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Calculation of longitudinal bending moment and shear force for Shanghai Yangtze River Tunnel: Application of lessons from Dutch research

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ABSTRACT

Conclusions from a published longitudinal beam action calculation of the tunnel lining at the Shanghai Yangtze River Tunnel (SYRT) are evaluated against experience gained in Dutch research on longitudinal beam action. The former aimed at quantifying the shear force in the tunnel lining during the construction phase of the tunnel in relation to the grouting process. For evaluation of calculated shear forces, a recently developed one-dimensional beam action model is applied. The paper compares the principles of the two calculation methods and the outcomes. Massive shear forces were predicted in the original calculations for the SYRT, whereas these are much smaller according to this recent model. This is attributed to differences in the treatment of boundary conditions, particularly regarding the longitudinal bending moment in the tunnel lining. It is advised to devise a method to measure the shear force that is transmitted by the set of hydraulic jacks between the TBM and the tunnel lining.

1. Introduction

Monitoring of tunnel construction projects in the Netherlands has provided quantified information on geotechnical aspects of tunnelling in soft soil, on mechanical stresses in the tunnel lining, on grout pressures around the tunnel lining and on the deformation and movements of the tunnel lining. Calculation models have been developed, Bezuijen and Van Lottum (2006). This concerns tunnels from 7 m diameter (2nd Heinenoord Tunnel) up into the large diameter league (14.5 m): Groene Hart Tunnel (GHT).

Tunnel diameters continue to increase with new projects, designs reaching nearly 20 m. As an example, the tunnel diameter of the Shanghai Yangtze River Tunnel (SYRT), also known as the Changjiang Tunnel (15.0 m), is 3.4% larger than that of the earlier built GHT. Highlights of monitoring results at GHT were published (Hoefsloot, 2009; Talmon and Bezuijen, 2009a,b, 2013). The construction of the tunnel lining of the GHT finished mid 2004. The report of the feasibility study of the SYRT was approved in November 2004, the project initiated in December 2004 and the preliminary design was approved in July 2005 (Huang, 2008b). The book "The Shanghai Yangtze River Tunnel: theory, design and construction" by Huang (2008a) contains detailed technical information on diverse design aspects of the SYRT. One aspect that draws the authors' attention is that, according to a shear force calculation published in this book, the connecting bolts in the tunnel lining are regarded as necessary structural elements during tunnel construction. They are not regarded as such at GHT. When building the SYRT, shear pins are installed in the lateral joints at shallow overburden and one chapter in this book shows how the grouting process dictates the maximum allowable advance rate of the Tunnel Boring Machine (TBM). Moreover, preliminary measurement results are presented: the tunnel was still under construction. It is conceivable that acquired knowledge from the monitoring of GHT and other projects could not timely be included into the design of the SYRT. One may therefore wonder what the outcome would be when this knowledge was applied.

To answer this question a recently published Bernoulli–Euler beam model is applied (Talmon and Bezuijen, 2013). The model is not very difficult to replicate and the outcome is verifiable. This model succeeds earlier more elaborate pioneer analytical models (Bogaards and Bakker, 1999; Hoefsloot, 2009). The model builds on experiences gained in pre-GHT monitoring (Bezuijen et al., 2004) and it is particularly validated with monitoring data of the GHT.

Regarding beam action, fluid-grout behind the TBM produces a buoyancy force on the tunnel lining. Further from the TBM, the tunnel lining becomes bedded into the surrounding soil. For a

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schematisation, see Fig. 1. The tunnel boring process produces bending moments and shear forces in the newly constructed tunnel lining. These are the result of buoyancy forces, vertical loads and non-uniformly distributed horizontal loads transferred from the TBM.

Mechanical stresses in the tunnel lining were measured by vibrating strain gauges that had been cast into the lining. These produced data from the instant of erection of the lining elements until after the passage of the rear of the back-up train of the TBM. The measured bending moment curve at GHT is shown in Fig. 2 (Hoefsloot, 2009; Talmon et al., 2009), together with the results of a one-dimensional calculation for a Bernoulli–Euler beam on an elastic foundation. It shows that far behind the TBM a longitudinal bending moment remains in the tunnel lining. This differs from textbook solutions for half-infinite Bernoulli–Euler beams on elastic foundations where the longitudinal bending moment converges to zero. The difference is attributed to the staged construction of the tunnel lining. By repeated calculations in which the loads and supports are forward translated every time a segmented ring is built, the construction processes can be simulated. Such a method was introduced by Bogaards and Bakker (1999) and was further refined by Hoefsloot (2009). Application of the method to GHT was described by Hoefsloot (2009) and Talmon et al. (2009). For the beam action of a tunnel lining that is constructed ring by ring it is, however, more convenient to use a co-ordinate system that translates with the advance of the TBM. In this approach the boundary conditions have to be adapted, but within these adapted conditions, already available analytical solutions for beam action may equally be applied. Employing such solutions, the DEltares Analytical BEam Action Model (DEABEAM) was developed: Talmon and Bezuijen (2013).

