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Empirical, analytical methods for surface settlement prediction due to TBM-tunnelling in Dutch soft soil

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ABSTRACT

TBM-tunnelling in soft soil causes a 3D-ground deformation field, developing in longitudinal direction (parallel to the axis of the tunnel) and transverse direction (perpendicular to the axis of the tunnels). Empirical based methods are used for the prediction of the distribution of ground movements in both directions. Consequently the differential settlements are used to predict the damage risks of adjacent buildings due to TBM-tunnelling in the design stage. The Gaussian-curve is commonly applied for the prediction of green field ground movements transverse to the tunnel axis. Different authors derived methods for determining the characteristic inputparameter i, being the point of inflexion for the settlement trough on surface level for tunnelling projects all over the world. The i-value determines the steepness of the trough. This paper presents a comparison between the different approaches derived from data of projects outside the Netherlands and the field data from three recently bored Dutch tunnelling projects (i.e. the Second Heinenoord Tunnel, the Botlek Railway Tunnel and the Sophia Railway Tunnel). Recommendations are suggested for the use of the empirical methods for Dutch soil conditions representing soft soil and high groundwater level.

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1. INTRODUCTION

Prediction of settlements and consequently the building damage of the adjacent structures forms an important part of settlement risk management of excavation works in urban surrounding (Netzel *et al.* 1999). It should be emphasized, that the analytical, empirical prediction methods are commonly used in the preliminary design stage. To gain more insight in the influence of boring process parameters (the tail void pressure and the front pressure) on the settlement distribution , advanced numerical calculations should be carried out in the definitive design stage. These design considerations should, in combination with monitoring of soil and structure, be used during construction to control the settlements and consequently minimize its impact on the adjacent buildings (Netzel *et al.* 2001).
Several recently finished Dutch TBM tunneling projects are assigned to be part of a national research program managed by the COB (Center of underground works in the Netherlands). The aim of this research program is, among other issues, to improve the settlement control of the TBM-boring process in Dutch soft soil with high groundwaterlevel. This paper considers the settlement field data of three COB-projects (two TBM-tunnels built with a slurry shield and one built with an EPB shield).

2.EMPIRICAL, ANALYTICAL SETTLEMENT PREDICTION

2.1General

TBM-tunnelling causes a 3D settlement wave consisting of the transverse and the (temporary) longitudinal settlement trough (see Fig. 1). Both have to be considered regarding the potential of damage on the adjacent buildings. It should be emphasized, that the longitudinal trough is a temporary phenomena, which occurs during the passage of the tunnel. The transverse settlement trough is the definitive trough perpendicular to the tunnelaxis, which is resting after the TBM passage.

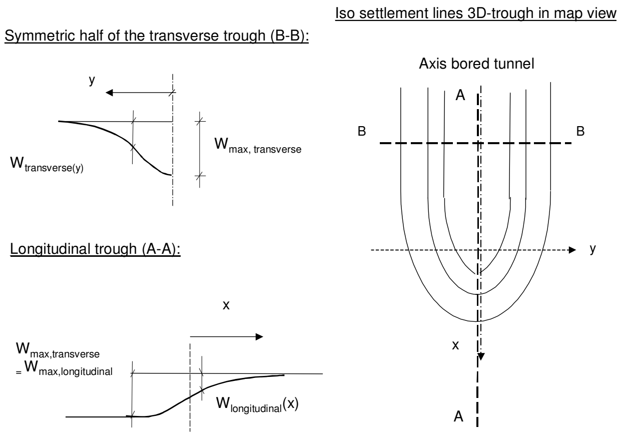

Fig.1: 3D settlements due to TBM tunnelling

It should be noted that due to varying ground conditions, tunneldepth and workmanship a definitive longitudinal trough can also occur. This longitudinal trough cannot be predicted with the approaches given in this paper and is therefore not considered.

Long term effects are also not referred to in this paper.

2.2 Transverse settlement trough

A Gaussian normal probability curve is commonly used to describe the form of the transverse settlement trough. Two parameters are determining the shape and magnitude of the trough: The point of inflexion i and the volume loss V (see Figure 2).

