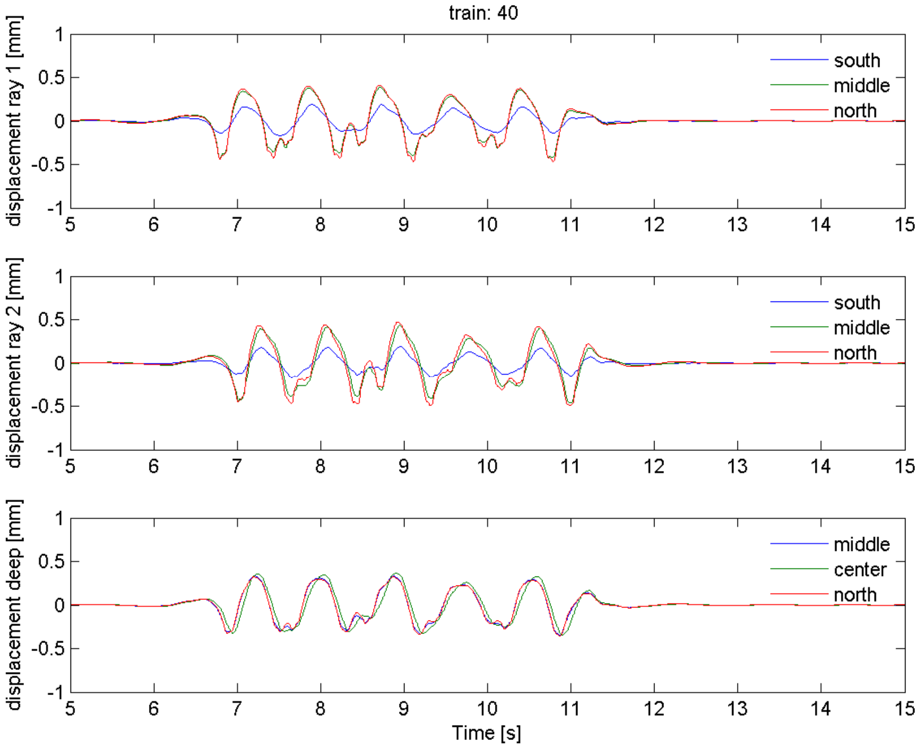

Figure 6.17 Vertical motion embankment, passing SGM speed 110 km/h

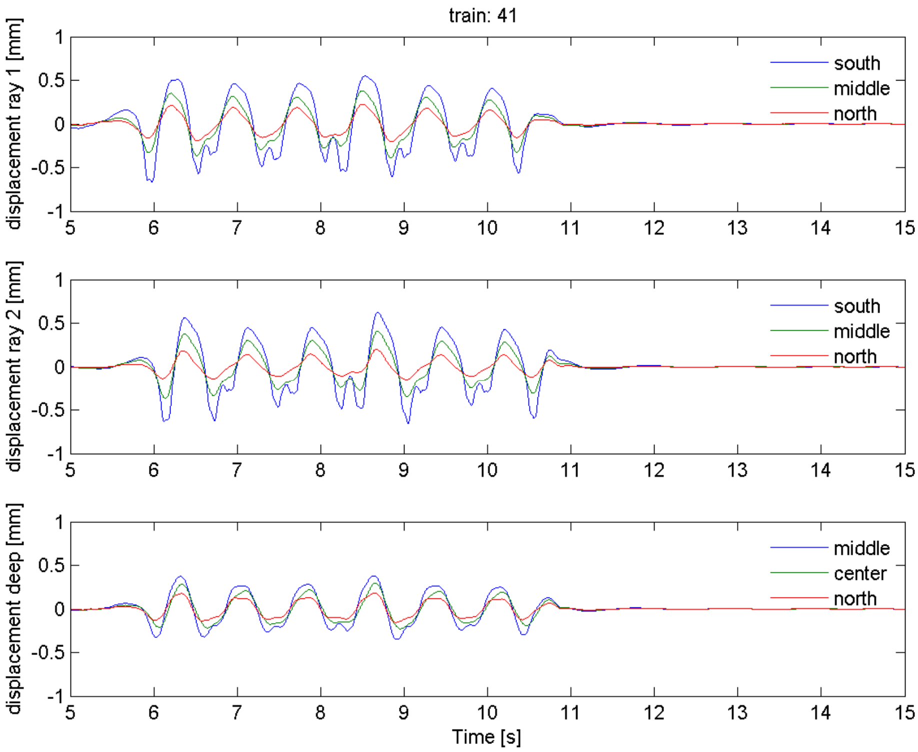

Figure 6.18 Vertical motion embankment, passing ICM speed 123 km/h

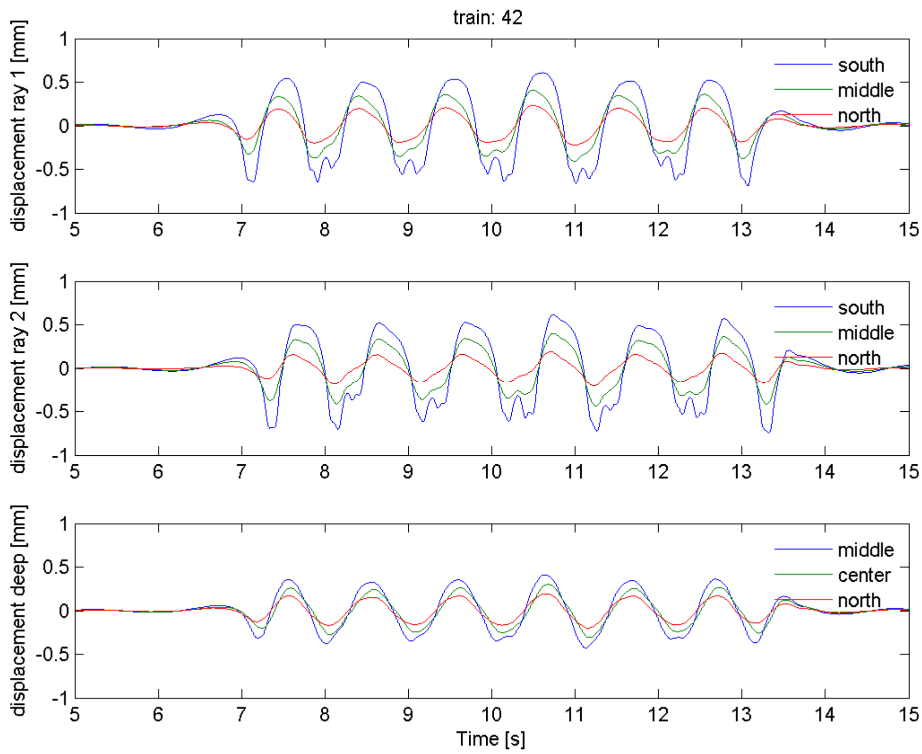

Figure 6.19 Vertical motion embankment, passing DDM speed 93 km/h

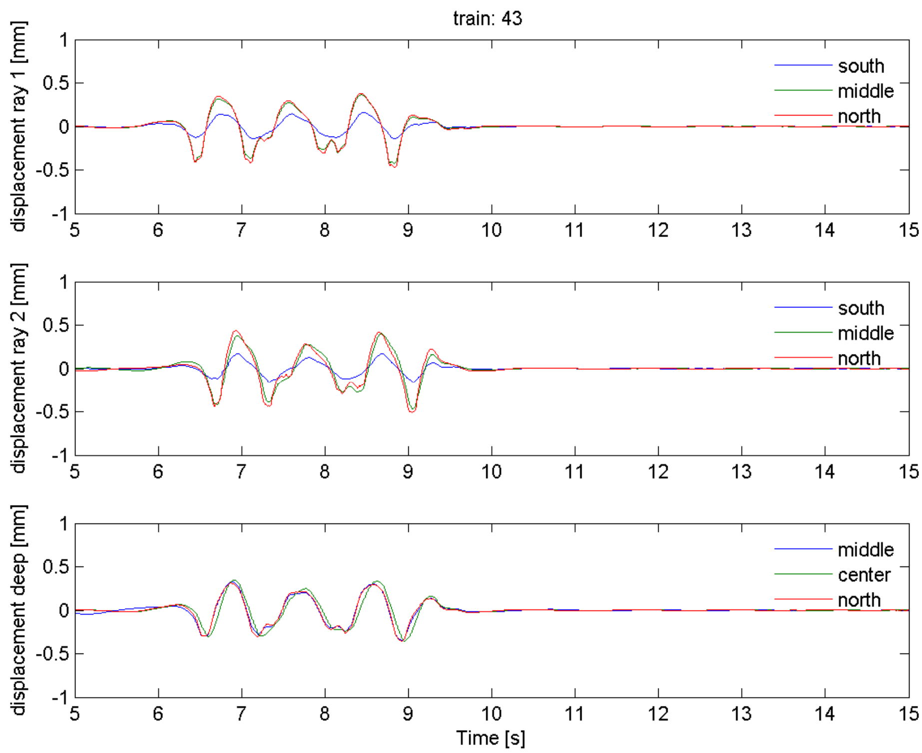

Figure 6.20 Vertical motion embankment, passing SGM speed 106 km/h

During the measurement most trains passed on the south track. The ballast measurement offers a good possibility to judge the influence of train type.

All these trains have more or less similar speed, see Table 6.3. For Train 66 one transducer failed. The signal ‘middle’ is missing (in fact shown by the green vertical lines).

Number	Type	Speed [m/s]	Speed [km/u]
61	Thalys	39.0	140
63	DDM 4	28.6	103
64	DDM 4+4	36.8	132
65	ICM 4+4	35.0	126
66	Freight	21.0	76
67	Int Loc + 7 carriages	21.9	79

Table 6.3 Train speed trains on track 2

The observed motion of the embankment shows the discussed behaviour and is identical for all fast trains.

Some remarks can be made:

- Figure 6.22 and Figure 6.23 shows the passage of DDM with 4 and 8 carriages Respectively. The final displacement of the short train (Figure 6.22) shows a decrease of the displacement, which is not observed in the longer train.
- The freight train (Figure 6.25) has a much lower displacement (note the difference in scale if the vertical axis). It might have been empty.
- The locomotion of the international train has a much smaller displacement than the lighter carriages, while the speed is similar.

These observations show that the speed and the train length together are responsible for the large motion. This means that a type of dynamic amplification (resonance) is active in this case. The behaviour of Train 63 might be explained for braking. Braking means deceleration, which moves the loading away from the ‘resonance’ values.

