

Settlements of HSL Immersed Tunnels

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ABSTRACT: This paper explains the prediction of the settlements of the two immersed tunnels in the Dutch High Speed railway Line (HSL) between Amsterdam and the Belgian border, designed and built by Drechtse Steden, and the relation between predicted values and measured settlements. Also the use of survey data in order to predict long term settlement behavior will be explained.

1 INTRODUCTION

The Dutch HSL comprises two immersed tunnels, the tunnel under the river "Dordtsche Kil" and the tunnel under the river "Oude Maas". Both tunnels consist of seven elements, each element existing of six segments. Although the shape and dimensions of both tunnels are almost identical, the geotechnical conditions vary considerably. The foundation of the Dordtsche Kil tunnel consists of sandy layers, while the foundation of the Oude Maas tunnel consists mostly of cohesive soil types. As soon as the elements were placed on their temporary supports, an extensive monitoring of the settlements was started. The results of these measurements were used as a decision tool for the contractor as well as the client to determine at which moment the necessary actions could take place.

2 IMMERSION PROCESS

The 14 tunnel elements were fabricated in the dry-dock at Barendrecht. At the rate of one element per weekend during autumn 2003, first the seven Oude Maas elements were towed to their final location, followed by the seven Dordtsche Kil elements. The elements were immersed and placed on four temporary foundations. At Oude Maas and Dordtsche Kil these were steel tubular piles filled with under water concrete plugs, while at Dordtsche Kil (river section) large precast concrete tiles, installed prior to the immersion of the elements, were used. The gap between the bottom of the dredged trench and bottom of the concrete element was filled by the sand-flow method. Once the adjacent element was immersed – and the sand-flow bed beneath that ele-

ment was realized – the pre-stressing cables between the concrete segments of the previous element were cut and its temporary supports were removed, allowing the tunnel to behave as a catenary.

3 DETERMINATION OF THE REQUIRED INNER HEIGHT OF THE TUNNELS

3.1 *Criteria for concrete tolerances*

The alignment of the tracks was fixed, as well as the required railway clearance profile. The combination of these data results into a theoretical inner height of the tunnel. This inner height is the sum of the vertical distance between top of rail and the top of the concrete floor on one hand, and the vertical distance between top of rail and the underside of the concrete roof on the other hand. Both distances have to be enlarged in order to allow for settlements, tolerances in the immersion process and tolerances in the concrete works.

3.2 *Tolerances for settlements*

The expected settlement of the tunnel is the combined settlement of the sand-flow layer beneath the tunnel (z_b) and the settlement of the existing soil layers (z_g). These values are the results of elaborate calculations, but still a statistical variation upon these results should be taken into account. Drechtse Steden decided to incorporate a variation $\alpha = 0,5$.

In this way the following maximum and minimum settlements were defined :

$$z_{\max} = (1 + \alpha) \cdot (z_g + z_b)$$

$$z_{\min} = (1 - \alpha) \cdot (z_g + z_b)$$

3.3 Tolerances for the immersion process

The elements are immersed on four temporary supports. The final vertical position can be achieved by using hydraulic jacks between these supports and the immersed element. The accuracy of this action is within 20 mm'. After the first correction, the element is filled with a certain amount of water to guarantee the stability of the element. Due to this extra weight, the temporary foundations will settle. Therefore, before the sand flow could take place, a second correction of the vertical position of the element is necessary. In order to avoid this extra handling, the expected settlements of the temporary piles (25 mm') and the concrete tiles (40 mm') were calculated and allowed for in the first correction. However due to the variation of these predicted values, a second (much smaller) correction was often still necessary.

3.4 Total overheights and required set up values

The total overheights for both critical distances have to fulfil the criteria as mentioned below :

$$z_{tb} \geq z_{\max} - z_{up}$$

z_{tb} = overheight for distance top of rail to underside roof

$$z_{to} \geq z_{up} - z_{\min}$$

z_{to} = overheight for distance top of rail to top of floor

In both equations z_{up} is the theoretical set-up value. As this set-up can only be realized in the phase when the immersed element is still placed upon its temporary supports, the element is still a pre-stressed rigid beam and the set-up values can only vary linear within one element.

