Active confinement pressure control with foam

A comparison between slurry and earth pressure balanced shields

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ABSTRACT: Ground conditions generally vary frequently within a single tunneling project, therefore selecting the most applicable TBM that best suits the anticipated geotechnical and geologic conditions interaction demands the most elaborate of decisions. In soft ground tunneling, one of the most difficult issues is to establish the correct support pressure in the tunneling machine to properly compensate for the earth and water pressure against the cutting wheel. This paper focuses on the theoretical models for confinement pressure calculations and pressure transmission and will provide an overview of some of the latest technological developments, concerns and consideration for soft ground TBM applications.

1 INTRODUCTION

In shield tunnelling through unstable soil beneath the groundwater table, the earth and water pressures have to be balanced by means of an adequate supporting medium. The pressure values necessary to support the tunnel face must be adjusted in such a way that the stability of the tunnel face is assured in order to guarantee low settlements at all time.

2 COMPARISON BETWEEN THE EPB AND SLURRY SHIELD PRINCIPLES

In slurry shields the pressure is transferred to the tunnel face by means of a bentonite suspension which acts as a secondary supporting medium. The bentonite is also used for the conveyance of the spoil. The pressure to be applied is controlled

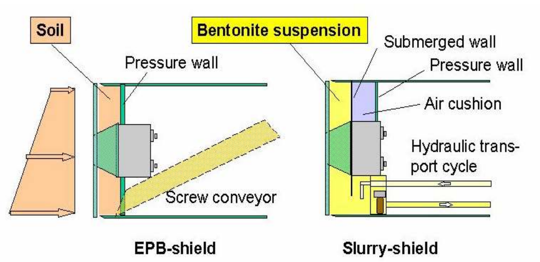

Figure 1. Operation principles of EPB and slurry shields.

through the compressed air cushion located behind the submerged wall. On the other hand, in EPB shields the same ground loosened by the cutterhead is used as supporting medium through the combination with ground conditioning as illustrated in Figure 1. Polymer foams are used as conditioning agents. The spoil is extracted from the excavation chamber by means of a pressurised screw conveyor (Maidl et al. 1995).

3 COMPARISON OF THE APPLICATION RANGES

The typical application ranges for EPB and slurry shields are illustrated in Figure 2. Sands and fine gravel represent the typical application range for slurry shields. In grounds with a higher fine fraction, the use of a slurry supported face results expensive and costly in terms of applied technology for the separation plant required to separate the solid fraction contained in the bentonite suspension recovered

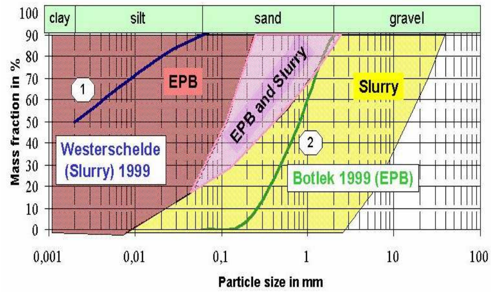

Figure 2. Grain distribution curves for the application ranges of EPB and slurry shields

from the tunnel face. The typical application range for EPB shields are plastic to soft clay-silt-sand mixed materials. By means of the foam conditioning it became possible to extend the application range of the EPB shields to sands and gravel, which really belong to the application range of the slurry shields (Maidl 1995).

4 CONFINEMENT PRESSURE CALCULATION

Next the mathematical models for the calculation of the confinement pressures will be presented.

4.1 *Tunnel face stability*

When using the traditional earth pressure model according to Jancsecz (1994). The active earth pressure on the tunnel face is determined by a limiting equilibrium approach with a three dimensional square failure wedge. The failure wedge is based on the earth wedge model of Horn (1961).

