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The influence of soil permeability on the properties of a foam mixture in a TBM

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ABSTRACT: The penetration velocity of foam into the soil at the front face of an EPB TBM is investigated. It is shown that groundwater flow determines this penetration velocity in saturated conditions and soil permeabilities of around 10^{-4} m/s or less. An approximate method to calculate the excess pore pressure and hydraulic gradient in the soil in front of the tunnel is presented. The results of this method are compared with field measurements. It appears that the difference between a slurry shield and an EPB shield is only small. It is further shown that the groundwater flow can also have a dominating influence on the moisture content in the muck. This can mean that only a limited reduction of permeability in the mixing chamber is possible. Furthermore the calculations show that in some cases only a limited pressure drop will be present over the front face, which has consequences for the way the stability of the front face is calculated.

1 INTRODUCTION

Foam is often used in an EPB (Earth Pressure Balanced) TBM (Tunnel Boring Machine) to improve soil conditions for boring of a tunnel, especially in granular material. The foam increases the porosity between the grains, reduces the permeability and increases compressibility. The amount of foam to be added is based on experience or trial and error when no experience is available. The mixture can be "too wet" or "too dry" in the eyes of the experts.

Field measurements (Joustra, 2002) and model experiments (Bezuijen 2000) have shown that "too wet" or "too dry" in a saturated sand does not only depend on the foam properties, the foam injection ratio (FIR) and foam expansion ratio (FER), but also depends on the interaction between foam and groundwater. In permeable sand the excess pressure in the foam with respect to the pore water will cause a groundwater flow from the tunnel face. As a result the foam will replace the pore water and the mixture in the mixing chamber will be relatively dry. In less permeable conditions the foam will not be able to replace the pore water and the mixture will be wet and much less foam will be needed to increase the porosity of the sand compared to permeable conditions.

The paper deals with the interaction between foam, grains and groundwater in granular material. Some functions of the foam when drilling granular material will be dealt with briefly. The paper concentrates on the interaction with ground water flow. The flow equation is derived for a simplified situation. This equation is used to estimate the flow velocity in front of the tunnel face and the penetration of foam in the soil. Consequences are discussed.

2 THEORY

2.1 *Functions of foam*

The main functions of foam were already mentioned in the introduction:

- Increasing the porosity between the grains. Measurements showed that the porosity is increased to values higher than the maximum porosity (Joustra, 2002). This leads to negligible grain stresses between the grains and reduces the torque necessary to turn around the rotor through the sand-water-foam mixture.
- Reduction of the permeability. A large permeability can lead to a water flow in the soil-water-foam mixture resulting in differences in porosity over the mixing chamber with the possibility of liquefaction
- Increasing of the compressibility. During boring with a TBM the front face pressure has to be more or less constant, to avoid instability in the soil. This is controlled by controlling the soil removal through the screw conveyer in a EPB shield. A compressible mixture in the mixing chamber will allow for difference in soil removal without large fluctuations in the pressure.

A consequence of the first function is that the excess pressure in the mixing chamber is a pore pressure. This will cause a groundwater flow from the tunnel face into the soil. The permeability of the mixture and or the flow properties of the subsoil determine the amount of water that flows into the tunnel face.

2.2 *Groundwater flow*

Permeability of the mixture

Only the air content determines the relative permeability of the mixture, compared to the permeability of the same mixture but without air. The properties of the foam have no influence and therefore theory for unsaturated flow can be used (Zhou & Rossen, 1995). However, for relatively high water contents in medium coarse sand an even simpler approach is possible. Experiments showed (Kleinjan & Hannink, 1997) that for relatively high water contents the permeability of a sand-water-foam mixture can be estimated assuming that the foam leads to bubbles with diameters of the same order as the mean diameter of the sand. Measurements were fitted with the Blake-Kozeny equation:

$$k = \frac{\rho g D_p^2}{150\mu} \frac{n^3}{(1-n)^2} \quad (1)$$

Where k is the permeability, ρ the density of the water, g the acceleration of gravity, μ the dynamic viscosity, D_p the mean grain size (approx. D_{15}) and n the porosity.