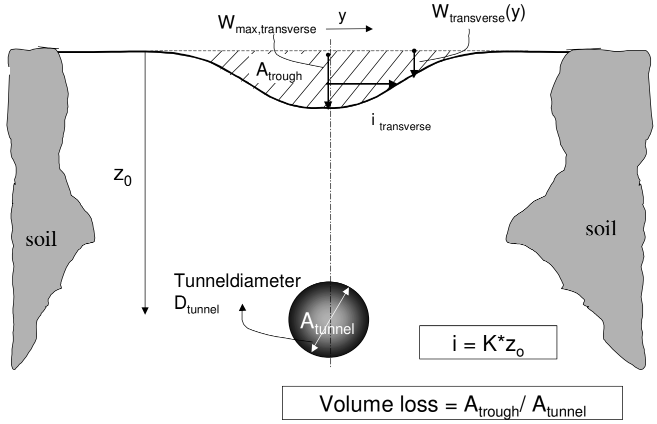

Fig. 2: Transverse settlement trough

The equation describing the form of the trough is given with:

$$w_{transverse}(y) = w_{max} \cdot e^{-\left(\frac{y^2}{2\cdot(i_{transverse})^2}\right)} \quad \text{or}$$

$$w_{transverse}(y) = 0.313 \cdot \frac{V \cdot D^2}{i_{transverse}} \cdot e^{-\left(\frac{y^2}{2\cdot(i_{transverse})^2}\right)} \qquad (1)$$

with

$$i_{transverse} = K \cdot z_0 \qquad (2)$$

V the volume loss
D the tunneldiameter

The point of inflexion (i) is determining the distribution of differential settlements and thus the steepness of the settlement trough and has therefore an important influence in the prediction of damage risks on adjacent buildings. The K-value presents a dimensionless factor in determining i. Different empirical approaches for K, derived form field data of international tunneling projects are given in chapter 4 and compared to the field data of the Dutch projects presented in chapter 3 and 4.

The volume loss develops due to different processes during tunneling (unbalance of the applied front and tail void pressures in the TBM with the initial soil pressures, overcutting etc.) and the conicity of the TBM.. The volume loss used as inputparameter for the settlement prediction in the preliminary design stage generally varies between practical bandwidths of 0.5% to 2% and is used to judge the damage risk susceptibility of the adjacent structures due to the tunneling works.

Current research of the Dutch organsations COB and Delft Cluster is focused on deriving empirical and numerical supported relationships between TBM-pressures and ground settlements (volume loss and point of inflexion).

2.3 Longitudinal settlement trough

The method suggested by Attewell (Attewell *et al.* 1986) is generally applied to determine the temporary settlement profile in longitudinal direction on the surface level ("the settlement wave"). The form of a cumulative probability curve is used based on the statistical mean (w_{max}) and the standard deviation ($i_{transverse}$) parameters as define the transverse Gaussian normal probability profile.

$$w_{y,longitudinal}(x) = w_{transverse}(y) \cdot \left\{ G\left(\frac{(x-x_i)}{i_{transvrese}}\right) - G\left(\frac{(x-x_f)}{i_{transverse}}\right) \right\} \qquad (3)$$

The terms for G(x-xi) and G(x-xf) may be determined from a standard probability table. Attewell remarks that compared with field data the use of equation (3) can lead to a slightly steeper trough (especially for clay soil) than measured and is therefore assumed to be conservative for the damage assessment of adjacent buildings. It should be noted, that this conclusion has to be seen in relation with the length of the building undergoing the longitudinal settlement trough.

Fig. 3 shows the normalized cumulative probability curve used for the prediction of longitudinal TBM-settlements parallel to the tunnelaxis.