The Shanghai Tunnel Engineering Co. (STEC), Lin et al. (2008), investigated the relationship between the early strength of simultaneously injected grout and the stability of the tunnel lining of the super-large diameter shield tunnel of the SYRT. An ANSYS structural analysis calculation was conducted. The objectives of this calculation were:

- to calculate the shear force in the lining in order to determine whether specific measures regarding the structural integrity were necessary,
- to determine the maximum advance rate of the TBM under shallow overburden in relation to the strength of the grout.

In 2009 two of these authors reported with co-authors of Tongji University on the application of the same technique to a smaller diameter tunnel ($D = 6.8$ m), Yang et al. (2009b). In the same year a very similar calculation, again for the SYRT, was reported by Yang et al. (2009a). For SYRT, the published graph of the calculated shear force in the lining shows a negative value of about 16 MN at clearing of the tail shield and it shows an overshoot of one-fourth of this value at some distance, see Section 4.4. Only the calculated shear force in the lining is given. This result led to investigate the beam

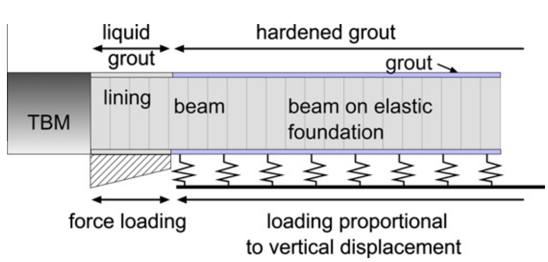

Fig. 1. Definition sketch buoyancy force loading in the zone where grout is in the liquid state.

action at SYRT in the light of recently developed knowledge, much of which is implemented in the DEABEAM.

Dutch research on beam action and tail void grouting has learned in summary that:

- The TBM jacks are exerting a bending moment on the tunnel lining in order to prevent the front-heavy TBM to nose-dive and to bend the free end of the tunnel lining downwards (Bezuijen et al., 2004, 2005). Recorded hydraulic oil pressures substantiate this. At GHT the measured bending moment is 65 MN m.
- Strain measurements show that the staged construction of the tunnel lining introduces a longitudinal bending moment in the finished lining. Since the finished lining is straight, some pre-curvature must have been introduced in the assembly process (Hoefsloot, 2009; Talmon et al., 2009).
- Grout pressure measurements show that, for grout with sufficient yield stress, the buoyancy force from the fluid-grout can be reduced by injecting relatively more grout through the injection pipes situated in the upper part of the TBM, depending on the yield stress of the grout (Talmon et al., 2001). At the time of injection, measured yield stresses are $\geqslant 0.8$ kPa, Bezuijen et al. (2004) and Talmon and Bezuijen (2009a).
- Grout pressures in the tail void should at least be larger than the pore water pressure in the surrounding soil.
- The end of the fluid-grout zone is situated near the point where the foundation force of the surrounding soil only stems from the buoyancy force of ground water. Beyond this point effective soil stresses are being transferred by the hardening grout (Hoefsloot, 2009; Talmon et al., 2009).
- In saturated porous soil, the fluid-grout zone extends typically to a distance of one half to one tunnel diameter behind the TBM (Bezuijen et al., 2004).
- Also in cases where cementing grout is used, the consolidation of the grout determines the distance of the fluid-grout zone and not the hardening of the cement (Bezuijen and Talmon, 2003). As a consequence slowly hardening puzzolanic fly-ash type grout as well as cementing grout are applicable in simultaneous grouting of the tail void.
- The bending stiffness of a segmented tunnel lining is significantly smaller than that of a theoretically non-segmented hollow cylindrical tube (Talmon et al., 2009).
- The vertical transverse shear force from the TBM is only a small fraction of the axial force. This has been concluded from 3-D numerical calculations for Sophia Rail tunnel (Hoefsloot and Verweij, 2006) and from beam action calculations conducted in back-analysis of the measured bending moment profile at GHT (Hoefsloot, 2009; Talmon et al., 2009). The latter led to a shear force of 1.5 MN.

2. Specific data on the Shanghai Yangtze River Tunnel

Each tube of the SYRT contains three road lanes. The length of each tube is 7.5 km. The tubes were constructed in the period 09-2006 to 09-2008. The diameter of the tunnel boring machines is 15.43 m. The design speed of the TBM during the drilling phase is 4.5 cm/min. The realised advance speed under normal conditions was 2–4 cm/min, Huang (2008b). The maximum realised advance rate is 8 rings/day (publicly announced at the IS-Shanghai congress 2008).

A sketch of the most important components of the TBM, the back-up train, the tunnel lining and the finished construction is given in Fig. 3. Centre road deck elements are installed 25 rings later than segment erection. The dimensions of the centre road deck are given in Di et al. (2008). In situ casting of the side road deck is taking place at a distance of 250–300 m from the segment erection