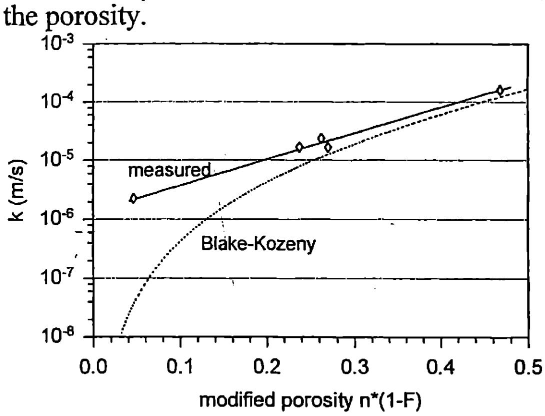

Figure 1. Permeabilities measured in a foam mixture compared with the Blake-Kozeny equation assuming that the foam only reduces the porosity. Figure modified from Kleinjan & Hannink (1999). F is the volume of air

Figure 1 shows that there is reasonable agreement between the measurements and the calculated values of the permeability for 'porosities' higher than 0.24. Porosities is between quotes because to perform the calculation it is assumed that foam is stable between the grains and that the porosity is not the usual porosity of the grains only but the porosity of the sand-foam mixture (thus the foam decreases the porosity of that mixture). Agreement is less at low porosities, because such low porosities can only be reached which a lot of foam. The foam bubbles will deviate from the sphere and Equation (1) is not valid for such low porosities. Results as presented in Figure 1 can be used to calculate the amount of replacement of the pore water by the foam necessary to have a real reduction of the permeability at the front face. A reasonable porosity increase of the sand grains themselves during drilling is from 0.4 to 0.55. This increase will lead to a decrease of the modified porosity (of grains and bubbles). The amount of this decrease depends on the amount of pore water that is replaced by the foam. The values found, using the volume balance, are shown in Table 1.

Table 1: Calculated permeabilities of a foam mixture where the porosity of the sand is increased from 0.4 to 0.55 by drilling and foam injection using foam with a FER of 10.

perc. replacement (-)	modified porosity (-)	permeability fitted (m/s)	permeability theory (m/s)
0	0.3	$2.9\ 10^{-5}$	$1.7\ 10^{-5}$
10	0.27	$2.1\ 10^{-5}$	$1.1\ 10^{-5}$
20	0.24	$1.6\ 10^{-5}$	$7.2\ 10^{-6}$
50	0.15	$6.2\ 10^{-6}$	$1.4.\ 10^{-6}$
90	0.03	$1.8\ 10^{-6}$	$8.6\ 10^{-9}$

The results show that according to the measurements the sand water foam mixture will always have a certain permeability. A significant reduction of the permeability is only possible when a significant part of the pore water is replaced by foam.

Flow in front of the tunnel

The groundwater flow in front of a TBM will be determined by the soil layering, the depth of the tunnel and the properties of the mixture in the mixing chamber. For a particular situation this 3-dimensional flow problem can be solved in detail only numerically. To get an idea about the flow properties some approximations were used. A tunnel is located in a homogeneous granular soil deep below the soil surface. The flow from the mixing chamber into the soil is evenly distributed over the front face. Furthermore quasi-static conditions are assumed.

With these assumptions the flow problem can be schemed as shown in Figure 2.

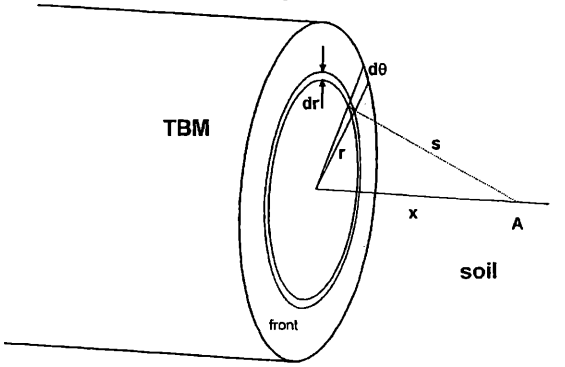

Figure 2. Sketch of tunnel face for flow computation.

Starting point of the calculation is the increase in piezometric head caused by a point source on the surface of a half space. A half space because only the flow in the soil in front of the tunnel face is taken into account.

The distribution of the piezometric head for such a situation can be written as:

$$\phi = \frac{Q}{2\pi ks} \tag{2}$$

With, ϕ the increase in piezometric head, Q the discharge of the point source, k the permeability of soil in the half space and s the distance between the point source and the point where the piezometric head is measured. For an uniformly distributed load as at the tunnel face the increase in piezometric head for one small area as indicated in Figure 2 can be written as:

$$d\phi = \frac{qrdrd\theta}{2\pi ks} \tag{3}$$

with q the specific discharge. For a point A in front of the tunnel on the axis of the tunnel, all points on the circle indicated in Figure 2, will have the same contribution to the piezometric head.