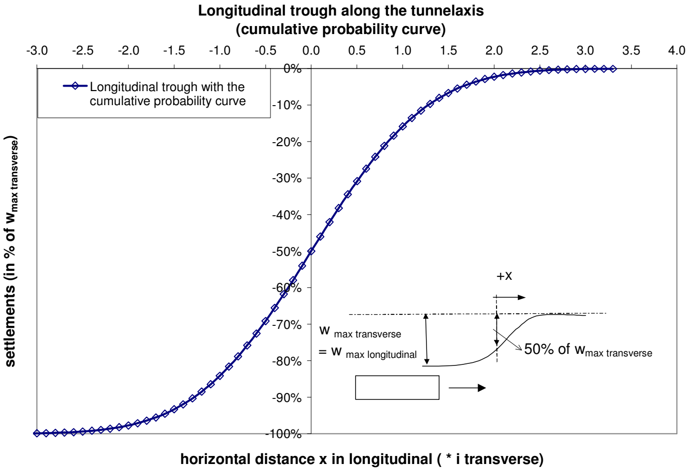

Fig. 3: Longitudinal settlement trough

3. CASE STUDIES

3.1 General

To fit the measured settlement data with the empirical analytical methods the following procedure is used. The volume loss of the monitored transverse settlement trough is calculated and used as input for the empirical , analytical approach. Consequently two k-values are derived for a fit of the maximum monitored settlement and the maximum monitored slope for the transverse trough according to the equations 1 and 2. The measured longitudinal troughs are fit with the values derived for the transverse trough according to equation 3.

In the following chapters one example for the fit of the field data for each of the three Dutch TBM-tunneling project is presented. In Chapter 4 the fitted k-values for all considered monitoring sections of the three projects are given and compared to the approaches suggested by other authors. The monitored volume losses are also summarized.

3.2 Second Heinenoord Tunnel

The characteristic soil profile and the variation of the tunnel depth in the considered monitoring cross sections of the tunneltrack is shown in figure 4. The twin tunnels of the Second Heinenoord Tunnel are built close to Rotterdam in the Netherlands. The soil in the monitoring cross sections consists mainly Holocene and Pleistocene sand layers. The groundwaterlevel is ca. 3m below surface level. The TBM-diameter is 8.3m. The twin tunnels are bored with a slurry shield.

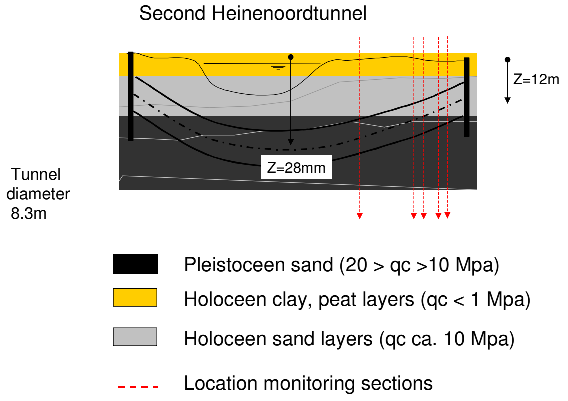

Fig. 4: Second Heinenoord Tunnel

The figures 5 to 8 show an example of the fit of the monitoring data with the analytical, empirical approaches for the symmetric transverse trough and the longitudinal trough along the tunnelaxis on surface level. The transverse trough (V=1.2%) shows a good fit for a bandwidth of the K-value between 0.39 en 0.42.