By establishing z_{tb} and $z_{to} = 140$ mm', due to the same formwork for all elements, an optimal set-up value for each end of an element could be determined.

The equations mentioned above could also be written as :

$$b_{\max} = z_{tb} + z_{up} - z_{\max} > 0$$

$$o_{\min} = -z_{to} + z_{up} - z_{\min} < 0$$

The smallest absolute values for b_{\max} (overheight for distance top of rail to underside roof after maximum settlement) or o_{\min} (overheight for distance top of rail to top of floor after minimum settlement) were designed to be larger than 50 mm'.

In the following table, for both tunnels these values are given for the tunnel sections at both tunnel ends and in the middle of the tunnel.

Table 1. Predicted settlements, set up values and tolerances.

| Section | z | z_{up} | b_{\max} | o_{\min} |
|---------|-----|----------|------------|------------|
| | mm | mm | mm | mm |
| OM1a | 110 | 110 | 85 | -85 |
| OM2a | 154 | 160 | 69 | -57 |
| OM4c | 86 | 95 | 106 | -88 |
| OM7f | 138 | 140 | 73 | -69 |
| DK1a | 61 | 60 | 108 | -110 |
| DK4c | 44 | 45 | 119 | -117 |
| DK7f | 51 | 50 | 113 | -115 |

The total overheights of 140 mm' were finally enlarged with 20 mm' for normal concrete tolerances and another 20 mm' for survey tolerances to a value of 180 mm'.

4 CALCULATED SETTLEMENTS

4.1 Calculation models

The settlements along the length of the tunnel were calculated using a two dimensional computer model (Plaxis). Basically this is a vertical longitudinal section over the length of the tunnel. Due to the two dimensional limitation, as a consequence, the tunnel is modelled with an infinite width.

To calibrate this longitudinal model, two cross sections (one in the embankment area and the second in the river area) were calculated using two different models. In the first model the cross section was modelled as it is in reality, thus with sheetpile walls (embankment area) or backfilled sloped trenches (river area). In the second model a tunnel cross section with an infinite width is used. From these two cross sections the correction factor is determined to calibrate for the schematisation with infinite width. The difference between the models was negligible for the embankment areas. For the river areas a fictitious overburden was introduced for the effect of backfilling the trenches.

4.2 Settlements versus time

The settlements are calculated by using the consolidation model of Terzaghi-Buisman. The basic equation is printed below :

$$z_t = z_{\text{prim}} \cdot U_t + z_{\text{creep};t}$$

with z_t = total settlement at time "t"

U_t = degree of consolidation at time "t"

$z_{\text{creep};t}$ = secular settlement part at time "t"

The vertical soil stresses underneath the tunnels are hardly different from the initial vertical soil stresses before the trenches were dredged. In these areas it was expected that the consolidation process of the primary part of the settlements is quickly achieved, while the secular part is negligible. Only at the connections with the cut & cover parts at Oude Maas, an increase of stress was calculated. To speed up the consolidation process in these areas, a temporary overburden of up to 6 metres was realized. The consolidation time for soil stresses below the original soil stress was thought to be about three months at the Oude Maas tunnel and about three to four weeks at the Dordtsche Kil tunnel.

5 SETTLEMENT MONITORING SYSTEM

5.1 High measurement bolts

Each tunnel element consists of six concrete segments, named "a" to "f". As the water tanks inside the tunnel tubes reached from one wall to the opposite wall, a wooden walkway was created above these tanks, about two metres under the concrete roof level. Because the water tanks remained filled during the consolidation phase, the monitoring was performed using 10 measurement bolts (five per tunnel tube), installed in the concrete roof. These bolts were named the "high measurement bolts". In the dry dock, all the inner dimensions of the tunnel elements were measured and related to an axis system in the dry dock. The coordinates of the high measurement bolts in the eastern tube were also related to this axis system. Consequently, all the coordinates were transposed to the theoretical axis system of the tunnel as it should be placed after the immersion process and after the correction with the set-up values.