Integration over the circumference of the circle leads to:

$$d\phi = \frac{qrdr}{ks} \tag{4}$$

Integration over all circles from r=0 to r=R and using: $s = \sqrt{x^2 + r^2}$ leads to:

$$\phi = \frac{q}{k}(\sqrt{x^2 + R^2} - x) \tag{5}$$

If the discharge is not known, but the piezometric head is known at the surface of the half space where the tunnel is located, the tunnel face, the equation can be written as:

$$\phi = \phi_0(\sqrt{1 + (x/R)^2} - x/R) \tag{6}$$

With ϕ_0 the piezometric head in the sand just in front of the tunnel face.

In this situation the piezometric head in the soil in front of the tunnel is only a function of the distance from the tunnel and the piezometric head just in front of the tunnel face, but does not depend on the permeability of the soil.

Rewriting Equation (5) to Equation (6) can be done because it was assumed beforehand that there was a uniform flow at the tunnel face. This assumption is not true in case of a constant piezometric head, but is used here as an approximation. Numerical calculations and measurements for a slurry shield have shown that it is a reasonable approximation (Bezuijen et al, 2001). Using numerical calculations It was shown that the approximation is reasonable for the priezometric head along the tunnel axis for C/D values of 1 or larger, where C is the cover of the tunnel and D the diameter.

The amount of penetration of the foam or slurry in front of the tunnel depends on the flow velocity at the tunnel face. Foam can only penetrate when the pore water is removed. The gradient in the pore water can be calculated from Equation (6). Differentiation results in the gradient at the tunnel face for a given excess pore pressure. At the tunnel face (x=0) this leads to the equation:

$$i = \phi_0 / R \tag{7}$$

with i the hydraulic gradient. The pore water velocity (v_p) in front of the tunnel can be written as:

$$v_p = \frac{ki}{n} = \frac{k\phi_0}{nR} \tag{8}$$

where k is the permeability of the sand and n the porosity.

This last equation also gives the velocity, which with foam can penetrate in front of the tunnel during drilling. If this velocity is larger than the drilling velocity, all pore water will be replaced by foam and the muck will be relatively dry. However, if this velocity is smaller than the drilling velocity there will always remain pore water in the soil that is excavated from the tunnel face and the foam will be relatively wet. Another consequence is that less foam is necessary, because some of the pore water is not replaced by foam.

Another way to describe the flow in front of a tunnel face was presented by Hoefsloot (2001) and Broere (2001). They used equations for unsteady flow in a semi-confined aquifer to calculate the pore pressure distribution. This is not followed here because not all soil layer distributions can be schemed to a semi-confined aquifer and the difference between both methods is limited close to the tunnel face, which is the situation most of interest for this paper. It is assumed here that it is more important to incorporate the 3-dimensional flow than the nonstationary flow, although this assumption has to be proved by further measurements. However, it should be taken into account that the gradient can be less than calculated here in case a tunnel is located in a thin semi-confined aquifer with a long leakage length.

3 MEASUREMENTS

Although only an approximation, the formula derived in this paper fitted quite well with measurements performed in front of a TBM at the 2nd Heinenoord Tunnel, see Figure 3, where a slurry shield was used. It also fitted well with one of measurement locations during drilling of the Botlek Rail

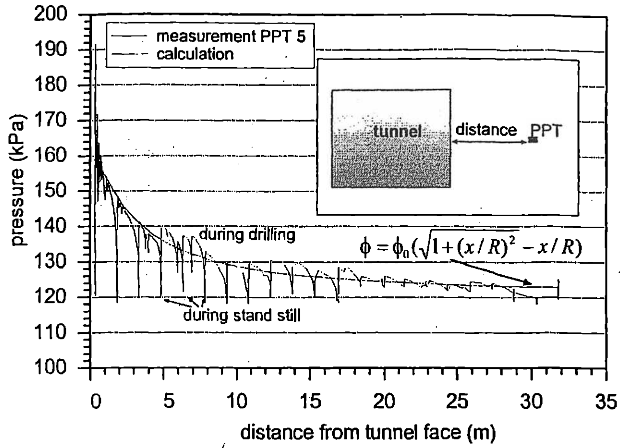

Figure 3: Measured excess pore pressure in front of a slurry shield and approximation (2nd Heinenoord Tunnel).