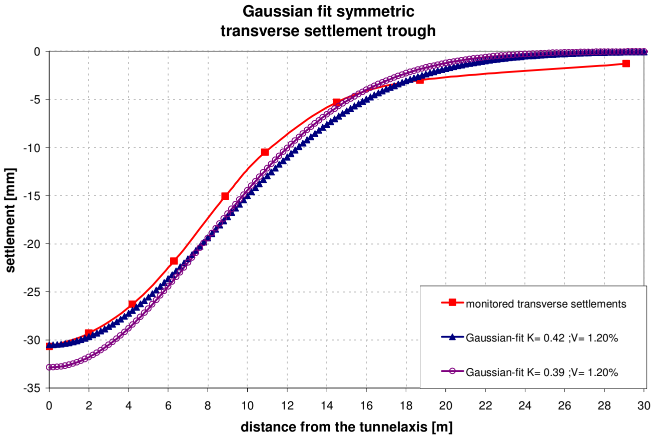

Fig. 5: Fit of the symmetric transverse settlement trough

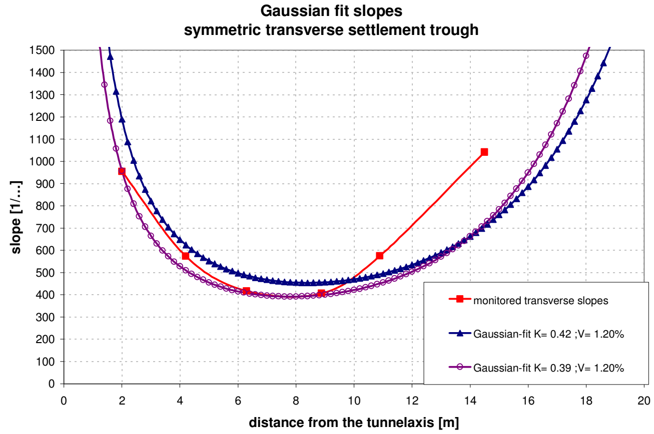

Fig. 6: Fit of the slopes of the transverse tough

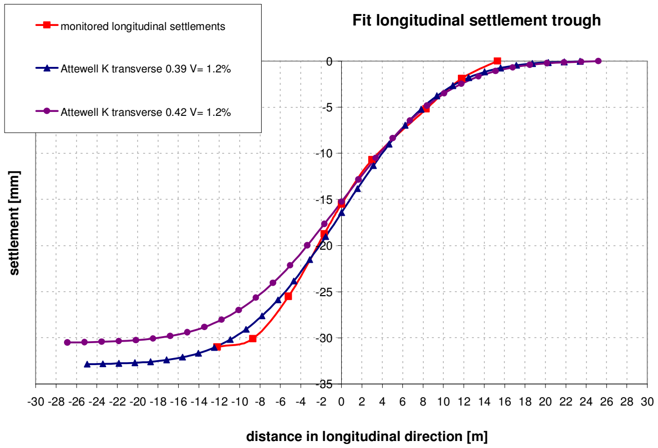

Fig. 7: Fit of the longitudinal settlement trough

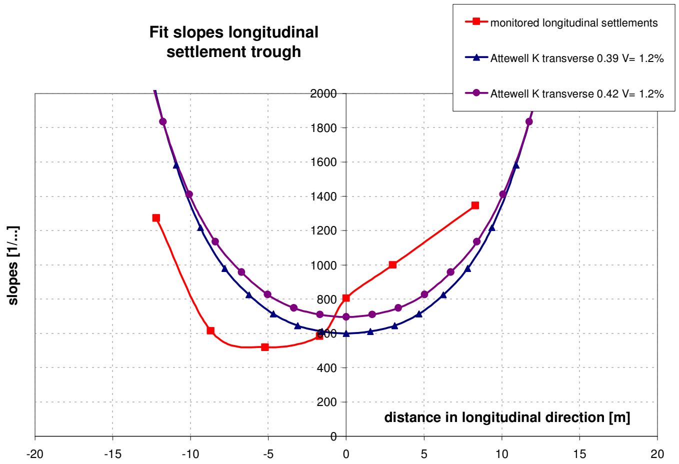

Fig.8: Fit of the slopes of the longitudinal trough

The Attewell approach gives a good fit for the longitudinal trough, although the maximum slope is underestimated with 20% (for the transverse fit with K=0.39) to 40% (for the transverse trough fit for K=0.42).

3.3 Botlek Railway Tunnel

The characteristic soil profile and the variation of the tunnel depth in the considered monitoring cross sections of the tunneltrack is shown in figure 9. The twin tunnels are built close to Rotterdam and are part of the Betuwe cargo line. The soil in the monitoring cross sections consists mostly of soft Holocene sand/clay layers and Pleistocene sand layers. The groundwaterlevel is ca. 3m below surface level. The TBM-diameter is 9.65m. The twin tunnels are bored in the EPB (Earth pressure balance)-mode.

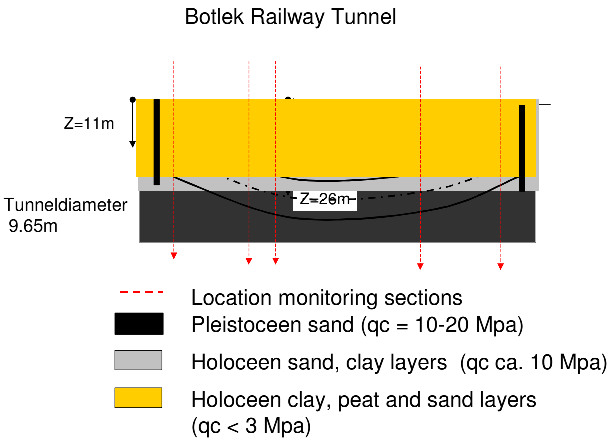

Fig. 9: Botlek RailwayTunnel

The figures 10 to 13 show an example of the fit of the monitoring data with the analytical, empirical approaches for the symmetric transverse trough and the longitudinal trough along the tunnelaxis on surface level.

