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# Large diameter tunnelling under polders

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**ABSTRACT:** The latest underground works show how the tunnel boring machines can face more and more difficult conditions. An example of this trend is the Groene Hart tunnel, part of the High Speed Link dutch network, at present under construction by the Bouygues-Koop Consortium. This tunnel, with about 15 m diameter, was bored with the world largest confining tunnel boring machine (TBM) up to now. On the tunnel track, measuring more than 7 km, many requirements have to be fulfilled. In particular, in a soil extremely sensitive to the boring conditions, stringent settlement limitation (10 mm in some areas) are imposed because of the presence of buildings, roads, railways and utilities. Besides, the specific geotechnical conditions created by polders induce a very notable and quite uncommon phenomenon of increase of the natural pore pressure in soil (called Excess Pore Pressure or EPP) during boring which can affect tunnel cover stability. Therefore, detailed monitoring campaigns aimed at better understanding the hydraulic and mechanical soil behaviour have been carried out at different locations on the track.

## 1 INTRODUCTION

### 1.1 General

In order to become part of the Trans-European network of high-speed rail links, Netherlands is working on the transport of the future: a high-speed line (HSL) connecting the Dutch capital with Antwerpen, Brussels and Paris. A quick sprint from Amsterdam to Rotterdam will take no more than thirty-five minutes.

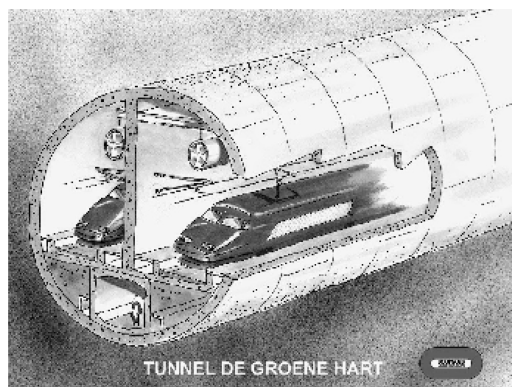
The route of the Dutch HSL is a gentle curve about 100 kilometers long running from Amsterdam to the Belgian border. These works were let in six large contracts, among them the tunnel under the Groene Hart, awarded to the Bouygues-Koop consortium, as a design and build contract.

### 1.2 The Groene Hart project

The solution with a bored tunnel was chosen to minimize the line's impact on the characteristic fenland landscape of the Groene Hart (the Green Heart of Holland, situated between The Hague, Amsterdam, Utrecht and Rotterdam). Seven kilometers long (8.5 km including approaches), under the Dutch polders, the tunnel will allow the line to follow the fastest route between Amsterdam and Rotterdam while leaving the countryside largely undisturbed.

The reference design of the project was a bi-tube with cross-passages every 300 m. The Bouygues-Koop consortium designed and submitted an alternative solution: a single tube with a bi-directional train

circulation, both circulation tracks being separated by a central wall, including escape doors each 150 m.



Typical cross-section of the Groene Hart tunnel.

This design was possible only because the consortium optimized the free air section in the tube, in order to get the minimal section providing to the passengers of the train the required comfort level, leading to an internal diameter of 13.30 m. The Bouygues-Koop consortium was awarded the design and build contract for this innovative alternative design.

### 1.3 The unusual dimensions of the project

With an internal diameter of 13.30 m, the tunnel was designed with a precast segmental lining, 0.60 m thick,

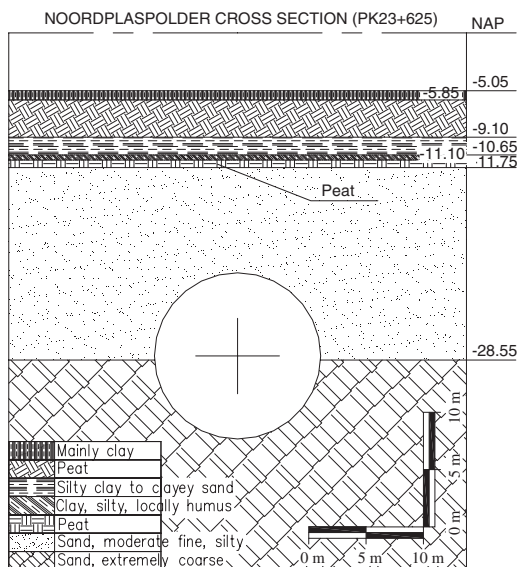


Figure 1. Noordplaspolder geotechnical cross-section.