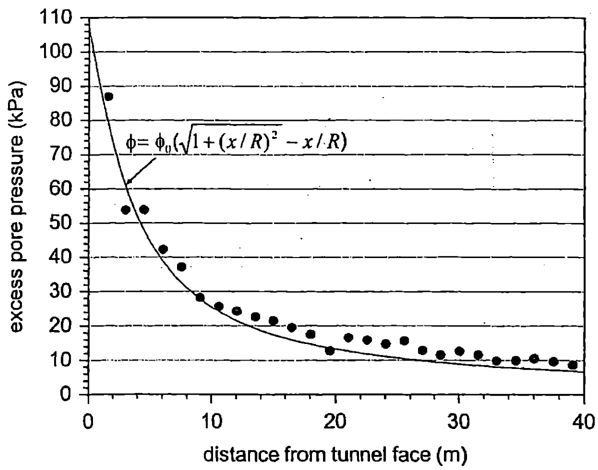

Figure 4: Measured excess pore pressure in front of an EPB shield (•) and approximation (Botlek Rail Tunnel, MQ1 South). Relatively impermeable subsoil (measurement data from Hoefsloot, 2001).

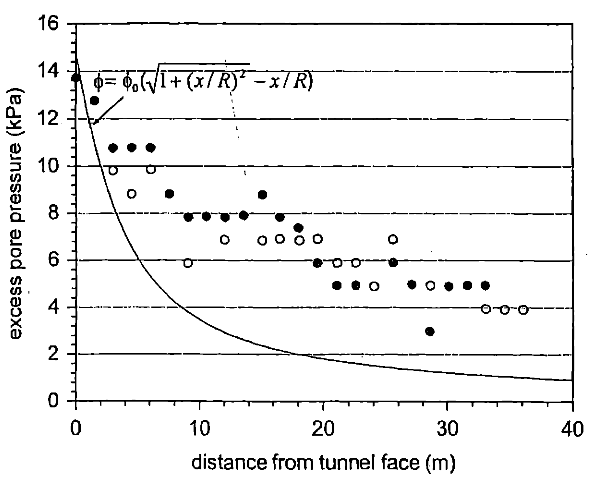

Figure 5: Measured excess pore pressure in front of an EPB shield (• pore pressure gauge 1, ○ pore pressure gauge 2)and approximation (Botlek Rail Tunnel, MQ4 South). Relatively permeable subsoil (measurement data from Hoefsloot, 2001).

Tunnel where an EPB shield was used, see Figure 4. At another location on the Botlek Rail Tunnel track, the calculated pressures further from the front face were too low, Figure 5. Here a semi-confined aquifer was present with a leakage length, estimated by Hoefsloot (2001), of 707 m and this influences the results.

Only point measurements of maximum excess pore pressure are presented for the Botlek Rail tunnel because the measured excess pore water pressure has to be corrected for the tide.

The figures for the Botlek used the data as presented by Hoefsloot (2001). It should be noted that the excess pressures are rather low in Figure 5. It is also possible that a small error in the determination of the tidal pressures causes the deviation.

4 CONSEQUENCES

4.1 *Wet and dry foam*

Starting with the pressure in the mixing chamber there can be a pressure drop at the tunnel face due to cake forming when a slurry shield is used or by penetration of foam in case of a EPB shield. Bezuijen (2001) elaborates the penetration of bentonite in case of a slurry shield. Here it is concentrated on a EPB shield. The maximum gradient in the soil in front of the tunnel face occurs when ϕ_0 is equal to the average pressure in the mixing chamber. For such a situation the pore water velocity is given with Equation (8) with ϕ_0 equal to the pressure in the working chamber. This equation predicts at what velocity the pore water is expelled, but it also presents the velocity that the foam can penetrate into the soil in front of the tunnel face. If the drilling velocity is higher than the penetration velocity of the foam, then pore water will partly remain in the excavated soil. If the drilling velocity is lower, then the foam will replace the pore water, or the foam is stopped by the granular material causing a pressure drop over the tunnel face.

One of the functions of foam is to increase the porosity between the grains, which enables the grains to move with respect to each other. Due to the possibility to expel pore water the increase of porosity is not only determined by the FIR (Foam Injection Ratio, defined as the volume of foam divided by the in situ volume of foam on which that foam volume is injected). It also depends on the drilling speed, the radius of the tunnel, the permeability of the soil and the excess pressure in the mixing chamber. Using the definitions for the porosity and the FIR and equation (3) and assuming homogeneous conditions, thus no segregation of the soil-water-foam mixture, it can be derived:

$$n_m = \frac{n - \frac{k\phi_0}{Rv_d} + FIR}{1 - \frac{k\phi_0}{Rv_d} + FIR} \quad (9)$$

Where n_m is the porosity of the grains in the mixing chamber and n the in situ porosity in the soil. In the derivation it is assumed that $n - k\phi_0 /(Rv_d) > 0$.