The transverse trough (V=1.3%) shows a good fit for a bandwidth of the K-value between 0.39 en 0.4. The Attewell approach gives a good fit for the longitudinal trough.

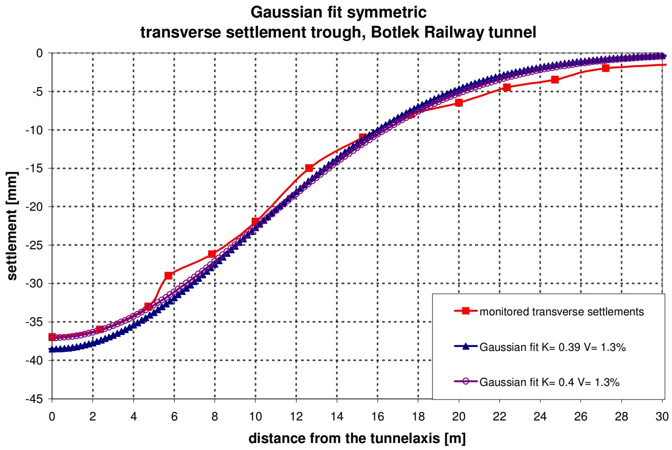

Fig. 10: Fit of the transverse settlement trough

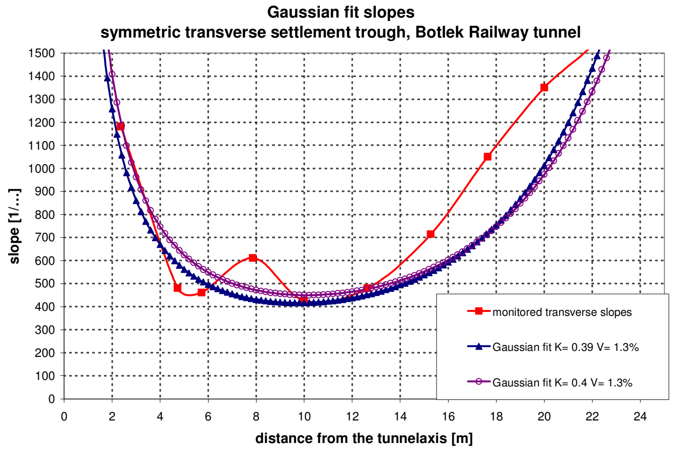

Fig. 11: Fit Slopes transverse trough

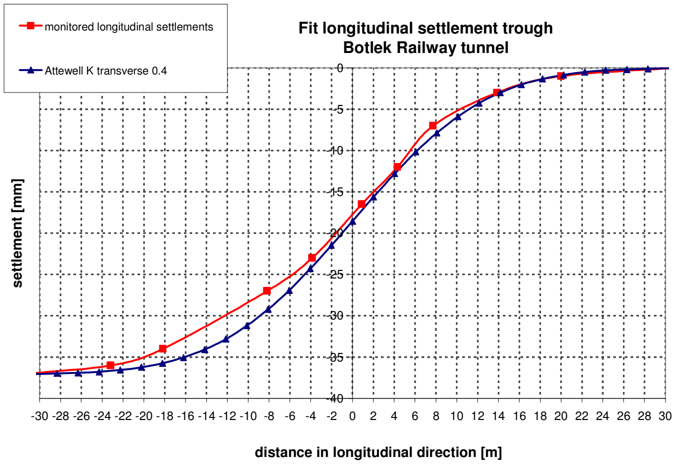

Fig. 12: Fit of the longitudinal settlement trough

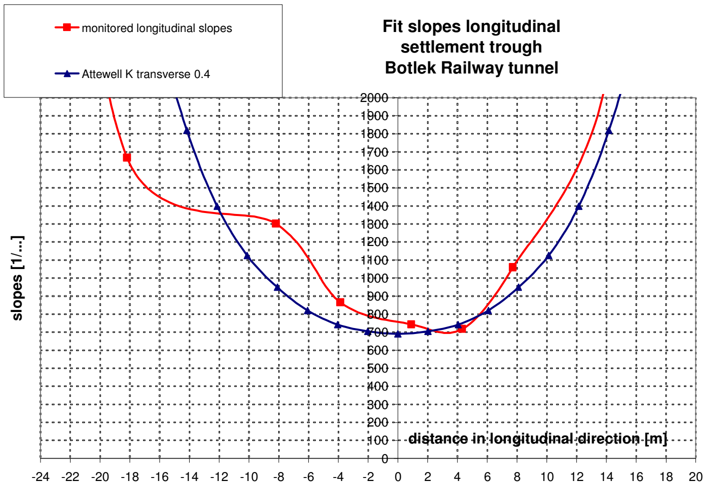

Fig.: 13: Fit of the slopes of the longitudinal trough

3.4 Sophia Railway Tunnel

The characteristic soil profile and the variation of the tunnel depth in the considered monitoring cross sections of the tunneltrack is shown in figure 14. The twin tunnels of the Sophia Railway Tunnel are built close to Rotterdam and are part of the Betuwe cargo line. The soil in the monitoring cross