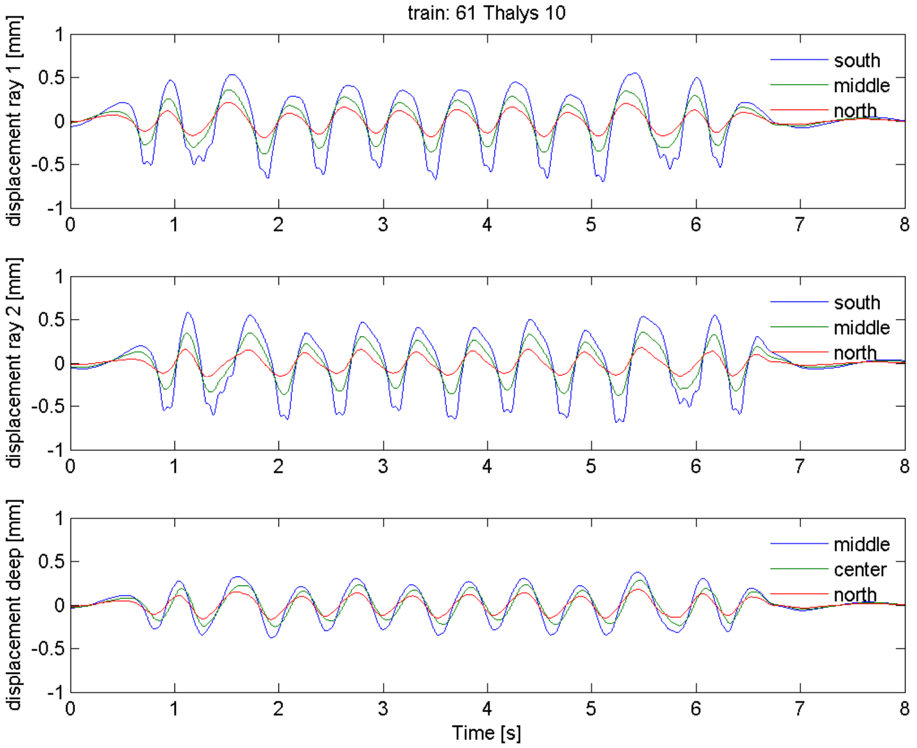

Figure 6.21 Embankment motion passage Train 61 Thalys on track 2

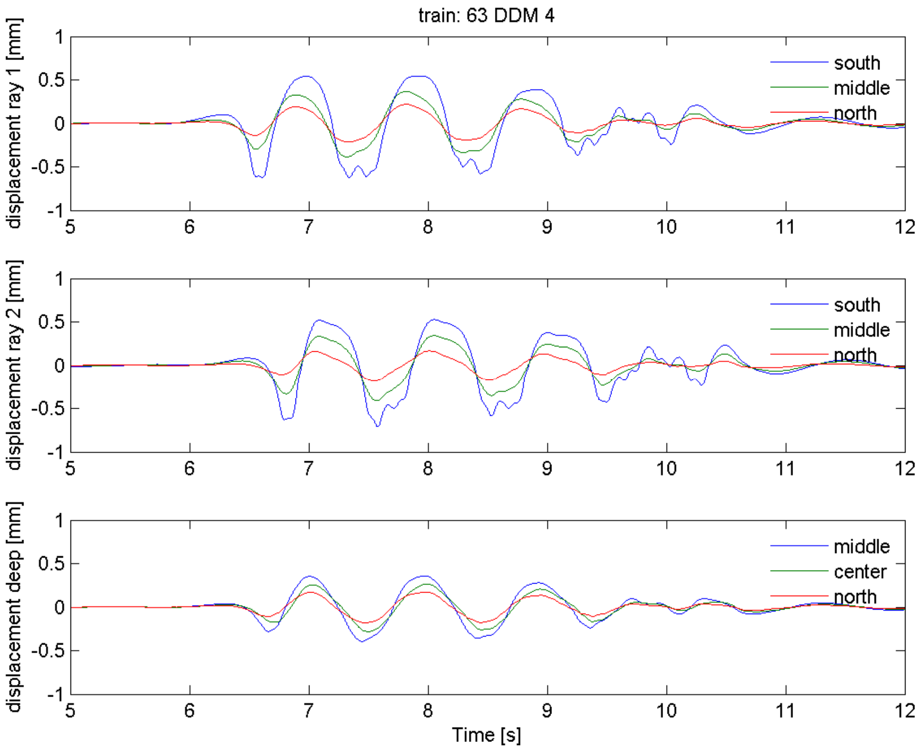

Figure 6.22 Embankment motion passage Train 63 DDM 4 on track 2

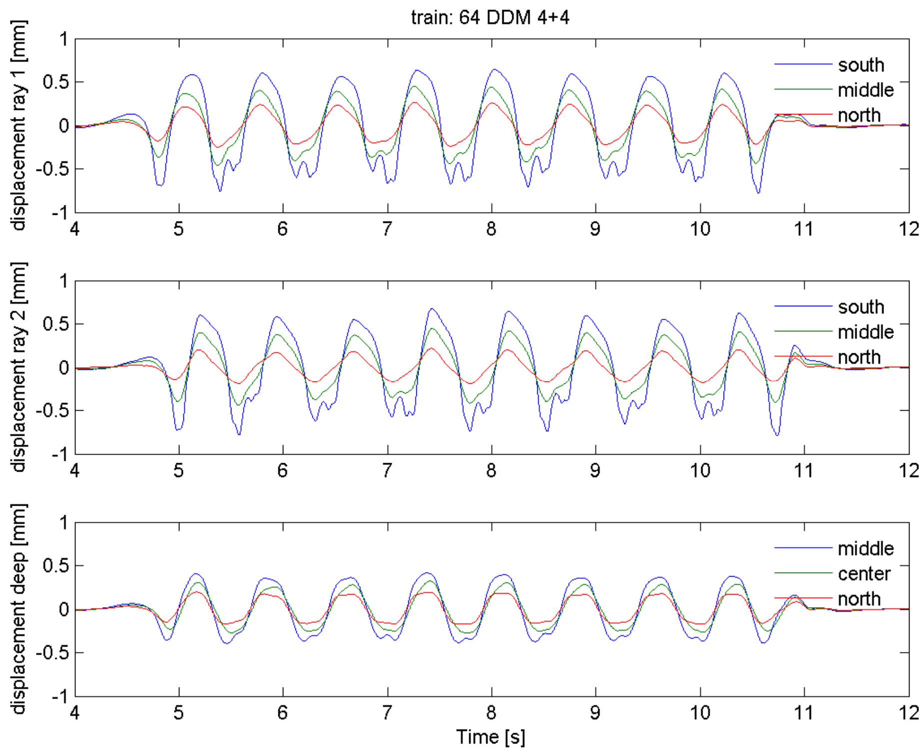

Figure 6.23 Embankment motion passage Train 64 DDM 4+4 on track 2

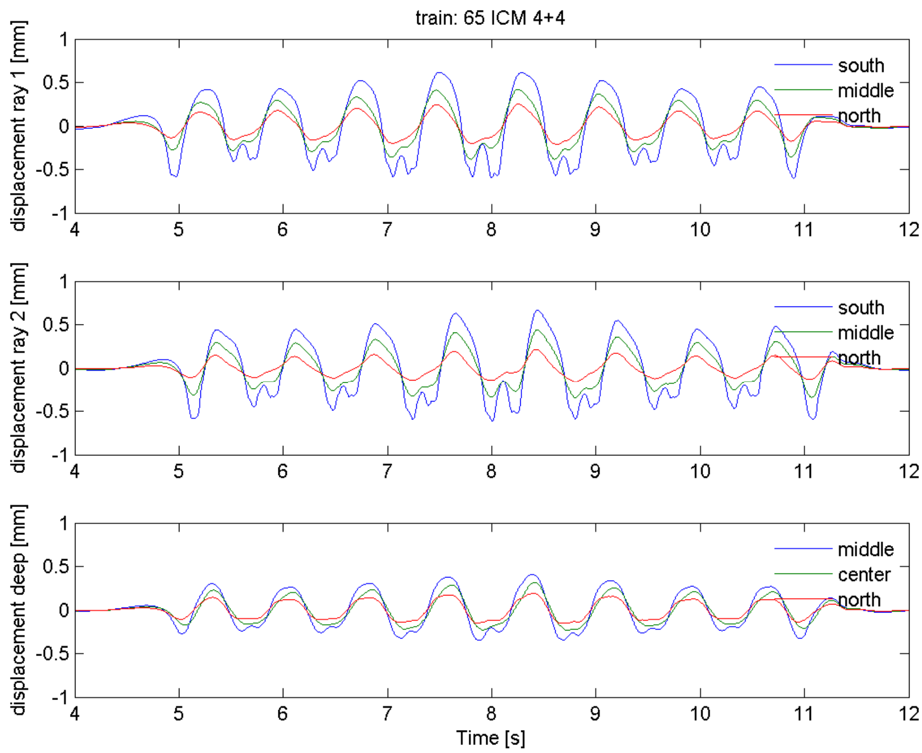

Figure 6.24 Embankment motion passage Train 65 ICM 4+4 on track 2

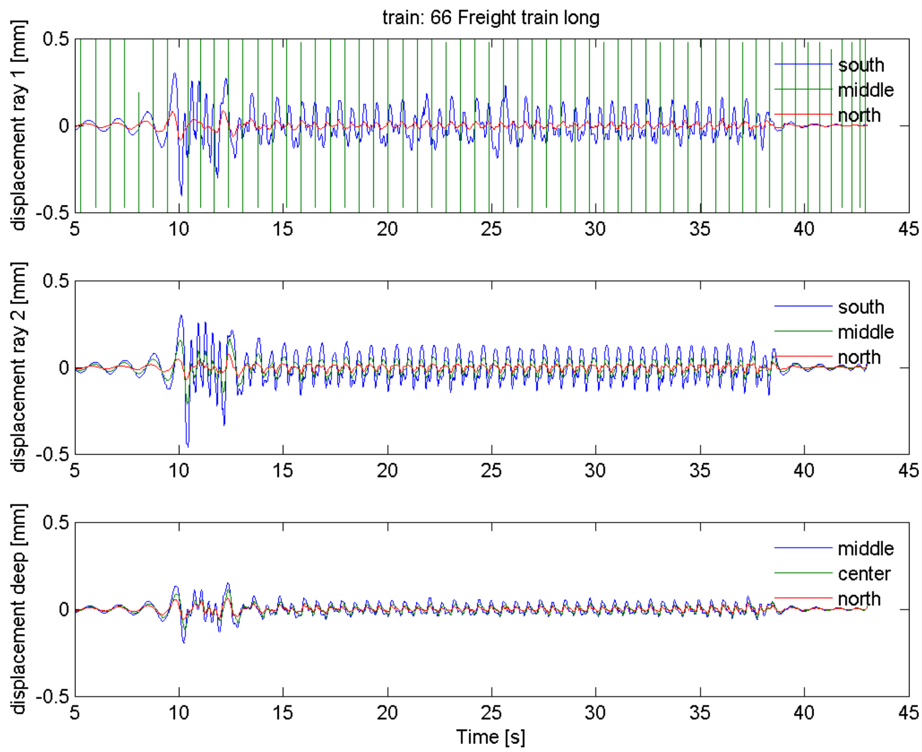

Figure 6.25 Embankment motion passage Train 66 freight train on track 2

