ABSTRACT

Infiltration and Excess Pore Water Pressures in front of a TBM
Experiments, Mechanisms and Computational models

The Tunnel Boring Machine (TBM) tunneling technique has been developed to construct tunnels that require strict settlement control, for example, in urban areas with a large amount of buildings, historic areas etc., or where the soil is very soft (for example when crossing a river or estuary). When tunnelling with a TBM below the phreatic zone, especially in saturated sandy ground, groundwater flow into the excavation face needs to be impeded. Both stability of the tunnel face and limitation of the groundwater flow are achieved by pressurising the drilling fluid or muck from the excavation chamber of the TBM at the tunnel face. An additional margin for the support pressure is required, depending on the depth of the tunnel, its diameter and the ground conditions.

Due to the pressure difference between the excavation chamber of the TBM and the ground, drilling fluid (slurry or foam) will infiltrate into the ground and thus there will be a flow in front of the tunnel face. In such a situation, part of support pressure applied through the drilling fluid at the tunnel face will be transferred into excess pore water pressure in the ground. As a result, the effective support pressure at the tunnel face and thus the stability of tunnel face will be reduced. The reduction of the effective support pressure depends on the infiltration distance, the infiltration velocity and the drilling speed. However, the infiltration distance of the foam or the slurry, influence of this infiltration on the permeability of the infiltrated ground, and consequently on the excess pore water pressure, are still only partly understood. Finding answers to these questions, therefore, is significantly important for the safety of tunnel.

The purpose of this study is to improve our understanding of the mechanism of drilling fluid infiltration in front of the tunnel face through laboratory experiments, and develop computational models considering such an infiltration process to predict the excess pore water pressures induced by TBM tunnelling. The research concerns both slurry and Earth Pressure

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Balance shields (EPB shields). With the results of the experiments, a sounder theoretical basis for the description of infiltration of drilling fluid (slurry or foam), and the computation of excess pore water pressure in front of tunnel face have been established.

In the experiments of infiltration of slurry into the saturated sand, it was found out that the mud spurt (is defined as the process whereby fluid passes through the filtration medium before a filter cake is formed) will stop when an impermeable external filter cake is formed on the sand surface and the infiltration distance during mud spurt is less than 12 cm in the specific experiments in this thesis. The infiltration distance depends on the medium pore diameter, i.e. grain size distribution, as well as properties of the slurry. The permeability of the infiltrated sand is $\sim 3 \times 10^5$ times lower than the permeability of the original sand. It is essential that the external filter cake makes such a low permeability layer that bentonite particles cannot migrate. When this filter cake is removed and fresh slurry is poured onto the sand surface, and pressure is applied so that the infiltration starts again, there will be two infiltrations before and after removing the filter cake: 1st and 2nd. The infiltration distance in the 2nd infiltration is more or less the same as in the 1st infiltration for low concentrations of bentonite (e.g. 40 and 50 g/l), but is much smaller for high concentrations of bentonite (e.g. 60 g/l). In all cases, the formation of the external filter cake blocks the mud spurt. However, at low concentrations, the mud spurt is much less, than what could occur if there was no external filter cake formation and after removing the external filter cake, the mud spurt starts again until it is again blocked by the internal filter cake. For higher concentrations of bentonite, the mud spurt of the first infiltration is closer to the mud spurt that would occur without external filter cake formation and because there is also some gelling of the bentonite, there will be hardly any further mud spurt and this also prevents the formation of an external filter cake.

Infiltration tests with sand added to the slurry to simulate the spoil of soil in the slurry during the drilling process were performed too. In infiltration of slurry containing sand, there is first mud spurt and after that deep filtration. The bentonite particles and fine sand grains are fixed in the existing sand layer. In this situation, there will a considerable larger infiltration distance than that measured in 'conventional' slurry infiltration tests performed with slurry without sand. This is positive for the safety of TBM tunnelling when air intervention is necessary at

the tunnel face, since a low permeable slurry-sand mixture is present over a larger thickness in front of the tunnel face than up to now anticipated based on tests with clean bentonite.