with a resulting external diameter of the lining of 14.50 m. The exceptional boring size of the tunnel, almost 15 m diameter, required a specially designed tunnel boring machine (TBM): Aurora, a slurry shield, the world largest confining TBM, with a boring diameter of 14.87 m, a 170 m<sup>2</sup> area of excavation, a back-up train 120 m long. Aurora bored 7250 m of the tunnel, that is to say 1,2 millions of m<sup>3</sup> of excavated soil.

Along the tunnel route, three 30 m diameter emergency shafts (Achthoven, N11 and Bent), also designed for TBM maintenance during construction, were crossed by the machine.

## 2 HYDRO GEOLOGICAL CONDITIONS

### 2.1 General

The geology along the tunnel route is relatively uniform. Apart from the area near the access ramps, the tunnel is bored approximately 25 m below ground level in a captive aquifer of brackish water, under the Dutch polders. The polders are tracts of low land reclaimed from the sea using dikes, mainly dedicated to agriculture.

On the major part of the project, the tunnel is bored in loose sand layers with an approximate sand cover above crown of ~7–8 m. Above the sand is a thin (less than 1 m) impermeable peat layer separating the two water tables: below the first captive aquifer of brackish water and above the free water table of fresh water. Above the peat are a variety of clayey soils, some of them with very low density. The piezometric level of the first aquifer is sometimes higher than the ground

level, depending on the season and the location along the tunnel route. A major concern with this geotechnical profile was the stability of the upper soil layers during the boring process.

### 2.2 Noordplaspolder area

One specific area along the tunnel route, in the southern part of the project, was identified as a sensitive area regarding the peat layer stability: the Noordplaspolder. In this area, tunnel axis level is around -28 m NAP (the reference sea level in the Netherlands). The peat layer, approximately 8 m above tunnel crown, is less than 70 cm thick. The ground level and the free water table level are -5 m NAP, and the piezometric level of the first aquifer is between -4 m NAP and -2.8 m NAP, which means it is higher than the free water table level. As a result of this configuration, the downward vertical stress at the peat layer is very low, which means a slight overpressure in the captive water table generating an upward vertical stress could modify the static equilibrium.

## 3 RISKS RELATED TO THE PROJECT CONDITIONS

### 3.1 Development of excess pore pressure

The application at the front face of a confining pressure greater than the existing pore water pressure in soil, when boring in a captive aquifer, generates an excess pore pressure all around the TBM cutterhead. During the boring process, the cake is locally destroyed by the tools and therefore slurry, which is in overpressure compared to the ground water pressure, can penetrate the soil during the cake built-up. This leakage through the face occurs because the TBM advance rate at each head rotation is greater than the cake thickness. Therefore the slurry in the excavation chamber is connected to the water table and generates an overpressure in front of the TBM. The soil propagates this overpressure as an excess pore pressure (EPP).

### 3.2 Excess pore pressure and polders

The specific conditions of this particular project, particularly the existing captive aquifer, induce a large propagation of the phenomena. The fragile static vertical equilibrium at the peat layer level could be destroyed because of the diffusion of these EPP. This would induce two kind of risks.

First, as the ground level is lower than the piezometric level of the first aquifer, a very pessimistic scenario would be the flooding of the polder, caused by local cracks in the peat layer induced by high pore pressures, creating vertical water circulation between sand and surface. However, this seems unrealistic as local cracks would be rapidly filled up with sand and fine particles.

Secondly, a less catastrophic scenario would be that local cracks in the peat layer, by creating a communication between the first aquifer (brackish water) and the free water table (fresh water), would induce pollution of the free water table by brackish water coming from the artesian water table. This is a major concern as the lands Aurora will be digging under are mainly intended for agriculture.