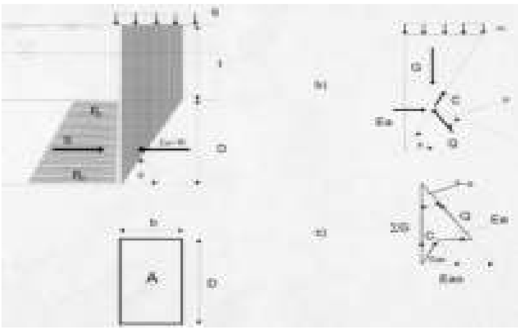

Fig. 3: Calculation of the confinement pressure in the excavation chamber by means of failure body examination a) approximation for the failure body acc. to HORN [1961], b) effective loads on the sliding wedge, c) force corner.

As a good approximation, the calculation of the earth pressure for an earth balanced pressure shield with internal friction can be performed from the equilibrium of the failure body represented in figure 3.

The circle shaped tunnel face is approximated assuming a square whose side length coincides with the tunnel diameter. The failure body in front of the tunnel face is made up of a sliding wedge. This wedge is vertically loaded with the earth block located over the tunnel up to the surface. The own weight of the earth block can be applied using the lowered vertical load σ_Z from JANSSEN's silo theory. The formulas are not cited here but are referred to in the corresponding expert literature instead.

4.2 *Safety for blow out and collapse*

The calculation of the safety for blow out and collapse is performed by simply imposing vertical equilibrium, without the consideration of friction forces, with a safety factor of η = 1.10. The compressed air interventions normally determine the maximum admissible confinement pressure values regarding safety against blow out and collapse.

5 TRANSMISSION OF THE CONFINEMENT PRESSURE ON THE TUNNEL FACE

The transmission of the stresses from the confinement pressure calculations on to the tunnel face takes place according to either the membrane model or the penetration model (Fig. 4). This transmission depends on the ground and the supporting medium properties.

5.1 *Membrane model (Figure 4)*

The main condition which characterises the membrane model is having a sufficiently low permeability in the ground to avoid the bentonite suspension to flow off. However, flowing of the pore water and of the filtration water from the suspension must be possible. The membrane model can be used

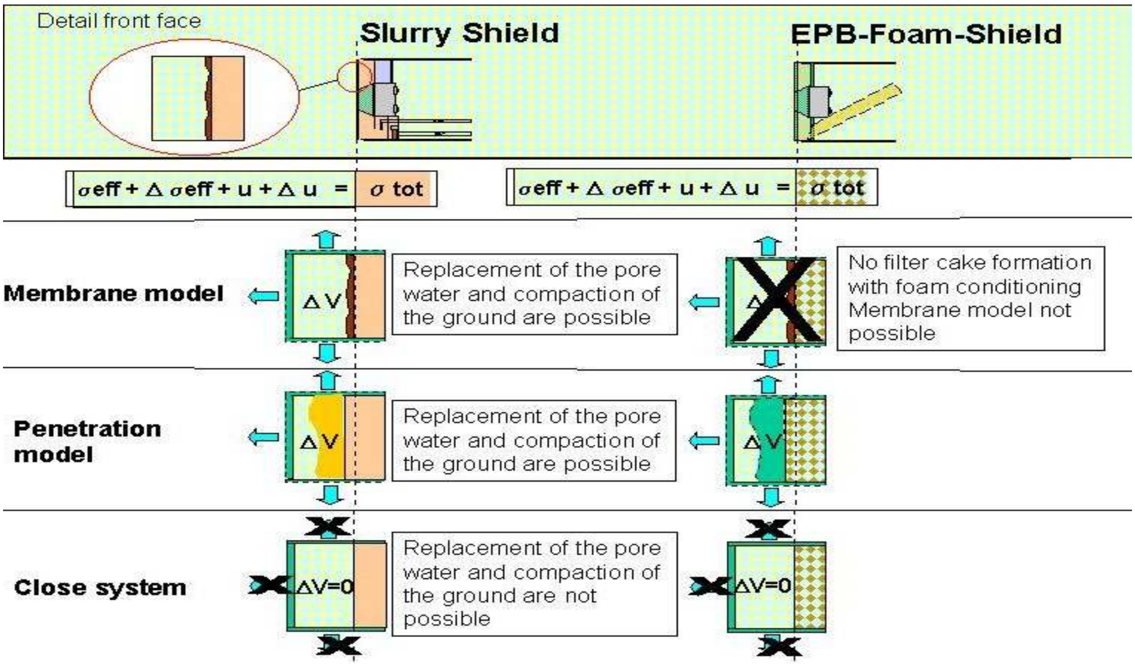

Figure 4. Application ranges for the membrane and the penetration models for EPB and slurry shields