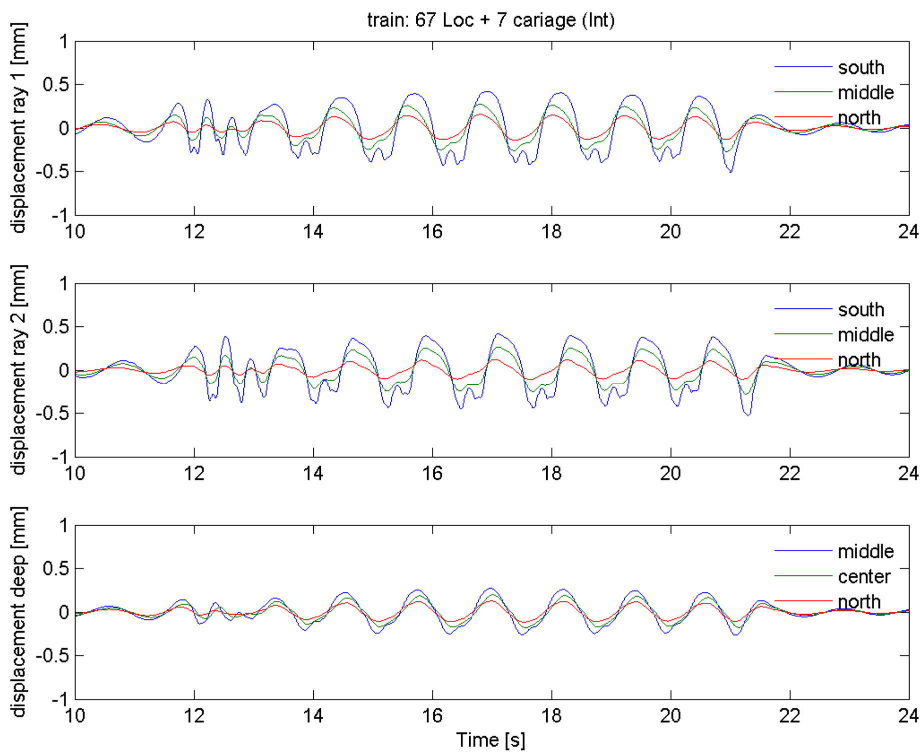

Figure 6.26 Embankment motion passage Train 67 loc + 7 cariages on Track 2

Finally, the displacements of the deep transducer are evaluated. The displacement is about 0.2 mm, which is indeed much smaller than the displacement of the embankment

(0.5-0.6 mm). This confirms the assumption that in this case the embankment moves as a body on the soft subsoil.

6.6 Motion of the approach slab