Assuming that the set-up adaptation of the elements was performed correct, the first measurement of the bolts can be set equal to a settlement value of 0 mm'. From that moment on, both tunnels were measured with a minimum frequency of once a week, while in the mean time, the changes in overburden by backfilling of the immersion trenches was accurately recorded.

5.2 Low measurement bolts

Once the backfilling was completed and the primary settlement was finished (this means that the degree of consolidation was close to 100%), the removal of the bulkheads and the water tanks of each element could take place. Depending upon the safety against uplift, the removal of the tanks could be done in one or more stages.

The wooden walkways were no longer accessible after the removal of the tanks and bulkheads and

thus new measurement bolts, the low measurement bolts, had to be installed. As those new bolts had to be related to the permanent monitoring system, the new bolts were installed at each concrete segment joint within the element and at both ends of the element. This resulted in 2 (tubes) times 7 = 14 bolts, named "a" to "g". The last settlement value of the high bolt "a" was set equal to the first value of the low bolt "a". This was also done for the bolts in the middle of the element and at the opposite end. For the other low bolts, the start value was interpolated. This method can cause some slight deviation in the absolute settlement values, but on the other hand it made possible to obtain settlement curves representing the whole construction period.

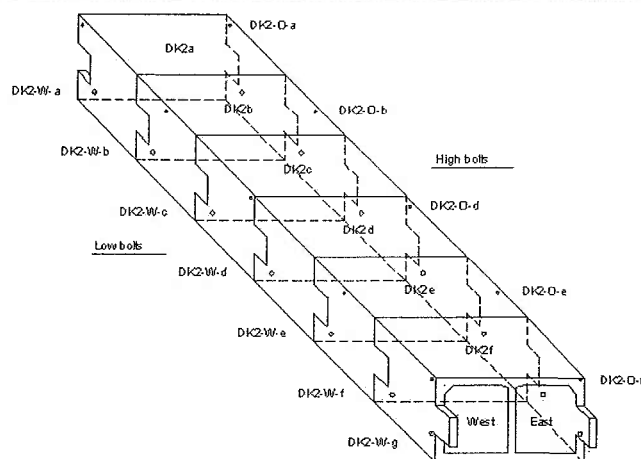
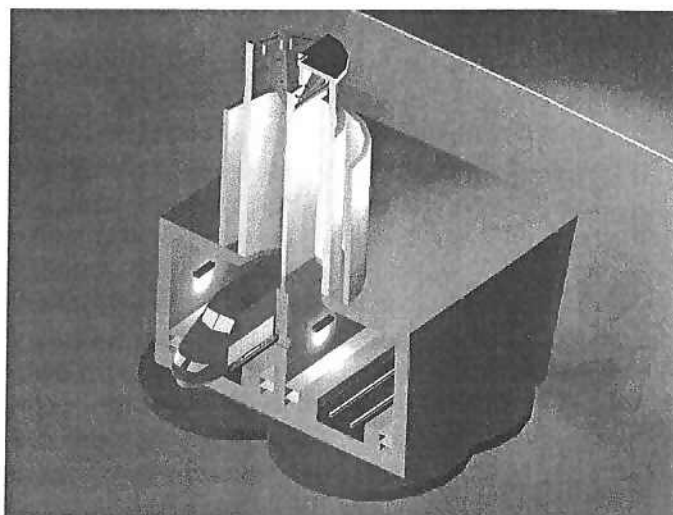


Figure 1. Artist impression of a tunnel element (above) and Tunnel element with location of high and low measurement bolts (below).

6 MONITORING RESULTS

6.1 Settlements along tunnel axis

In figure 2, settlements are given along the tunnel axis of the Oude Maas tunnel. Figure 3 represents the same output, but now for the Dordtsche Kil tunnel.