In the experiments of infiltration of foam into the saturated sand, unlike during the infiltration of slurry, no external filter cake will be formed on the sand surface. There will be a low permeable layer formed in the sand. In this layer, the foam bubbles are blocked by the sand grains while the water between the bubbles still flows due to the pressure gradient, resulting in an area with low water content and consequently a low permeability. Like in the slurry experiments, the permeability of the low permeable layer is ~ 2000 times lower than the permeability of the original sand. It was found out that a 'dry' foam (FER (Foam Expansion Ratio) = 20) is not essential for formation of a low permeable layer in the sand, even a 'wet' foam (FER = 5) can form a low permeable layer, because in all cases the water in between the bubbles flows away. The permeability of sand for foam decreased with increasing FER of the foam until FER of approximately 15 in this study. For higher FERs the permeability remains more or less constant.

When adding sand into the foam, as done in the slurry experiments, foam and sand will be deposited on the original sand. There are now 2 sand layers: one of the original sand and one of the deposited sand with a higher porosity. The water permeability of foam-infiltrated sand decreases with increasing air fraction and decreasing liquid fraction with a given solid fraction, or decreases with increasing air fraction and decreasing solid fraction with a given liquid fraction. The permeability of foam-infiltrated sand decreases with Foam Injection Ratio (FIR) and a FIR of 35 - 40 Vol% is recommended for EPB shield tunnelling in sandy soils. Furthermore, with increasing volumetric water content (water fraction), the permeability decreases. The permeability is determined by the water film that is around the bubbles.

Two analytical models are presented to describe the development and decline of the excess pore water pressures in front of a TBM in saturated sandy ground. The first model considers transient flow in a semi-confined aquifer with elastic storage, while the second one assumes different conditions of unconfined steady-state flow governed by the infiltration of slurry into the soil. Based on the experimental data of infiltration of slurry or foam, the input parameters can be obtained, such as, the final infiltration distance, the infiltration distance with time etc.

for the second model. Both models are validated with measurements from the Green Heart Tunnel (GHT) and Amsterdam North/South Metro Line (N/S Line) in the Netherlands. It is shown that both analytical theories can predict the excess pore water pressures in front of slurry shield. The second one seems more appropriate because it reflects the effect of slurry (or foam) infiltration. Furthermore, the measurements seem to indicate that the influence of elastic storage is smaller as assumed in the first theory.

This study has practical consequences for TBM tunnelling in saturated sand:

For drilling with a slurry TBM, the filter cake is beneficial to the stability of tunnel face, but this filter cake is quite thin and thus vulnerable to damage. An external filter cake will not be formed when the density of the slurry is larger than 1100 kg/m^3 or during drilling activity that removes the cake. When a filter cake is formed during a stop in drilling (for example for ring building), this will be almost instantly removed when drilling starts again. When there has been depth infiltration the excess pore water pressures will increase gradually. By measuring the pore water pressure in front of or next to a tunnel face, it is possible to investigate the process that occurs.

During drilling with an EPB shield, the foam bubbles are trapped in the sand grains of the soil-foam-mixture mixture causing a reduction of the permeability. If this is the case, this has consequences when drilling starts after a stop. Most of the low permeable soil will be immediately removed when the cutter head starts drilling.

In most field situations there is no 'clean foam' or 'clean slurry'. In these situations, there is no low permeable 'foam cake', but over a larger distance, there is a sand-foam mixture with a low permeability. This is positive for the safety of tunnelling with a TBM when air intervention is necessary at the tunnel face, because it means that a low permeable slurry-sand mixture is present over a larger thickness in front of the tunnel face than up to now anticipated. Determining the necessary support pressure at the tunnel face, it has to be taken into account that this support pressure partly transfers to excess pore water pressure. The analytical models in this study can be used for a first estimation. When it appears that the stability of the tunnel face is critical, additional numerical calculations may be possible.