Figure 6.27 and Figure 6.28 compare the slab displacement from the geophone and the accelerometer. These are in good agreement, showing that the displacements are reliable.

Figure 6.29 and Figure 6.30 show the displacement of the slab and the ballast, all derived by integration of accelerometer measurements.

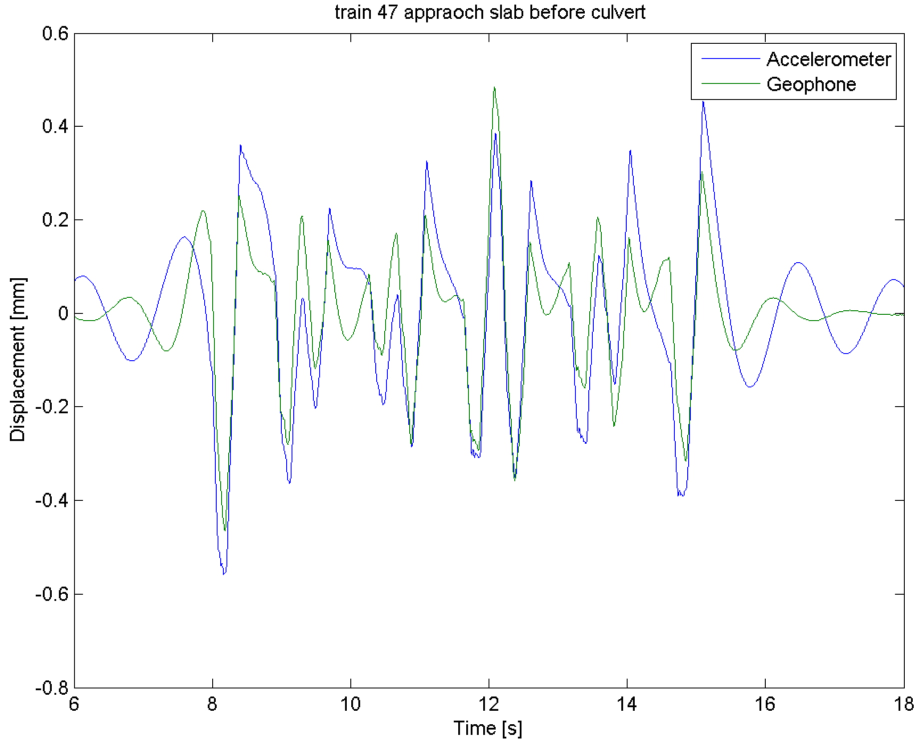

Figure 6.27 Motion of the slab from geophone and accelerometer, Train 47 speed 67 km/h

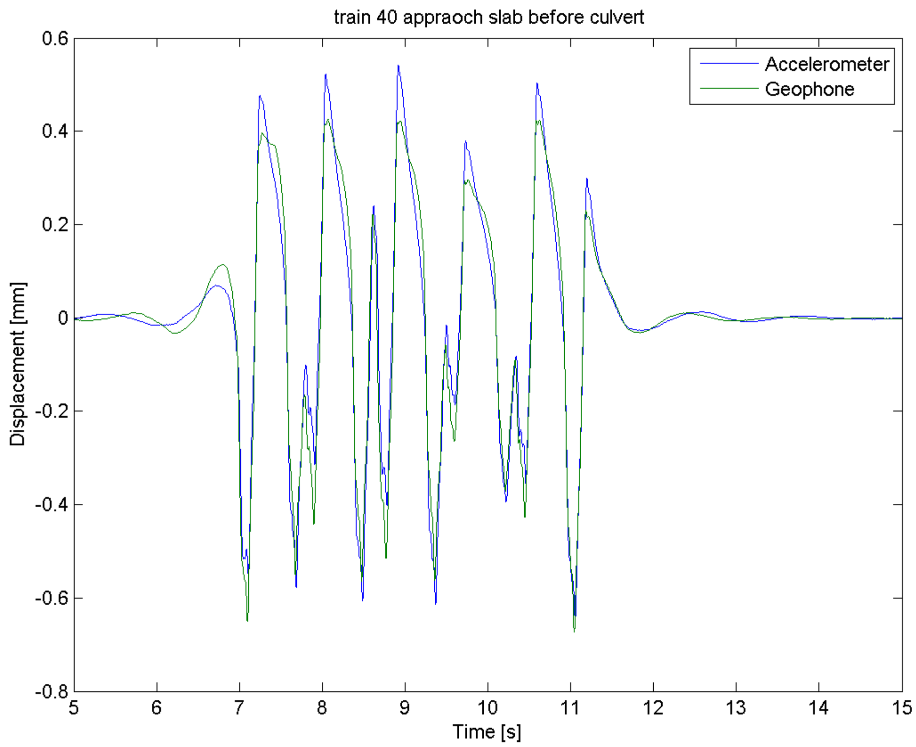

Figure 6.28 *Motion of the slab from geophone and accelerometer, Train 40 speed 110 km/h*