sections consists mostly of soft Holocene sand/clay layers and Pleistocene sand layers. The groundwaterlevel is ca. 3m below surface level. The TBM-diameter is 9.65m. The twin tunnels are bored in the slurry-mode.

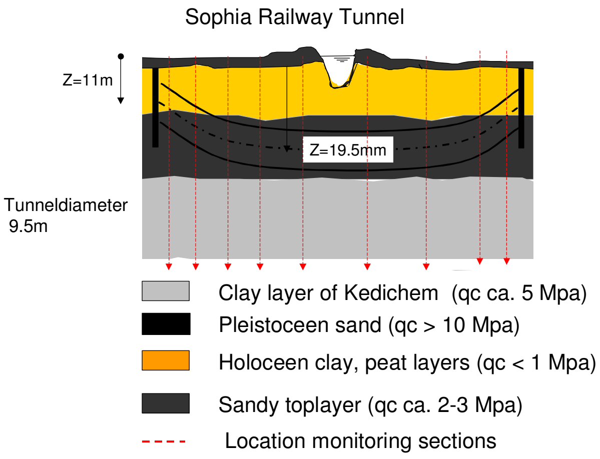

Fig. 14: Sophia Railway tunnel

The figures 15 to 18 show an example of the fit of monitoring data with the analytical, empirical approaches. It should be noted, that the field data in this specific example represents heave of the ground surface instead of a trough, as shown in the previous examples. The empirical methods given in chapter are also applied for fitting the heave monitoring results by using a negative “volume loss” (of 0.9%).
The transverse heave shows a good fit for a bandwidth of the K-value between 0.33 en 0.32.

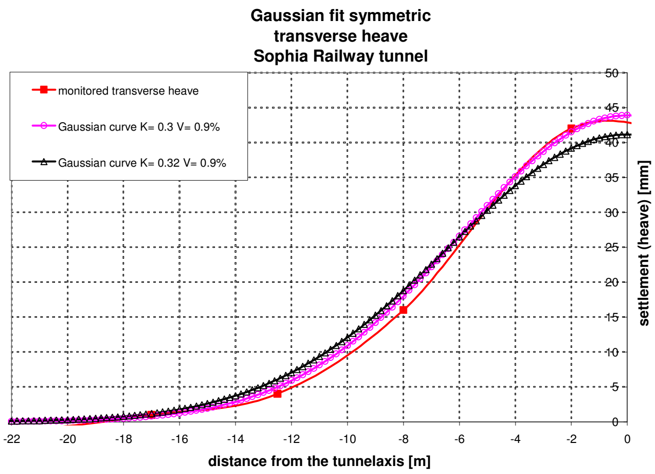

Fig. 15: Transverse (heave)