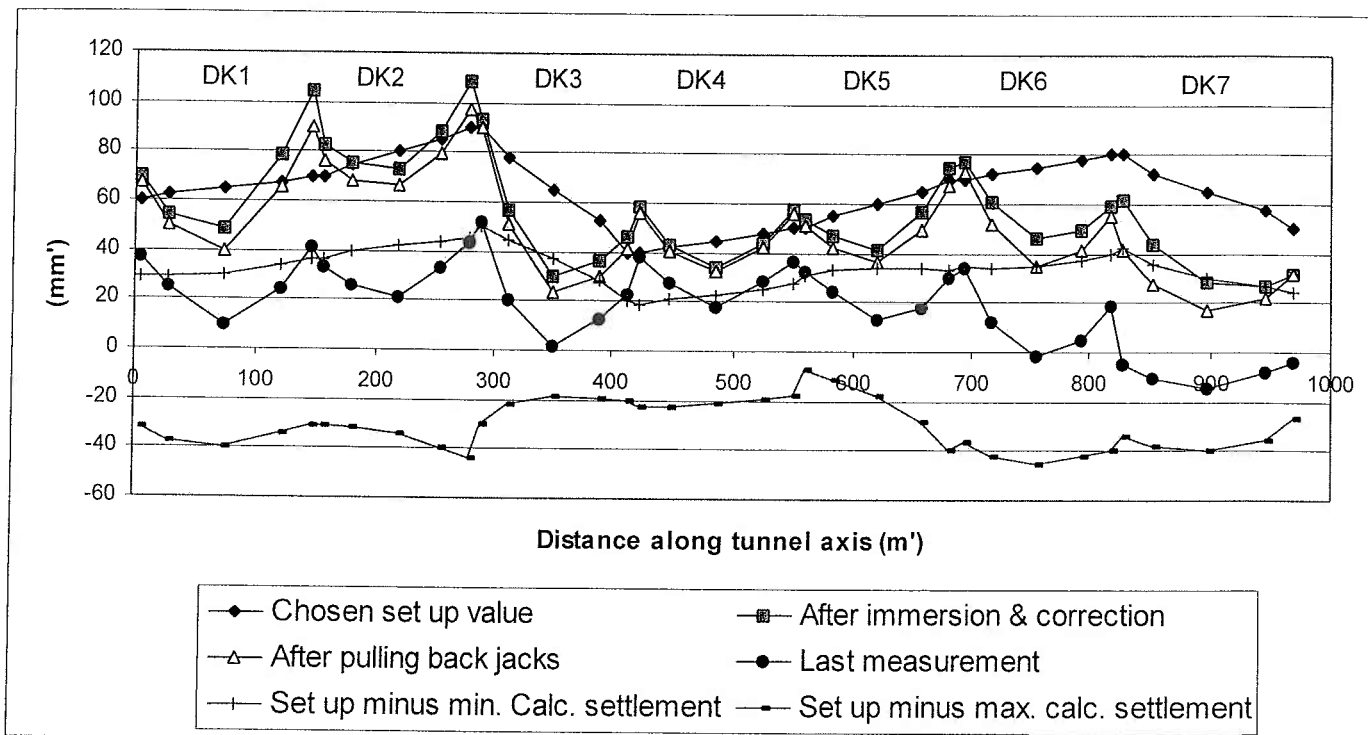


Figure 2. Evolution of settlements tunnel Dordtsche Kil along tunnel axis.