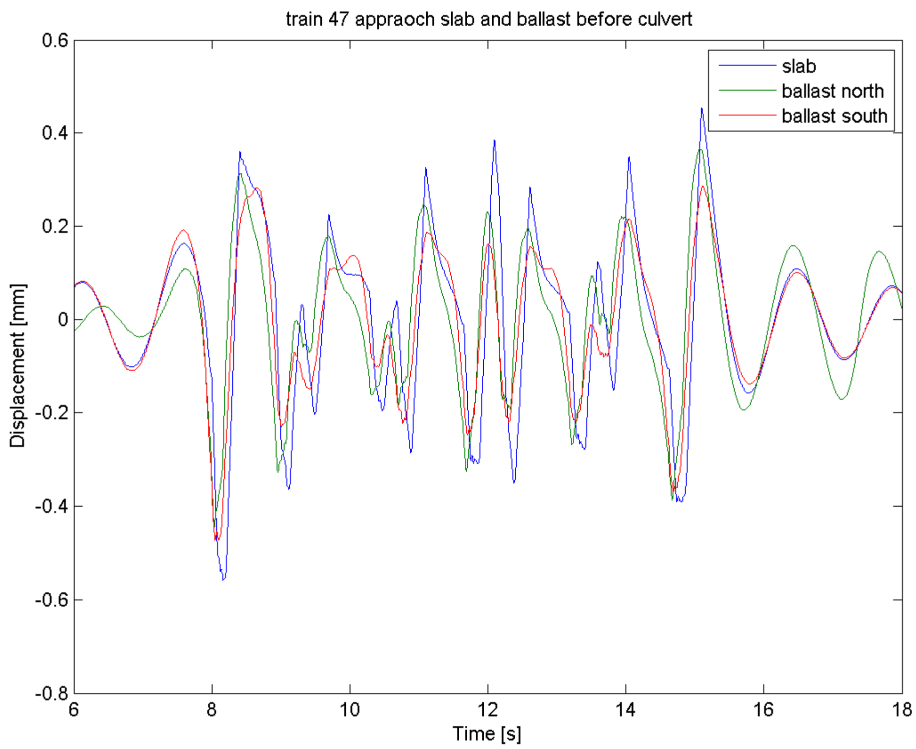

Figure 6.29 *Motion of the slab and ballast, Train 47 speed 67 km/h*

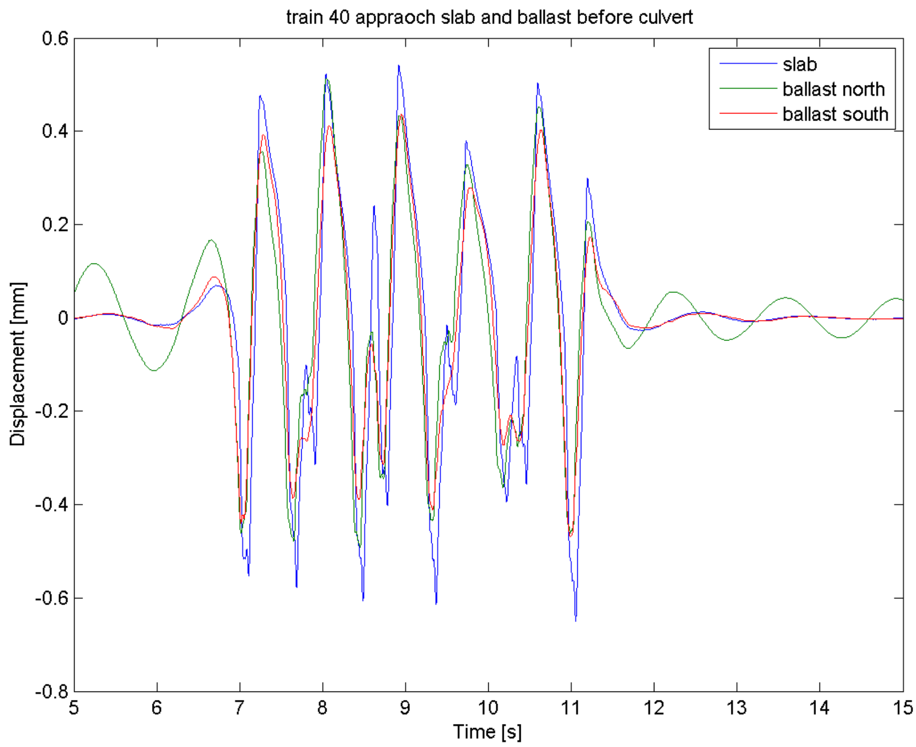

Figure 6.30 Motion of the slab and ballast, Train 40 speed 110 km/h

From the 2008 measurement, the dynamic motion of both slab centre and slab toe is measured (slab head is at the culverts, so the displacement of the head is zero).Passage of an ICM train (D15_50) shows peak displacements of 1.1 mm in the plate centre and 0.5 mm close to the toe. The axle load was about 135 kN.
The slab can be modelled by a bending beam, which is supported by a hinge at the head and a spring at the toe. Assuming that the slab is not cracked, the beam behaves elastically. The slab toe moves 0.5 mm. This motion is due to rotation around the slab's head only. In the centre the motion is the summation of rotation and bending. The contribution from the rotation equals about 2/3 of the rotation of the toe (the measurement position is about 2.5 m from the head), thus 0.35 mm. The additional part is due to bending, thus 1.1 mm (measured)
– 0.35 mm (rotation) = 0.75 mm (bending). [Freriks, 2008] estimated the bending of the uncracked slab (thickness 0.3 m, effective length 3.5 m and concrete B35) under an 150 kN axle load at 0.9 mm. This is a reasonable agreement.

The measurement of slab motion in the 2009 measurement shows for a Sprinter (with a slightly lower axle load) a displacement of about 0.8 mm in the ballast above the toe of the slab, and about 1.1 mm in the slab, close to the centre. The 0.8 mm is a little bit larger than the value measured with the shallow turbo cones (0.7 mm, see e.g. Figure 6.17). The value measured in 2008 close by the toe is relatively small compared with the values measured in 2009. The reason of this difference is not clear.

7 Conclusions and recommendations

7.1 General overview

This paragraph shortly discusses the results of the admeasurements and the interpretation. Table 7.1 shows a summary.

In the literature review the first ideas on the variables that should be measured. These are mentioned in the upper part of the Table. Based on the first field test and further study, some changes ware made. The additional variables are mentioned in the lower part of the Table

Mechanism	Measured parameter	Result measurement	Result interpretation
Height difference	levelling	good	good
Stiffness jump	dynamic displacements sleepers	camera good geophone reasonable	good
Loose-lying sleepers	cavity beneath the sleeper	satisfactory	good
Post-compaction of ballast	not measured		
Ballast expansion	inclinometers	satisfactory	reasonable
Penetration of ballast into embankment	hand-dug holes	poor	uncertain
Post-compaction of embankment	not measured		
Expansion of embankment	inclinometers	satisfactory	reasonable
Softening of embankment	not measured		
Cavity beneath approach slab	not measured		
Settlement of head approach slab	levelling in holes	good	good
Dynamic displacement embankment	accelerometers	reasonable	good
Pore water pressure	PR transducers	static reasonable dynamic poor	good uncertain
Axle loads	strain gauges	good	reasonable
BHM system	level devices accelerometers	good good	reasonable reasonable

Table 7.1 Short summary results field test

Most equipment functioned according reasonable expectations.