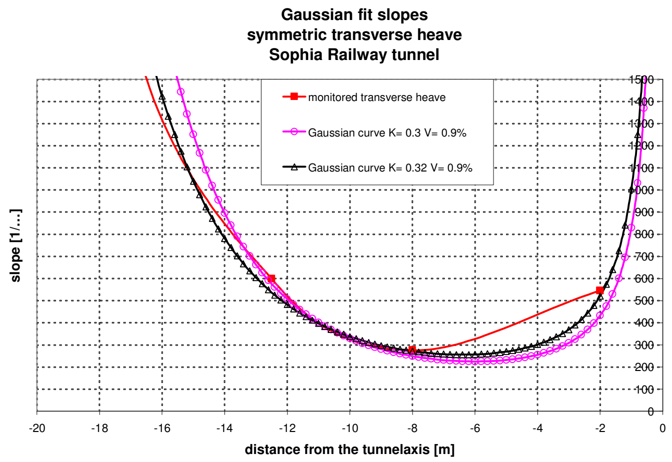

Fig. 16: Slopes in the transverse heave distribution

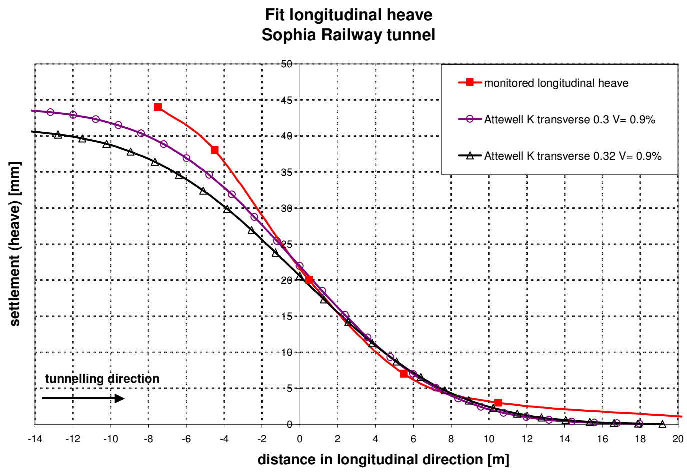

Fig. 17: Longitudinal settlement trough (heave)

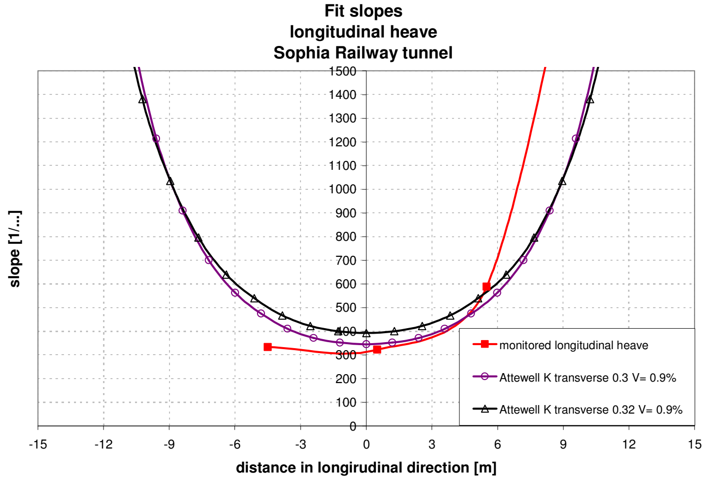

Fig.18:Slopes of the longitudinal settlement trough

The Attewell approach gives a reasonable good fit for the longitudinal heave wave, although the maximum slope is underestimated with 12% (for the transverse fit with K=0.3) up to 30% (for the transverse trough fit for K=0.32). The Attewell approach shows a clearly better fit in the “sagging” part of the

longitudinal heave wave than in the “hogging” part.
The heave in this monitoring section occurred due to locally high applied front pressures and tail void pressures in the TBM. Current research comprises detailed analyses of the relationship between TBM-pressures and surface settlements cq. heave.

4. COMPARISON FIELD DATA WITH LITERATURE

4.1 K-values

The fitted K-values of all considered surface monitoring sections of the three Dutch tunneling projects are given in figure 19, dependant of the depth of the tunnel in the considered sections. Different approaches for K-values for surface settlement troughs of other authors (Clough *et al* 1977, New *et al* 1991and Peck 1969) derived from international tunnelling projects (in sandy soils) are also included in the figure 19.

