

Settlements of HSL Immersed Tunnels

H. Mortier

CFE Beton- en waterbouw, Dordrecht, Netherlands

Ch. J. A. Hakkaart

BAM / Delta Marine Consultants, Gouda, Netherlands

W.M. 't Hart

Ballast Nedam Infra, Nieuwegein, Netherlands

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.

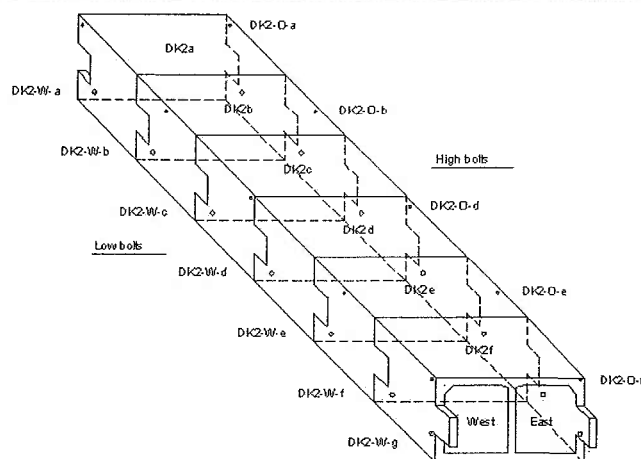
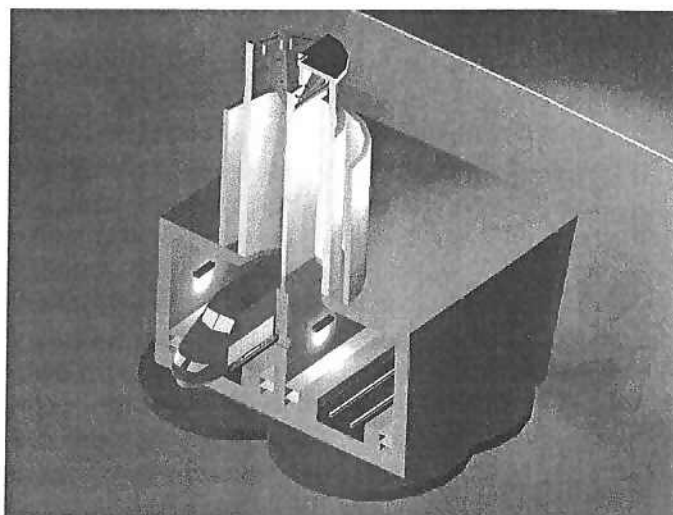


Figure 1. Artist impression of a tunnel element (above) and Tunnel element with location of high and low measurement bolts (below).

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.