7.2 Conclusions on long-term behaviour

From the analysis of the measurement data the following conclusions are drawn with respect to the formulated research questions on the long-term behaviour (Section 1.2):

- Development of hanging distance of the sleepers.

Right above the approach slab large hanging distances were observed. Near the culvert the hanging distance was 10 mm, decreasing to 3 mm near the toe of the slab. It is shown that the hanging distance develops shortly after maintenance. Within the measurement period with the Vortok void indicators (6-8 months after maintenance) no development of the hanging distance in time could be observed:

- Development of track level.

The settlement of the track level consist of two components:

1. The first component comes from post-densification of the tamped ballast, caused by the train passages. The contribution of this component to the total settlement amounts about 3 mm for the culvert and 7 mm for the free embankment. Fitting the measured post-densification development using theoretical fitting curves for laboratory experiments on densification, shows that this component develops shortly after tamping. After 1 month this component is almost fully developed. It leads to a differential settlement of about 4 mm.
2. The second component is the autonomous settlement of the subsoil due to settlement of the peat and clay layers. For the test location this amounts to 1 mm/month and is continuous in time. What has been identified as autonomous settlement may well consist of different components, such as compression of the underlying soil, mixing of sand and ballast, crushing of ballast and some ongoing densification of the ballast and sand. The available data do not allow to distinguish the different components. However, from the Gaasperdam research it is know that consolidation and secondary compression of the holocene layers plays an important role.

An indicative calculation of a bending beam on Winkler foundation shows that already a small settlement of the ballast and subsoil may result in a significant length of free hanging track over the transition zone at both sides of the culvert:

Influence of autonomous settlement on hanging distance
The hanging sleepers are within a short time created by the post-densification of the ballast. It takes at the test site 4 month of autonomous settlement to double the hanging distance created by the ballast post-densification.

Horizontal deformation of ballast and embankment
No horizontal deformations outside the accuracy range of the used measurement device could be observed. From this it is concluded that the horizontal deformation, if present, is less as 2.5 mm/year. Using a horizontal displacement of 2 mm/year, a first guess of the resulting vertical settlement is 1.2 mm. This is small compared with the measured vertical settlement of 12 mm/year.

Contribution of the motion of the approach slab
The settlement of the toe of the approach slab is 2.5 times the autonomous settlement of the subsoil. This larger settlement can be explained from sand migration required to maintain the contact length between slab and underlying sand. It is expected that no other mechanism will be present, however these cannot be fully excluded. The average vertical displacement of the slab is 1.25 times the autonomous settlement. Assuming that the ballast spreads over the approach slab, this means that the hanging distance created by the slab is a bit larger than expected by autonomous settlement. Since the flow of sand under the slab in horizontal direction will always occur, it seems reasonable to conclude that the contribution of the plate is neither extremely negative nor extremely positive with respect to the horizontal movement.

Water table in the embankment
Variation of the water table in the embankment is limited (a few decimetres). Most likely the water table fluctuates with rainfall and possible the water level of the adjacent polder ditches. Measurement of the water level in the ditches was not part of the measurement campaign.

7.3 Conclusions on short-term behaviour

From the analysis of the measurement data the following conclusions are drawn with respect to the formulated research questions on the short-term behaviour:

Is the response symmetric over the culvert
The behaviour of both track and embankment are symmetric over the culvert. The cantilever behaviour of the track is observed at both sides. The rotation point is probably at the edge of the culvert at the side nearest-by the axle load.

What is the background of the sharp upward peaks
The peaks are in time related with the moment that the axle group passes the edge of the culvert. The peaks behind the culvert are related to the passage of the front culvert edge by the first axle of the axle group, the peaks in front of the culvert are related to the passage of the rear culvert edge by the last axle of the axle group.

Vertical motion embankment as a rigid body
The embankment moves more or less as a rigid body on the soft subsoil.

Rotational motion of embankment
During passage of trains on the outer track (Track 1), the motion is vertical without rotation. During passage on the inner track (Track 2), the embankment rotates towards the south direction. This suggests a poor support of the new embankment by the old embankment. In the Gaasperdam Measurement also strong difference in properties due to older embankments were observed.

7.4 Conclusions on BHM (Track Level Measurement System)

From the report on the measurements [Baas, 2009], the following conclusions can be drawn:

- The long -term displacements derived form the BHM turns out to be reliable.
- The short-term displacements derived from the BHM are not yet always reliable.
- The practical usage of the Track Level Measurement System needs improvement
- The reliability (uptime) in the field was lower than expected.

7.5 Recommendations

7.5.1 For reduction of maintenance

It is concluded that the densification of the ballast due to passing trains is much smaller above the culvert than above the embankment. This consumes a large portion of the 'available' differential settlement between two maintenance activities. Measures to increase the settlement in the ballast above the culvert are recommended. The application of a ballast mat on top of the culvert (to decrease the soundboard properties of the culvert) and loosening the ballast above the culvert (instead of tamping) are feasible methods.
It is worthwhile to anticipate on this difference. Directly after maintenance, the track level above the culvert can be about 4 mm lower than above the embankment. Than, after about 1

month, the track is almost horizontal. The differential settlement will increase with the autonomous value of about 1 mm/month

7.5.2 Recommendations for construction of new transition zones

The approach slab settles much faster than the embankment. This is understandable from the ‘flow’ of sand from the region under the slab towards the culvert and in other (horizontal) directions. In the design of an approach slab, it must be considered that the approach slab must settle faster than the embankment in order to keep structural contact with the embankment.

Measures that reduce this horizontal flow will reduce the hanging distance and therefore elongate the period to the next maintenance action. The geogrid solution that was applied at line Amsterdam-Utrecht reduces the horizontal flow. Soil stabilisation does have similar effects.

The sharp edge of the structure generates peaks in the dynamic motion of the track. In new designs it might be worthwhile to add a ballast mat on the structure with decreasing stiffness near the edges, and soft undersleeper pads under the first (and last) sleeper on the structure or even bevel off the edges of the structure.

7.5.3 For further research

The measurements performed at Gouda Goverwelle give a quite complete overview of the mechanisms identified beforehand from literature and expert knowledge. During data analysis several additional research questions were raised, some very interesting to investigate in order to optimise current transition zone design.

It is recommended to start measurements that will show the validity of the volumetric model developed in Chapter 5. The following measurements at a transition zone are required to give a valid empirical support for the model:

- The flow of sand from the region under the approach slab to the region under the culvert.
- The horizontal flow of the sand from the region under the approach slab perpendicular to the track and in the direction parallel to the track away from the culvert.
- The free space under the approach slab.

These aspects could not be evaluated by the measurements at Gouda Goverwelle, as the large settlement of the slab relative to the embankment came as a result of these measurements.

The behaviour of the transition zone will be simulated with a continuum model, *e.g.* finite elements, and tune the Varandas model to the measurements. Consequently, these models can be used more adequately to analyse the measures suggested in the previous Section and to give guidelines for design.