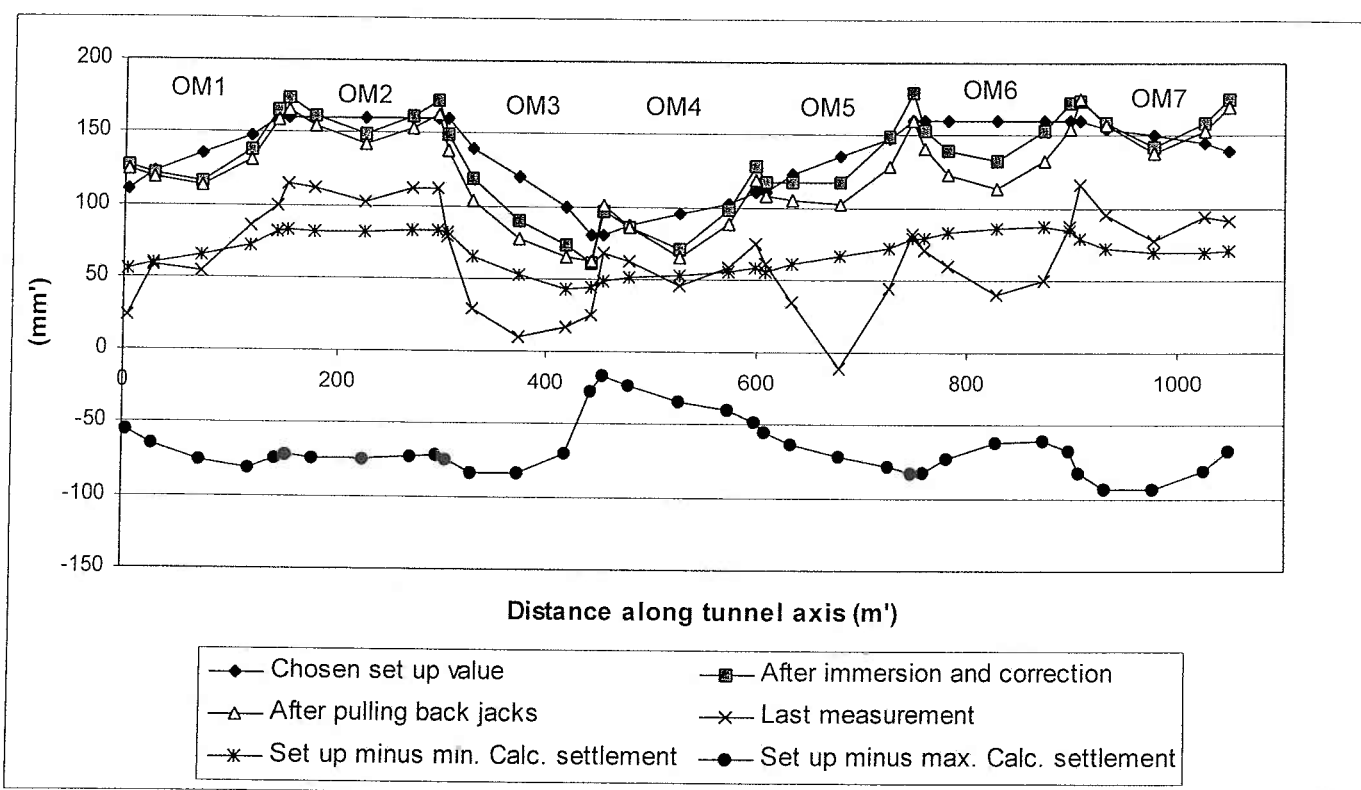


Figure 3. Evolution of settlements tunnel Oude Maas along tunnel axis.

Settlements are given for three different stages in time. The upper line shows the vertical position of the concrete segments just after the immersion and the correction has taken place. As there are each time five measurement points per immersed element, one can clearly see that both ends of each element have the extreme vertical values, while the vertical position of the "c/d" concrete segments (segments in the middle of each element) always tends to a minimum value. Moreover, some times the ends of the elements have a position, higher than the foreseen

set-up position. This is caused by the fact that the vertical position and correction took place by using jacks at the beginning of the second concrete segment (segment b) and at the end of the fifth concrete segment (segment e). The big differences between the realized and theoretical position of the element ends of DK1 and DK2 are due to the fact, that the temporary foundations beneath these elements didn't settle as much as expected, combined with the decision to leave the element as it was, because of the availability of overheight of the cross section (see paragraph 3.4).

The line just below the before mentioned line shows the vertical position of the concrete segments at the moment the jacks between the elements and the temporary supports have been released. As the primary settlement of the sand bed happens instantaneous, the difference between the two settlement lines gives a good indication about the settlements in the sand bed. The predicted value for this immediate settlement was about 40 mm', while the results show values between zero to 25 mm'. A comparison between the amount of sand used per concrete segment and the settlement of the concrete segment during this phase showed that no logic relation was detectable.

