Measurements and evaluation of the influence of two bored tunnels at reduced distance (<0.5 D) in a homogenous sand layer

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ABSTRACT: Measurements were carried out during construction of the Pannerdensch Canal tunnel (one of the three bore tunnels of the Betuweroute), in order to investigate the influence of the boring of the second tube on the first tube, with a reduced distance between the tubes (<0.5 D). The Pannerdensch Canal tunnel (D = 9.5 m) is mainly situated in middle to well compacted sand layers. The expected and measured influences are presented in this paper.

1 INTRODUCTION

The Pannerdensch Canal tunnel (PC) is one of the three bored tunnels of the Betuweroute, a new railway link between the harbour of Rotterdam and Germany. Since the surroundings of the PC tunnel are of great environmental importance, a bored tunnel was chosen instead of a steel bridge. An overview of the tunnel is given in figure 1. The client ProRail, Managementgroup Betuweroute, integrated the research programme of the Centre of Underground Construction (COB) in the Design and Construct contract. The contractors venture Comol Tunnelbouw (Vinci, CFE, TBI & Welling) started construction in 2000 and completed the bored tunnel in 2003.

The total length of the PK tunnel is 2680 m including the entrance and exit ramps. The length of each bored tube is 1615 m. The outside diameter of each tube is 9.5 m and the lining thickness is 0.42 m. The bored tunnel passes a lake (the sand pit Kandia) which had, in order to allow the construction of a bore tunnel under this site, to be refilled with 500,000 m³ of sand. This backfill was necessary to support the tunnel lining and to prevent a blow out during boring. At the location of the former sandpit the distance between the two tunnel tubes is reduced. The mechanical properties of the sand fill are uniform and well documented giving an ideal research environment approaching laboratory conditions.

The COB initiated a research programme (F502) to carry out field investigations at the shield driven PC tunnel. The main goal of this research programme is to investigate the influence of the second bore tunnel on the first tunnel, in the situation of a reduced distance between the tubes. At the research location (refilled sand pit) the distance between the tubes varies from 3.0 m to 5 m (approx. 0.30 D to 0.5 D).

2 SOIL PROFILE

The sand pit Kandia is located at the eastside of the PC. The excavation level of the pit varies between NAP −6.0 m and NAP −11.0 m. The underside level of the tunnel is set between NAP −7.0 m and NAP −0.5 m, as shown in the longitudinal cross section of the Kandidam below (figure 2). An existing 3 m thick clay/loam layer is located at 3 m underneath the bottom
level of the pit. Further, the natural underground consists of middle to well compacted sand layers. The ground cover above the bore tunnel at the research location varies between 1.0 D and 0.6 D.

The water level in the Canal, and also in the sand pit, varies in an extreme way; from NAP +6.8 m during summer periods to NAP +15.3 m during winter periods.

3 LITERATURE STUDY AND PREDICTIONS

An international literature study was implemented to find out if measurements of ground stresses and tunnel lining deformations for bored tunnels with relative small distance (up to 0.5 D) between the tubes, without taking mitigating measures before boring (for instance jet grouting), were available. This study didn’t bring up such international literature on this subject, so it was concluded that this research project was unique (Hielkema & Kwast 2002).

Measurements carried out in Japan (Ikeda et al. 1996 and Hashimoto et al. 2002) and in The Netherlands (Hoefsloot et al. 1999/2001) indicates possible increase of ground and groundwater stresses at various distances of the tunnel lining while back fill grouting is performed during the first passage of the shield tunnel (ground cover 1.5 D–2 D). The indicated increase of the maximum change of the lateral ground stresses reaches values from 150 kPa at 0.5 m out of the tunnel lining to 100 kPa at 4.0 m outside the tunnel lining. The maximum change of groundwater stresses increase from 60 kPa nearby the tunnel lining to 35 kPa at a distance of 4.0 m at the lining.

Based upon the results of parametric 2D EEM calculations (Empel et al. 1999), it was concluded that with a distance of 0.25 D to 0.5 D between the two bored tunnels (with a ground cover of 1 D), the maximum horizontal and vertical ovalisation during construction of the first tube was respectively +4 mm and −6 mm. During boring of the second tube, the calculated ovalisation of the first tube is very limited (±1 mm). In addition 2D EEM (Plaxis, HS-model) calculations were performed (Gerritsen & Linthof 2003). Hereby, the ground and groundwater conditions at the PC tunnel, the measured settlements, the ovalisation of the first tube and the grout pressure were taken into account to calculate the change in ground stresses between the tubes and the ovalisation of the first tube during construction of the second tube. The results of these calculations show a maximum horizontal and vertical ovalisation of the outer diameter of the tunnel of respectively −0.02% (−2 mm) and +0.02% (+2 mm). The maximum change of lateral ground stresses during grouting of the second tube was calculated to be 35 kPa for a distance of 1.0 m out of the lining of the second tube (e.g. to 4.0 m out of the lining of the first tube) and 0 kPa for a distance of 4.0 m out of the lining of the second tube (e.g. to 1.0 m out of the lining of the first tube). At the forefront, based on the results of literature studies and calculations, a rather wide range of changes of lateral ground stresses could be expected. However, the predicted ovalisation of the tunnel lining of the first tube during construction of the second tube (distance between the tubes equal to 0.5 D) remained rather limited, with a maximum value of ±2 mm.
4 MEASUREMENTS

4.1 Measurement programme

An overview of the measurements stations at the Kandiadam is given in figure 3.

The regular measurements at the research location, to be placed in the underground and at the tunnel lining, were specified in the contract; that is:

- 5 settlement points at the surface each 25 m above the two tubes;
- cross section (MQ 5) with 22 settlement points at the surface (in longitudinal and cross direction) and 4 extensometers next to and above the tubes;
- piezometers in the surrounding;
- grout pressure measurements at the lining;
- convergence measurements up to 50 m behind the TBM;
- TBM measurements to control the bore process.