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A Sketches of the measurement set-up

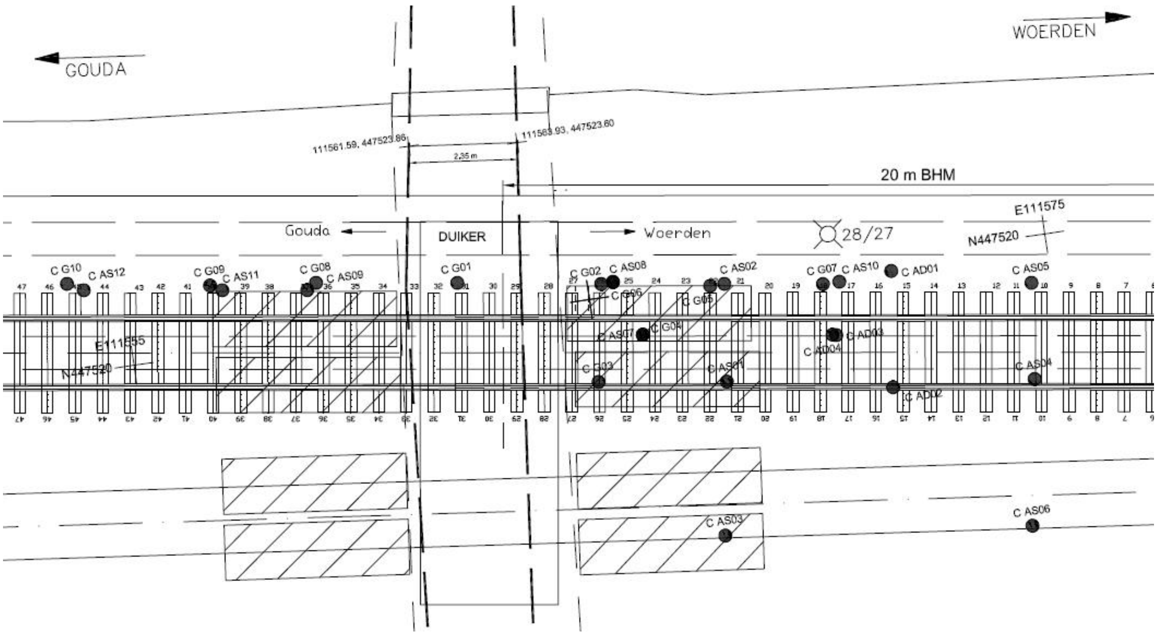

Figure A.1 Position of geophones (C G-code) and accelerometers (C A-codes)
AS are surface positions, AD are deep positions

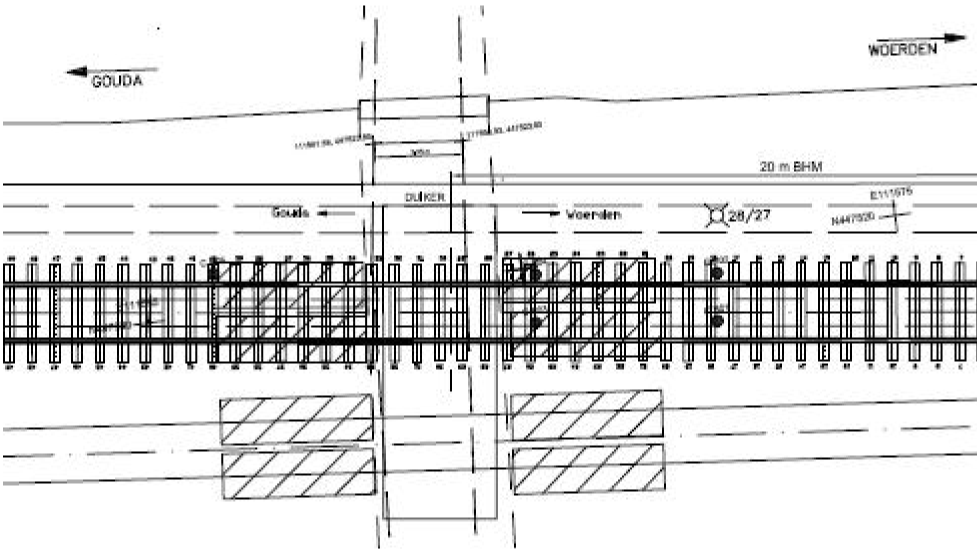

Figure A.2 Position of strain-gauges (marked with C R-code)