for slurry shields in sands. The model cannot be applied to EPB shields working with foam conditioning. The limited lifetime of the foam as well as the lack of the solid fraction in the foam hinders the formation of a membrane (Maidl 1995).

During the filtration process at the tunnel face, the pore water is pressed out. As shown in Figs. 5 and 6 the filter cake which is created seals the tunnel face in the same way as a membrane.

The transmission of the confinement pressure σ_{tot} takes place in form of total stresses over the filter cake. The small amount of filtration water in the filter cake presses out the pore water. This results in an increase of the pore water pressure Δu. The rise of pore water pressure Δu is confirmed by measurements in front of the tunnel face (Broere 2001). The evolution in time of this pressure increase depends on the surrounding conditions. However it can be assumed that it is a short process in time. The ground immediately consolidates with the membrane being constantly loaded by total stresses σ_{tot}. The pore water is pressed out whereby a stress overlay takes places on the grain structure. If the total stresses σ_{tot} remain constant, this results in a reduction of the excess pore water pressure Δu and an increase of the effective stresses $\Delta\sigma_{eff}$.

Together with the stress increase, this effect results in an instantaneous transmission of the confinement pressure to the ground which directly strongly limits the settlements in front of the shield.

5.2 *Penetration model (Figure 4)*

The use of the penetration model basically presupposes a higher permeability of the ground. This way, the penetration of the bentonite suspension or the foam into the ground is possible (Figs. 4, 5, 6).

For slurry shield tunneling, the application range lies within the gravel-sands as well as within the coarse sands which allow the filtration of the bentonite suspension, hindering thereby the formation of a membrane.

For the EPB shield tunneling with foam conditioning, the application range lies within the sands.

The foam injected in front of the EPB shield penetrates into the pores of the ground (Fig. 9) and reduces the permeability of the ground to the targeted value. The previously open system will be transformed in a

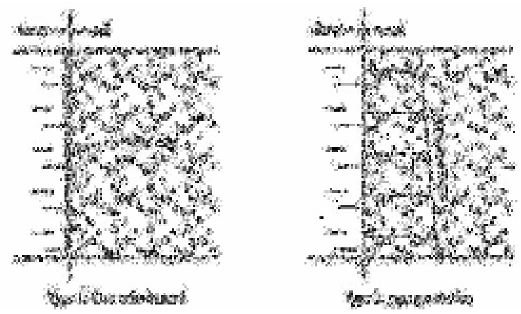

Figure 5. Membrane- / Penetration model, (Müller-Kirchenbauer 1977).

quasi-membrane model in the same way as in the tests perfomed by Maidl (1995). Using slurry shields the penetration of the suspension in the ground and the transmission of the confinement pressure takes place through the transference of the shear stresses on the grain structure.

The penetration depth is determined from the integration of the shear stresses between the supporting medium and the ground until stagnation. This way the required supporting force is transferred uniformly to the granular structure along the penetration depth.

Excess pore water pressures result from the pressing out of the pore water as well as from the penetration of the bentonite suspension or the foam. In slurry shields only small excess pore water pressures appear due to the high permeability of the ground provided the surrounding conditions allow the flowing of the pore water. A large amount of foam can flow when using the EPB method, thereby long-term influence on the pressure-balance of the pore water can be attained.

In addition, a momentary excess pore water pressure is created due to the compaction of the ground (reduction of the porosity) in an amount dV.

5.3 *Application limits (Figure 7)*

In completely closed systems the application limits can be attained, since the pore water cannot flow away due to the surrounding impermeable conditions.