### 3.3 Risk management

As the risk was identified early in the project development, a specific procedure was established, to evaluate, control and mitigate the risk.

A first instrumented plot had to be implemented, at the beginning of the bored tunnel, in order to measure the amplitude of the phenomena.

If the first instrumented plot showed that the phenomena was not neglectible, a second instrumented plot had to be implemented, before the sensitive area, in order to evaluate how the phenomena affects the peat layer. The specific geotechnical and hydrological conditions of the project made it essential to measure the diffusion and dissipation of the overpressure generated during the boring process.

The measures were to be analysed using a FE-model, in order to be able to understand and quantify the phenomena, and then anticipate the boring effects in the Noordplaspolder area.

Finally a mitigation measure had to be designed, if necessary.

## 4 THE FIRST INSTRUMENTED PLOT: MEASURING THE AMPLITUDE OF EPP

The first important step in the risk management procedure was to confirm the reality of the EPP phenomena and its order of magnitude under the Groene Hart boring conditions. Therefore settlements and pressure measurements were taken in an instrumented plot, located at the end of the learning curve.

These measures showed that EPP did develop in the soil, due to the boring process. Furthermore, the amplitude of the phenomena was such that it could not be neglected for the Noordplaspolder area: an EPP of up to 50 kPa in front of the TBM, at axis level, was measured. These results proved that the identified risk was real, and thus the next step of the risk analysis was a second instrumented plot.

## 5 THE SECOND INSTRUMENTED PLOT

### 5.1 Definition of the second instrumented plot

An extensive measurement campaign was carried out to observe the development of EPP and the influence

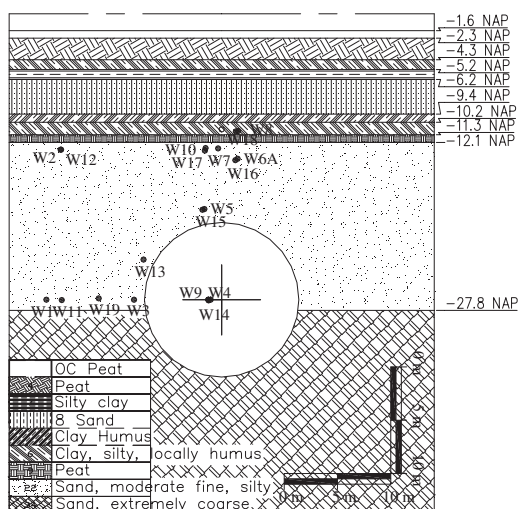


Figure 2. Geotechnical cross section at monitoring site.

on the mechanical behaviour of the soil. The main objectives were:

- Establish the spatial distribution of the excess pore pressures during the TBM boring cycle.
- From this distribution, estimate the relevant soil parameters (permeability, anisotropy and storage coefficient) necessary for numerical modelling calibration.
- Analyse the behaviour of the peat layer subject to two levels of confinement and induced EPP.
- See if any ground displacements, due to the relaxation in effective stress (increase of water pressure), could occur at the peat layer interface.
- See the influence of confinement pressure on the observed phenomena.

The monitoring plot was located just before the N11 Emergency Shaft, between PK26+340 and PK26+290, (i.e. close to the mid-length of the tunnel).

The installed instruments were 13 settlement gauges at the surface, 19 pressure cells and 2 extensometers. All instruments were located around 2 main measurement sections at PK26+340 and PK26+290. Both sections had practically the same geotechnical cross section, and were 50 m apart. The pressure cells were positioned as presented in Figure 2.