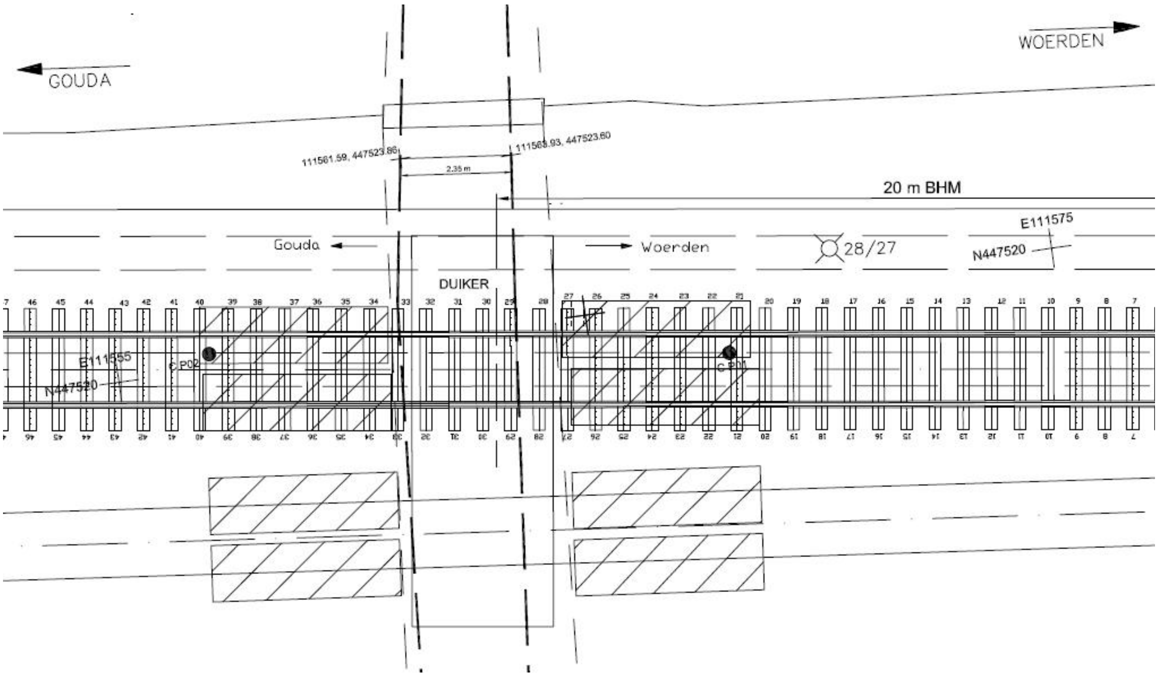

Figure A.3 Position of pore water transducers

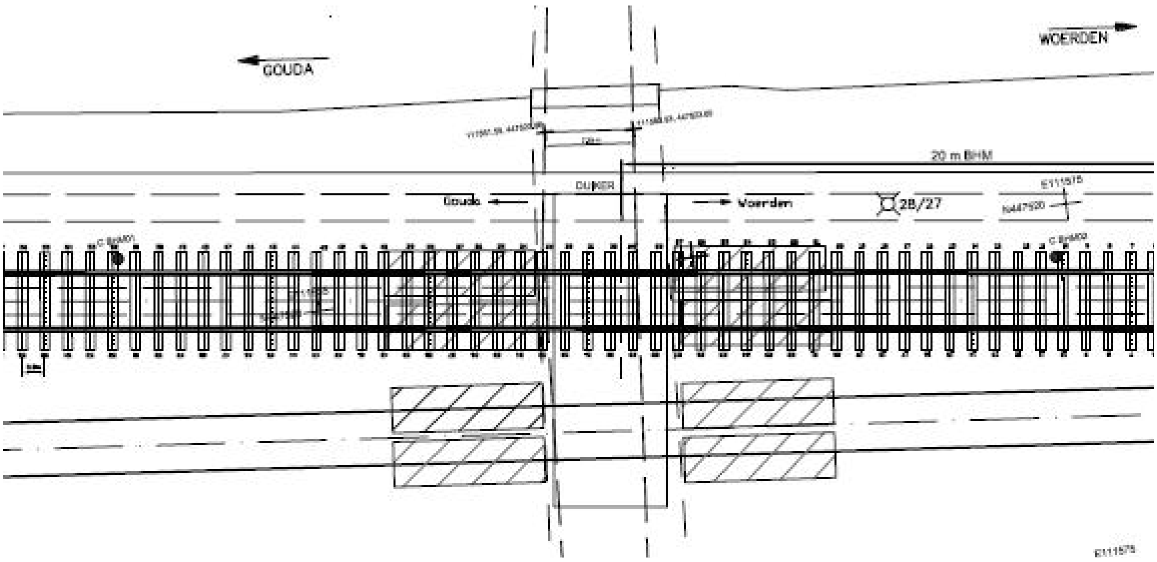

Figure A.4 Start and end position of TLMS (BHM-system)

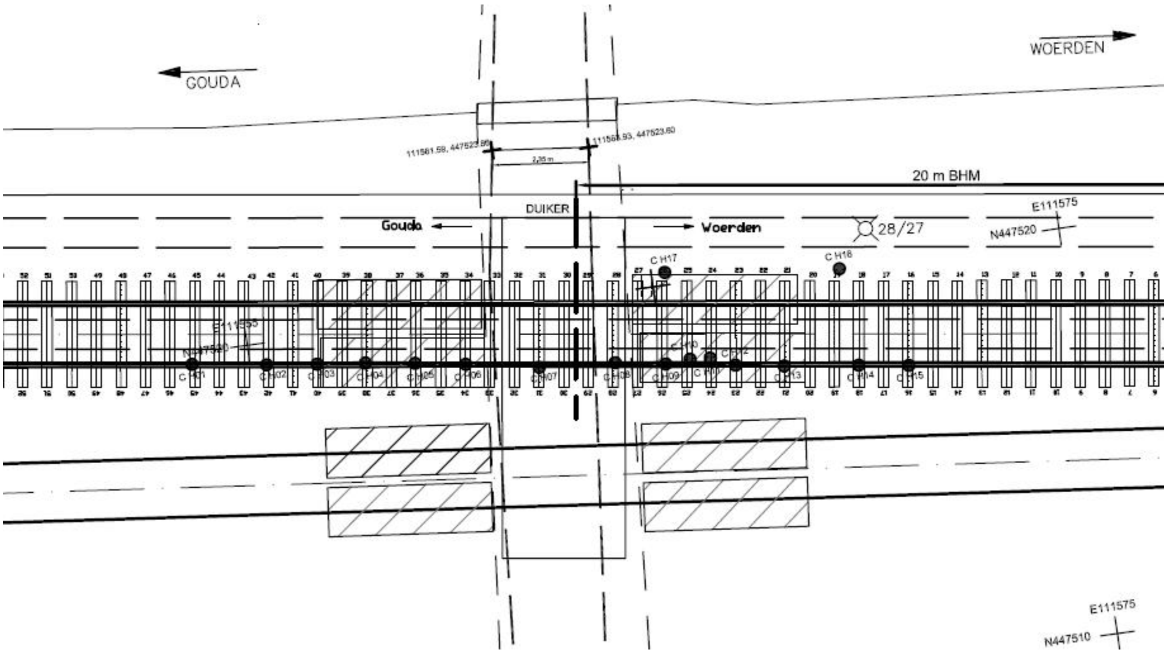

Figure A.5 Positions inclinometers (marked with c H-code)

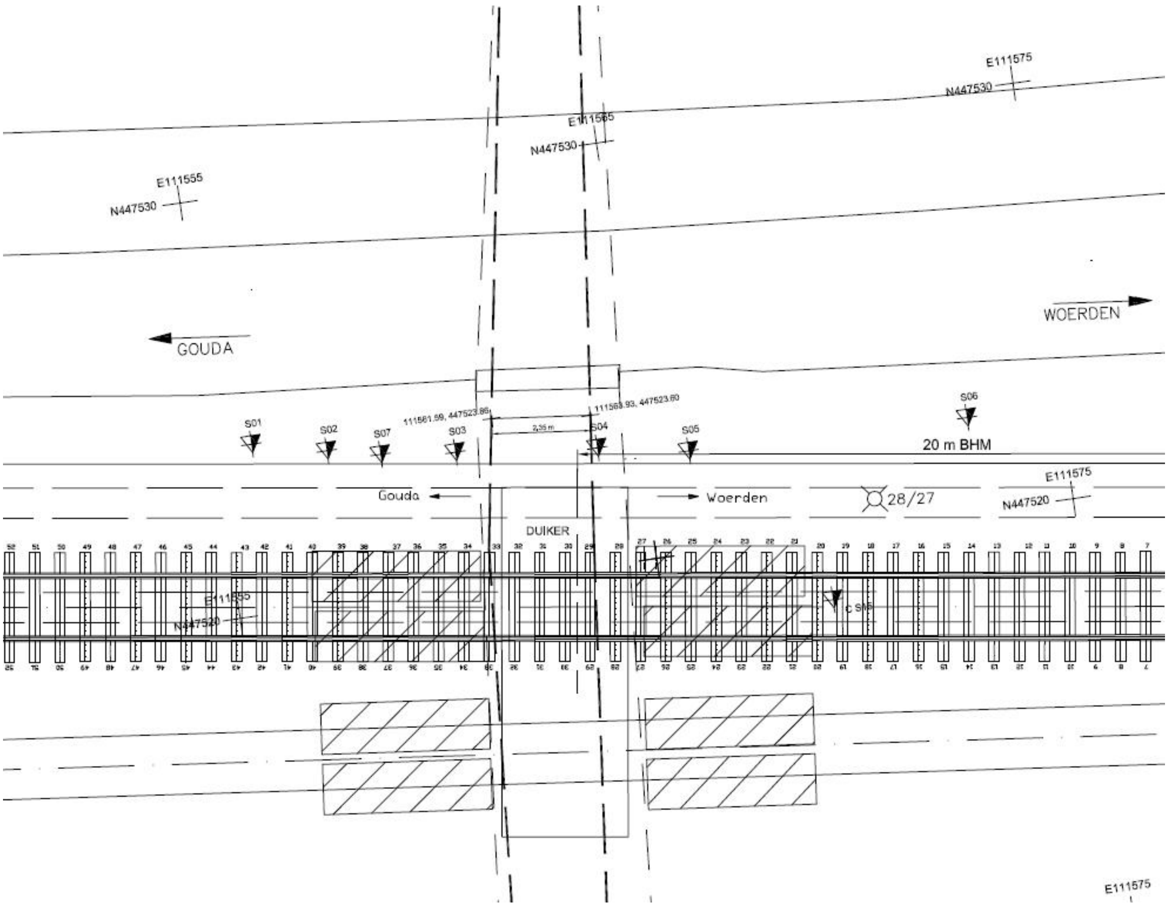

Figure A.6 Position CPT and VSPT