In addition, the following measurements were carried out by the COB in order to meet the goals of the research programme:

- measurements of the change of (lateral) ground and groundwater pressures by the use of 11 spade cells in 3 cross sections;
- convergence measurements of the first tube during construction of the second tube (50 m before to 50 m behind the TBM passage) at 3 cross sections.

4.2 Convergence measurements

Additional convergence measurements in the first southern tube were carried out by Comol during construction of the second northern tube. At 50 m before the TBM passage (−50 m) in the northern tube, initial convergence measurements were performed in the southern tube. Furthermore, the relative change in diameter of the southern tube was measured by means of a theodolite before the TBM’s passage at −10 m and −5 m, during TBM’s passage at 0 m and after TBM’s passage at +5 m, +10 m and +50 m. The measured horizontal and vertical changes of diameter, compared to the theoretical perfect round diameter, of the southern tube are given respectively in figure 4 and 5. These measurements were twice implemented and the mean value is given for 3 cross sections. The distance between the tubes at the 3 locations is respectively 5.0 m, 4.0 m and 3.5 m.

Based on the results of the convergence measurements (Wiersema & Caan 2004) it can be concluded that:

- initial measurements (0-situation) shows a vertical egg ovalisation of the south tube;
- the changes of ovalisation of the south tube are rather small, the range of decreasing and increasing of the diameter of the south tube during construction of the north tube is ±2 mm, the final alteration does not exceed ±1 mm for the south tube;
the measured change of ovalisation is in the range of the measurement accuracy ($\pm 1$ mm).

4.3 Ground pressure measurements

In 3 cross sections spade cells (gauges) were placed above the first tube, at $45^\circ$ angle with the first tube and two spade cells between the tubes, each at a distance of $1.0$ m from the tunnel lining. For the evaluation of the measurements, 2 cross sections (MQ 5 and MQ 5.1), placed at a distance of respectively $5.0$ m and $3.5$ m between the tubes were analysed. The locations of the spade cells for these cross sections are shown in figures 6 and 7.

The spade cells were tested at the production unit by the supplier as well as on site. Calibration of the spade cells was performed during the positioning of the spade cells in a bore hole by measuring the depth of the instrument below the water level. This depth had to match the pressure registered by the separate pore pressure sensor of the spade cell. These tests gave reliable results.

At the bottom of the bore hole, the spade cells were forced into the underground by $1.0$ m, to prevent any disturbance of the initial ground pressure. The bearing of the spade cell, parallel to the tubes, was also controlled during installation. After installation, the measured lateral ground pressure showed some differences with theoretical ground pressure, which could have been caused by the low pressure range. The initial lateral ground pressures before TBM passage were corrected (set up) to match the theoretical values.

The frequency of the measured ground pressure during the TBM’s passage for the first tube was once per minute. During the second passage, due to disturbance of the data logger during excavation, the measurement frequency was very low, only just once per 90 minutes. This inadequate measurement frequency during the second TBM’s passage could have lead to miss the maximum value of the ground and water pressures. The maximum values appeared during grouting of the slurry separator. It seems that this spade cell was placed at a distance of respectively $5.0$ m and $3.5$ m between the tubes. The locations of the spade cells for these cross sections are shown in figures 6 and 7.

The spade cells at the top of the south tube, spade cell 6 (MQ 5.1) gave no signal after the TBM’s passage. This spade cell was later recovered in the back fill void, where the boring process was very fast (boring and building of a complete ring in less than 1 hour).

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of ground pressure during TBM passage in the south tube at 45° angle, by spade cells 2 and 6 is respectively 200 kPa and 125 kPa. The rather high increase of ground pressure at these locations is caused by the nearby located injection point of the TBM. In the middle of the south tube, spade cells 3 and 7 both placed at 1.0 m from the lining, shows an increase of respectively 150 kPa and 75 kPa. During the process of the boring of the second tube, a 25 kPa increase is measured at a 4.0 m (spade cell 3) and 2.5 m (spade cell 7) distance. Spade cells 4 and 8 gave non uniform results, as can be seen in figures 6 and 7.

After the first passage of the TBM, the measured ground pressures stayed at a constant higher level. The increase of lateral ground pressure is about 50 kPa. The measured water pressures are not shown, but the maximum increase during TBM passage is 40 kPa and disappear just after passage of the TBM.

The increase of lateral ground pressure can be related to the injected grout volume. Based on the TBM’s data, it can be deducted that the injected grout volume exceed for all the rings the theoretical needed volume of 9.3 m³ per ring. The grout injection pressure was stable during TBM passage. The excess pore pressures can be attributed to the (slurry) infiltration at the excavation face at the front of the TBM. An overview of the results of the spade cell measurements is given in table 3.

It is notable that for this project, the surface settlements were relatively limited, namely 0 mm to 15 mm.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results of this research project it can be concluded that:

- The change of ovalisation of the first tube during construction of the second tube is negligible. This is in accordance to what was predicted and measured;
- The maximum increase of lateral ground stresses and water pressures is in the range of measurements at other projects, but the variation in increase, at the equal distance to the tunnel lining, is relatively high;
- No measurable influences due to construction of the second tube were observed on the first tube with reduced distance between the tubes of 3.0 m to 5.0 m (approx. 0.30 D to 0.5 D). Significant for this conclusion is the fact that the underground of the research site consists mainly of middle to well compacted sand layers.

5.2 Recommendations

The most important recommendation is to investigate the behaviour of the first tube during construction of the second tube at reduced distance for geologic profiles in the western part of the Netherlands, where bore tunnels are mainly situated in soft ground layers from the Holocene.

REFERENCES