The pressure cells were placed at different depths in the ground and at different distances from the tunnel axis to measure the EPP spatial distribution. In particular three of the cells (W4, W9 and W14) were exactly on the tunnel axis and therefore were destroyed by the TBM during its advancement. All pressure cells were in the captive water table except W8 and W18, placed in the free water table. These two cells had proved

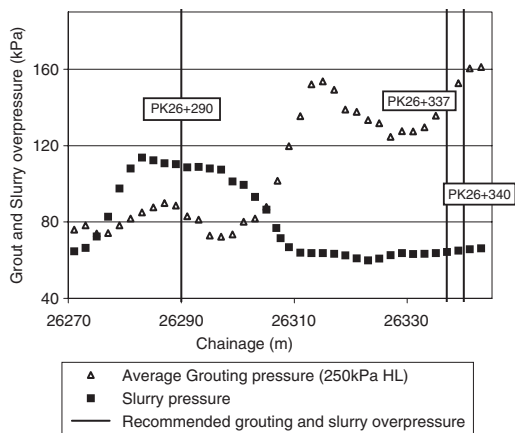


Figure 3. Recommended and applied slurry and grout overpressure in the instrumented sections.

very important for the comprehension of the global behaviour of the ground at the TBM arrival, since they were hydraulically disconnected (at least at the beginning for sure) from the tunnel front and therefore not affected by the EPP development. What they measured was the free water table level. The two extensometers were, at depth, anchored at the peat layer level and thus they were intended to record the relative displacement between the peat layer and the surface.

Measurements of the TBM parameters were taken from 400m before the first instrumented section (PK 26+340) until the TBM was 100m beyond the second section (PK26+290).

The recommended slurry overpressure and grout overpressure as well as the pressures applied by the TBM during the boring process in the area of the instrumented plot are presented on Figure 3, overpressure meaning the pressure exceeding the water pressure already existing in the soil.

## 5.2 Presentation of the measurements

There was a settlement of about 30 mm at PK26+340 and about 1 mm at PK26+290, as shown on Figure 4. The different soil reactions at the two instrumented sections were due to the different slurry confining pressures applied, as discussed later in this paper.

The vertical black lines on the diagrams (Figure 4 & 5) indicate the TBM passage below the two measurements sections.

The pore pressure data (see Figure 5 and Figure 6) clearly show every boring cycle, the maintenance stops and the TBM arrival by an accumulation process on the maximum EPP value of each boring cycle. The logarithmic shape of the EPP peaks distribution openly confirms that the EPP diffusion in the ground is ruled

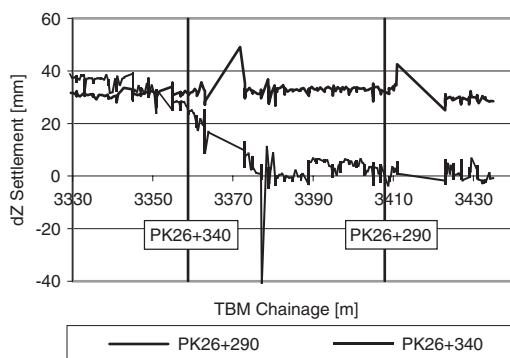


Figure 4. Settlements at PK26+340 and 26+290.

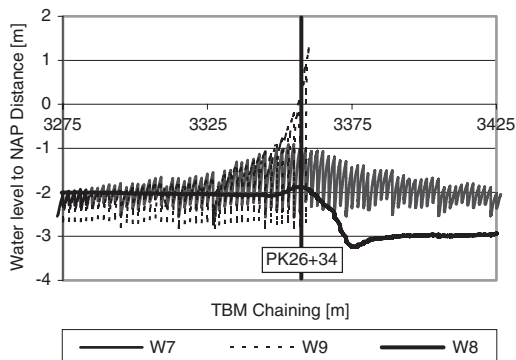


Figure 5. Experimental pressure at PK26+340.

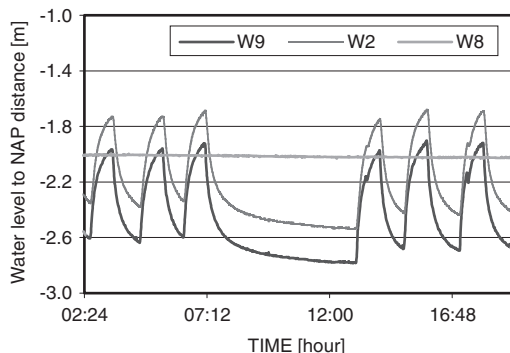


Figure 6. Measured EPP at PK26+340, detail of several hours.

by Darcy's law:

$$\frac{\partial h}{\partial t} = \frac{1}{s} \cdot \text{div}(\underline{K} \cdot \text{grad}(h))$$

where  $h$  is the piezometric level,  $K$  is the soil permeability and  $s$  is the storage coefficient of the soil.