Finally the figures show the most recent measurement of the settlements (October 2004) before this article was transmitted for publication. If we compare these results with the upper and lower boundaries, named the "set up minus minimum calculated settlement" and the "set up minus maximum calculated settlement", it becomes clear that the soil layers beneath the tunnels have a rather stiff behavior. It is the intention that the most recent measurement will be between the both lines mentioned above, to fulfill all criteria related to the train system. The settlement lines of both tunnels lie close to the upper boundary or, at some locations, slightly above the upper boundary. Due to the extra available space, this is acceptable.

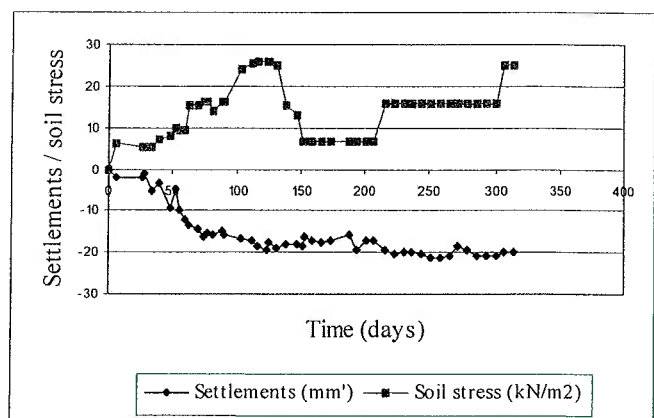
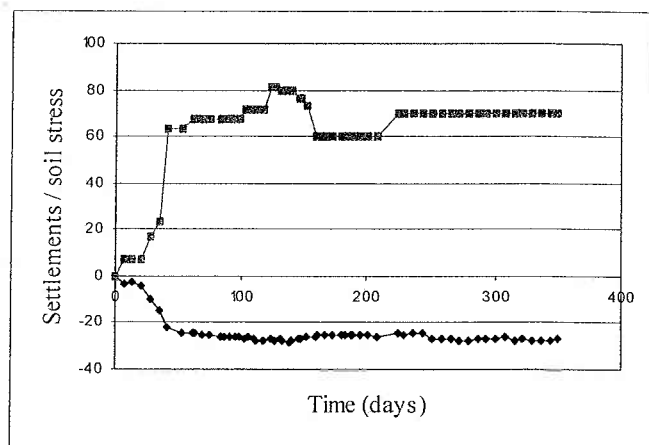
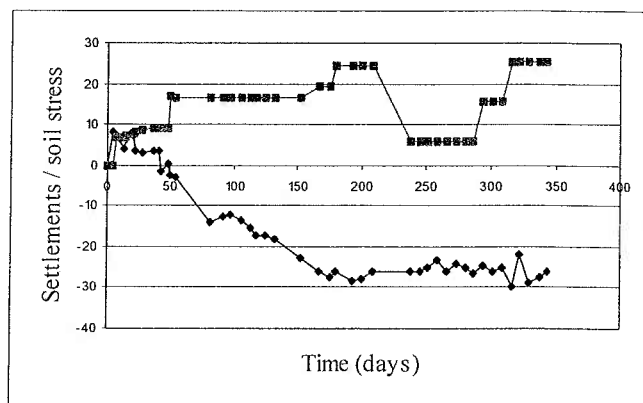
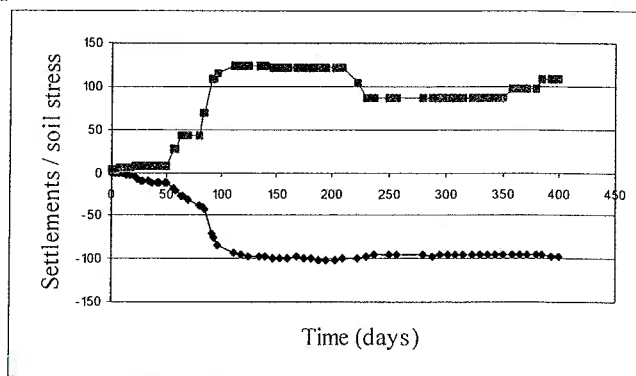
6.2 Settlements and corresponding soil stresses

Figures 4 and 5 represent the settlements and the corresponding vertical soil stresses just beneath the floor plate of the concrete segments OM1a and OM4a during the period the monitoring took place. Figures 6 and 7 give the same information, but this time for concrete segments DK1a en DK4a.