Soils with a low permeability are critical. Equally critical are the sand lenses embedded in the clays. Soft clay layers in the sands also represent a high risk potential (Fig. 6). Due to the low permeability of the surrounding ground layers or of the kind of soil present at the tunnel face, no penetration of the supporting medium (bentonite suspension or foam) into the tunnel face can take place. Therefore, neither the conditions for the formation of a membrane nor for penetration into the granular structure are fulfilled. In these cases, the pore water pressure in front

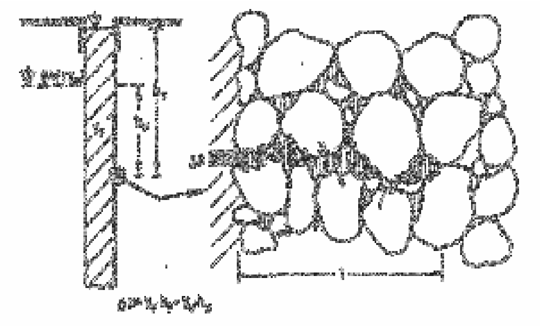

Figure 6. Penetration model, Walz & Steinhoff (1994)

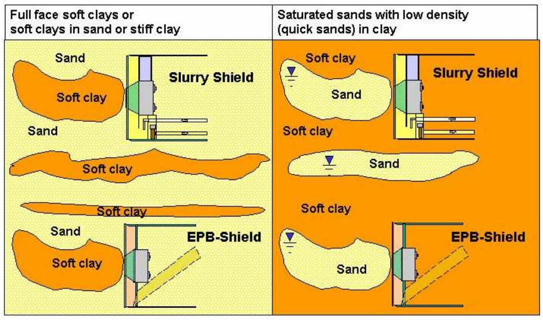

Figure 7. Application limits for EPB and slurry shield tunneling

of the tunnel face rises up to the level of the confinement pressure. Theoretically no increase of the effective stresses $\Delta\sigma_{eff}$ occurs. If the original effective stresses σ_{eff} are low, e.g. in loose packed sands (quick sands), stability is threatened by the risk of liquefaction of the sands due to an increase of the excess pore water pressure Δu. This danger is specially present in slurry shield tunneling because the excavation chamber is filled up with a supporting medium with a lower specific weight which cannot impede the liquefaction of the soil.

In fact, the observation concerning the liquefaction potential has to be seen as theoretical, since in reality only a slight penetration is necessary in order to assure the formation of the membrane or the penetration model and this way effective stresses on the grain structure.

In EPB shield tunneling this situation is more controllable since the excavation chamber is filled up with the spoil. Hence no acute stability problem has to be feared.

6 APPLICATION PROBLEMS

6.1 *EPB in coarse high-permeable soil groups*

The application limit is reached if the permeability of the ground is too high and no penetration zone at the tunnel face can be created as shown in Fig. 9. In coarse gravel but even in coarse sands a sedimentation process in the mining chamber starts, especially when high foam injection ratios (FIR) are used.

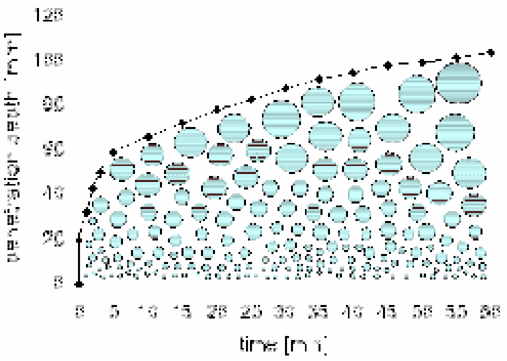

Figure 8: Foam penetration in sand (0-2mm)

High FIR values yield the sedimentation process of the supporting medium, specially during standstills. The specific weight of the supporting medium varies between the top and bottom levels inside the excavation chamber, which is represented in by line 1.