One curve, (W8), shows a shape completely different from the others, because it was obtained in the free water table and was not affected by the EPP development due to the tunnel boring. This is important as it shows that there was no instantaneous equilibrium between the two water tables. This means that no communication was established through the peat layer i.e. no cracking occurred.

Both extensometers indicated a positive differential settlement between the peat layer and the surface, the positive sign meaning that the instrument had lengthened at the TBM passage. The peat layer had settled more than the surface. This is fully consistent with the physical phenomenon since the maximum stress variation and therefore the maximum strain and displacement takes place at the tunnel lining.

### 5.3 Analysis of the experimental data

Once the experimental data had been collected, they were used as a basis for numerical modelling of the tunnel. The hydraulic and mechanical simulations are carried out uncoupled, using the Terzaghi theory (1945). This theory is a simplification of the coupled Biot's theory (1941), obtained assuming that the average total stress  $p$  remains constant with time and only the hydraulic overpressure varies. This allows the indefinite equilibrium equations (Navier's equations) to be neglected, and therefore uncouples the mechanical and hydraulic aspects. The justification of this simplification is that the sand layers involved in the EPP phenomenon are quite permeable ( $K \sim 10^{-4}$  m/s) and quite rigid ( $E \sim 10^2$  MPa) and therefore the stress variations have no influence on permeability.

A 3D FE model of the tunnel (600 m long  $\times$  200 m deep  $\times$  100 m high) was used to simulate the hydraulic ground behaviour and back-calculate the permeability and storage coefficient parameters. The model considers a transient analysis of the effect of the resulting overpressure in the soil after the loss through the cake. The numerical results that best fitted the experimental data validated the parameters' range based on the first instrumented plot ( $K_{xx} = K_{yy} = 4 \cdot 10^{-4}$  m/s;  $K_{xx}/K_{zz} = 2$ ;  $s = 2 \cdot 10^{-5}$ ), and are presented on Figure 7.

### 5.4 Main results of the plot analysis

The analysis of the second instrumented plot lead to some important conclusions :

- The EPP reach the peat layer
- The upper aquifer is not affected by the boring process, as far as the deformations of the peat layer are limited.
- Due to stringent equilibrium in the Noordplaspolder area, a precise extrapolation using a model is required.

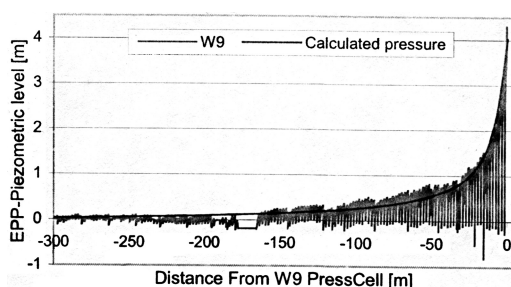


Figure 7. FEM calculation fitting experimental data.

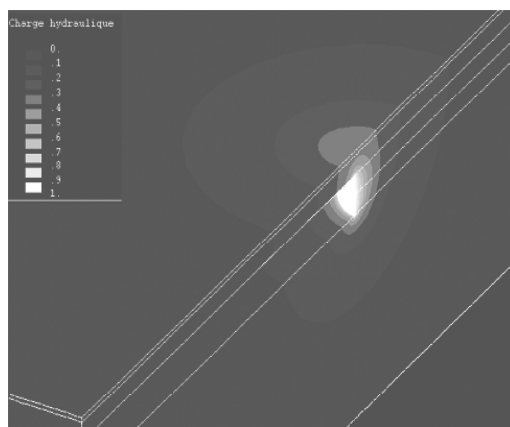


Figure 8. Diffusion of the EPP in the soil around TBM.