The "4a" segments are typical river element segments. For these elements, the soil stresses in the final phase are very low. The "1a" segments have a much higher soil stress in the final phase, due to the overburden. In the contract it was requested, that the settlements occurring in the period after installation of the rails until the expiration of the design lifetime of 100 years, would be less than 30 mm'. Moreover, at each joint the differential settlement (during the same period) should be less than 2 mm'. If this value of 2 mm' can not be assured, a transition plate with a maximum slope of 1:350 should be used. Except for the joints at the cut and cover segments, all joints were provided with concrete dowels, to prevent differential settlements of over 2 mm'.

The elements with their water tanks completely filled, combined with 100% of the final backfill, induced the same vertical soil stress as the tunnel in final phase with all equipment (concrete evacuation platforms, second phase concrete (or ballast), overhead catenary system) included. As the consolida-

tion phase was finished and the secular settlement was negligible because the soil stresses remained below the initial soil stresses (before dredging of the trenches), no further significant settlements are expected.



Figures 4 to 7. Settlements versus soil stresses for segments OM1a, OM4a, DK1a and DK4a.

At the joints between the immersed tunnels and the piled cut & cover sections, concrete dowels were not possible, this to avoid the immersed tunnel to be supported by the C&C. A temporary overburden was placed on the first concrete segments. By doing this, the soil stresses increased to a level above the initial soil stress. By defining the optimum period of time for the presence of this overburden, the expected settlements in the final phase after rail installation could be reduced to values within the tolerances. To cope with a possible variation in the results of these calculations, transition plates were foreseen at every C&C-joint.

To have an idea of the secular settlements at $t = 100$ years, the monitoring results of the period after the consolidation phase are used to obtain a logarithmic regression line. By anticipation with temporary overburden and transition plates, the criteria were fulfilled.

The monitoring data were also used to define the final level of the concrete evacuation platforms. Therefore, the amount of swelling of the subsoil, due to the emptying of the water tanks was studied. This value gave an idea about the possible settlement when the concrete of the evacuation paths was placed. Measurements showed that the platforms could be made by using the theoretical levels, because no additional settlement was expected (amount of swelling was smaller than assumed concrete works tolerances).

In the settlement figures, some irregularities are shown (strongly differing values for one particular measurement). In most cases, the measurement bolts seemed to be hit by machinery during the many works in the tunnel. Before the next measurement the bolt was adjusted, so the aberrant measurement could be neglected. This belongs to the famous noise in survey data.

7 COMPARISON WITH OTHER IMMERSSED TUNNEL SETTLEMENT DATA

The Caland Tunnel, a recently immersed tunnel is situated in the vicinity of the two HSL-tunnels. The geotechnical circumstances are therefore much alike. The six elements A to F consisted each of 5 concrete sections. The settlement values of the Caland tunnel are very similar to those of the river sections of Oude Maas and Dordtsche Kil tunnel (settlements between 20 to 40 mm'). All Caland tunnel elements have only about 1,00 m' of soil cover on top which explains the small settlement data along the whole tunnel length. The consolidation time could also be clearly defined on basis of the settlement data and showed a great similarity to the consolidation times of especially the Dordtsche Kil Tunnel (3 to 4 weeks).

The Piet Hein Tunnel is situated at the city of Amsterdam; also in the river delta area of the Netherlands. This tunnel comprises 8 elements, each element consisting of 6 concrete sections. Again the values are comparable to those of the river sections of the HSL-tunnels. The greater values obtained at the embankment areas of the HSL-tunnels are mostly due to the greater height of the soil cover.

8 RESULT

The two immersed tunnels in the HSL in the soft soils of the Netherlands are, with other tunnels some of the few structures, which are not supported by permanent piles to the deep sand layers. The criteria for a High Speed railway Line are much more severe than for traffic tunnels. Nevertheless the design of the details of both immersed tunnels and the temporary measures to reduce consolidation time and final settlements were such, that the criteria were met.