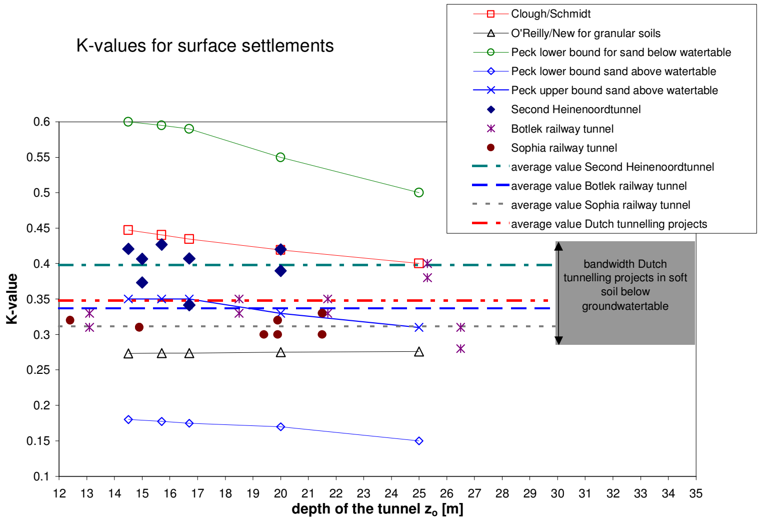

Fig.19 : K-values for surface ground deformations due to TBM-tunnelling in sandy soils

For the three Dutch tunnelling projects a bandwidth for the K-value of 0.28 to 0.43 covers the whole range of the monitored surface settlements (see shaded are in figure 19). This bandwidth fits well within the approaches suggested by Clough/Schmidt and New/O’Reilly for sandy soils. The average K-value for all Dutch projects is 0.35 with a standard deviation of 0.045.

4.2 TBM performance (volume loss cq. heave)

The monitored volume changes on surface level are shown in figure 20. It should be noted that heave effects (see example chapter 3.4) are also included in the figure as positive values, because the figure is meant to show the overall performance of TBM-tunnelling compared to the initial undisturbed situation regardless if the perfomance is a negative or a positive volume change. Both effects can cause damage to the adjacent buildings, it should however of course be taken into account that hogging and sagging parts are oppositely for a settlement trough cq. a heave effect. It should be noted that the heave of 0.9% shown in chapter 3.4 was an exception. Small heave values were observed (around 0.2%) in only a few other monitoring sections.
The volume changes vary between 0.15 and 1.5% with an average value of all three projects of 0.6% and a standard deviation of 0.4.

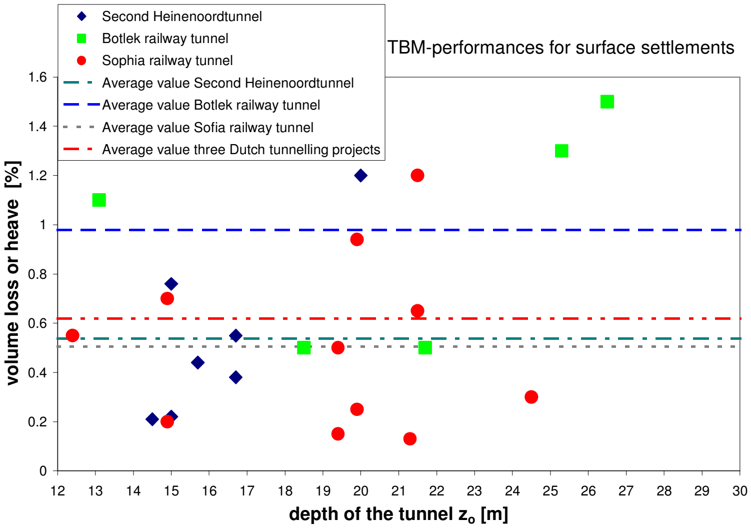

Fig. 20: Monitored volume changes for Dutch TBM projects

CONCLUSION

The settlement field data of three TBM-projects could be properly fit with empirical, analytical methods.
An average K-value (determining the point of inflexion and thus the steepness of the trough) of 0.35 with a standard deviation of 0.05 is suggested for prediction of the surface transverse trough for comparable Dutch soil conditions.
The fit of the longitudinal wave using the cumulative probability curve showed slight underestimations of the steepness of the (temporary) longitudinal troughs.
Current research is focused on deriving relationships between the field data of the TBM-processparameters (face pressures and tail void injection quantities and pressures) and the settlement profile.

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