- The limitation of the confining slurry pressure reduces the phenomena; therefore a recommendation of a 50 kPa (minimum overpressure required to ensure front stability) confining pressure was given for the Noordplaspolder area.

## 6 ANTICIPATING FOR NOORDPLASPOLDER

The calibration of the FE model with the results of the second instrumented plot was the essential milestone to get an accurate extrapolation for the sensitive area of the Noordplaspolder. In this polder, an analysis of the stress distribution before TBM passage showed a negative stress condition at the peat layer level. This result is obtained with the water levels and soil density defined for the project design. Although unrealistic, it is significant as it shows that there is a precarious equilibrium in the polder at rest, 500 m along the tunnel route.

The FE modelling of the EPP behaviour in Noordplaspolder area gave an estimate of the maximum EPP that will be developed during the boring process: about 14 kPa for an applied confinement overpressure of 50 kPa. The spatial extension of the phenomena is given on Figure 8, the top of the model

being the bottom of the peat layer. The pressure isovalues are given in percentage of the EPP developed just in front of the TBM, as the analysis process showed an overpressure loss through the cake: the maximum EPP developed at the front of the TBM was only 75% of the applied confinement pressure in the excavation chamber.

The extrapolation for Noordplaspolder area indicates that an overpressure of 14 kPa is to be expected under the peat layer, for a confining pressure limited to 50 kPa. The next step of the analysis was to determine the acceptable overpressure at the peat layer level and find a mitigation measure adapted to the project.

## 7 MITIGATION MEASURE IN NOORDPLASPOLDER

An analysis of the water levels of both aquifers during the previous year showed that this sensitive area already experienced 9 kPa water overpressure, without any noticeable damage. Therefore, to prevent the polder from the identified risks, a mitigation measure was taken for the developed EPP exceeding 9 kPa.

The FE calculation carried out for Noordplaspolder, combined with the critical value of 9 kPa, defines the area of the mitigation measures. The area forms a strip of land, 50 m wide centred on the tunnel axis.

A feasibility analysis showed that the only reasonable and efficient mitigation measure was to increase the vertical downward load at the peat/sand interface

by placing backfill at ground level on the tunnel route. The width and height of this backfill were calculated in order to get an equivalent overpressure always less than 9 kPa. The equivalent overpressure is the pressure resulting from the combination of the EPP generated upward overpressure and the downward pressure due to backfill (see Figure 9). As a result a 1 m high and 24 m wide backfill (centred on tunnel axis) was placed on top of the tunnel route.

## 8 CONCLUSION

In order to control the behaviour of the soil (especially the peat layer) during the boring process in the Noordplaspolder, settlements and pressure gauges were installed. The field data was used to validate an FE analysis of the tunnelling process and justify the mitigation measures.

The tunnel was bored under the sensitive area of the Noordplaspolder in Autumn 2003, the measures taken were in complete accordance with the FE model with 14 kPa overpressure measured at the peat layer. As a result of the mitigation measure, there was no disruption of the tunnelling or damage to the polder area.

This successful procedure of risk management was possible because of a good interaction between the design office (i.e. technical department of Bouygues Travaux Publics) and in-situ works for every step of the process: from the identification of the risk to the determination of a reasonable and efficient mitigation measure.

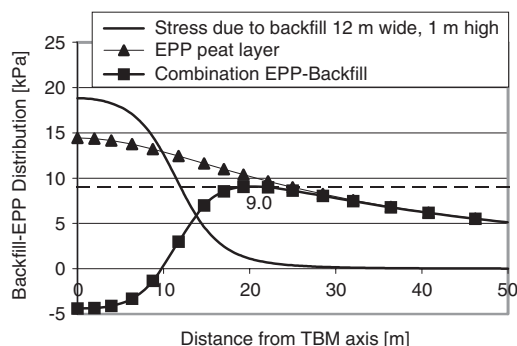


Figure 9. Combined effect of backfill and EPP on the vertical stress.

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