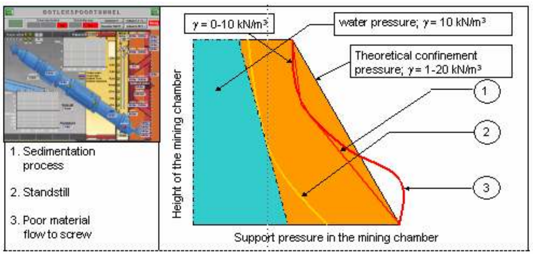

Fig. 9: Sedimentation process in the mining chamber

In the crown area the gradient is very steep, the ground specific weight is below the most loosen packing grade of the sands. Thus, the confinement pressure in the crown is only transmitted through the foam (air pore pressure).

The clearly higher specific weight in the lower part of the excavation chamber yields a flatter confinement pressure distribution. The pressure is mainly transmitted by means of the grain to grain forces (effective stresses).

In longer standstills, due to its limited lifetime the foam flowed out from the excavation chamber and the confinement pressure sank down partially to the hydrostatic water pressure distribution, as illustrated in line 2.

By means of the foam conditioning in front of the rotating cutter head and in the excavation chamber, it was possible to rise the confinement pressure during the standstills, see line 1. However, it proved very difficult to influence the unfavorable specific weight distribution caused by sedimentation process.

Further on, when re-starting the advance, a great part of the confinement pressure in the invert area was transmitted by effective stresses, see line 3. This affects negatively.

The consequences are poor material flow, obstructions in the lower half of the chamber. In turn this results in procedural difficulties such as a higher cutter-head torque, higher propulsion thrust and made it more difficult to govern the shield.

6.2 *Slurry shield in sticky clays*

In highly adhesive clays stickiness causes difficulties using slurry shields.

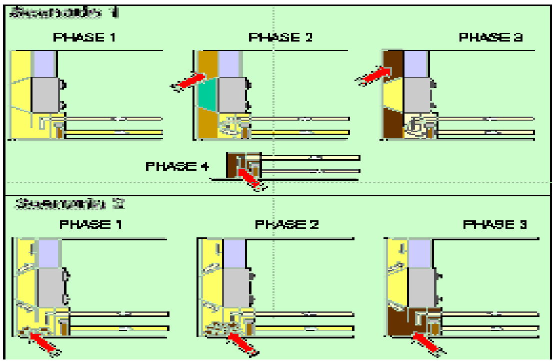

Figure 10: Schematic diagram of the two stickiness problem scenarios.

Fig. 10 shows two critical scenarios. Definition of critical working conditions: In scenario 1 (Fig. 10), the speed of the TBM above a critical limit results in a build-up of soil in the mud pressure chamber (phase 2). The bentonite supply in the suction area only circulates within the chamber, instead of transporting the material. If the speed increases to phase 3, the soil in the mud pressure chamber thickens. In the worst case (phase 4), the whole suction area will be blocked. It is then necessary to clean the machine under high air-pressure before it can be used again.

In the Westerschelde project, cleaning is only possible by divers entering the mud chamber which is very good reason for wanting to make such cleaning an exception.

In the scenario 2, delay is caused by an increase of density. Suspension flow near the bulkhead is too small [2] and the large clay blocks require mechanical devices to move them in front of the cutter hole. A shortened holding time in the mud pressure chamber decreases the softening of the clay.

This increase in clutching of the clay can lead to a complete blockage of the suction area in phase 3.

So when considering actual operation, it is not only cohesion and adhesion that are important, but the fluid mechanical characteristics in the mud pressure chamber.

The speed of the bore fluid leaving the slurry pipe is about 1.5m/s to 3.7m/s. The speed of the bentonite-suspension near the dividing wall openings depends solely on the conditions in the mud pressure chamber.

But even with a 100% supply from the diving wall, this gives only a maximum velocity of 0.14m/s near the suction area. The drag forces that can be executed on large clay lumps are too little to guarantee transport of material without delay. Agitators are placed to assure a good suction flow.

Formatiert: Nummerierung und Aufzählungszeichen

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