It is clear that for a constant ϕ_0 and FIR n_m can change as drilling velocity or permeability of the soil change. To keep the porosity constant it is necessary to increase the FIR when the drilling speed is decreased or a sand layer with a higher permeability is encountered.

Pore water that is not replaced by foam during the drilling will remain in the mixture and will result in a 'wetter' foam in the muck than originally injected. The amount of water in the foam is defined with the FER (Foam Expansion Ratio, defined as the total foam volume divided by the water volume in the foam). Again using Equation (8) and the definitions of the FER, the porosity and the FIR it is possible to calculate the FER in a muck (FER_s, with 'foam water' and the remaining pore water):

$$FER_s = \frac{FER}{1 + \frac{FER}{FIR}(n - \frac{k\phi_0}{Rv_b})} \quad (10)$$

Where the FER is the Foam Expansion Ratio of the injected foam.

In the case of a low permeability soil and a relatively high FER of the original foam it is possible that the resulting FER_s is completely independent for the original FER. For $k\phi_0/(nRv_b) << 1$ and $n.FER/FIR >> 1$ the equation reduces to:

$$FER_S = \frac{FIR}{n} \quad (11)$$

For this situation 'dryer foam' will not help if the resulting muck looks 'too wet'. It is only possible to increase the FIR (but this will also increase the porosity in the muck and reduce the friction in the screw conveyer) or to reduce drilling speed to replace more pore water in front of the tunnel face. As mentioned in Section 2.2 such 'wet' muck will also have a relatively large permeability and therefore it can be unstable.

4.2 *Pressure drop at the tunnel face*

The name of the drilling method (earth pressure balance shield) suggests that the shield controls the earth pressure. This earth pressure is not a very well defined term in soil mechanics. Soil mechanics defines total stresses, pore water pressures and effective stresses. Earth pressures most likely corresponds with the total stresses. However, as was mentioned before, using foam will result in a porosity in the mixing chamber that is higher than the maximum porosity and thus the effective stress in the mixing chamber will be zero. This means that a change in pressure in the mixing chamber will be a change of pore pressure. During the drilling through fine sand at the measurement location MQ 1, of which Figure 4 shows results, the pore pressure present in the mixing chamber is equal to the pore pressure in the soil just in front of the tunnel. For that situation the stability of the tunnel face is not determined by controlling the total pressure but by controlling only the pore pressure in the soil. In such a situation the stability of the front face with respect to the minimum allowable pressure has to be calculated taking into account the influence of the excess pore pressure and using methods as described by Broere (2001) and Bezuijen et al (2001). The situation is very much comparable to a slurry shield. With respect to the stability of the soil at the tunnel face there is no difference. As mentioned in Bezuijen et al (2001) during drilling with a slurry shield in fine sand, it was also found that there was hardly a pressure drop over the front face of the tunnel during drilling and that plastering only occurred during stand still.

In the coarse sand that was encountered in measurement location MQ 4 an excess pore pressure in the mixing chamber of approx. 60 kPa was applied (Joustra, 2002). It appears from Figure 5 that in this case only 1.5 m water corresponding with an excess pore water pressure of approximately 15 kPa was found in the soil in front of the tunnel, which means that in this case there is a considerable pressure drop at the tunnel face.

The reason for the difference in behaviour for these 2 locations is the difference in permeability and due to that the difference in penetration velocity of the foam, see Table 2.

Table 2: Parameters for the 2 measurement locations.

Parameter	MQ 1	MQ 4
permeability (m/s)	5.8 10^{-6}	3.0 10^{-4}
porosity soil (-)	0.4	0.38
excess pressure front (kPa)	180	60
v_p, Equation (8) (m/s)	3.3 10^{-5}	9.9 10^{-4}
drilling velocity (m/s)	7.5 10^{-4}	6.6 10^{-4}
perc. penetration in front (%)	4.4	100

In MQ 1 the groundwater flow limited the penetration of the foam into the soil. In MQ 4 this is much less the case.

Maidl (1995) and Quebaud et al (1998) have reported experiments where foam penetrated into sand using a high pressure gradient over the foam and sand. In these experiments the foam penetrated fast for 30 to 60 mm (depending on the type of sand), but the penetration slowed down afterwards. This means that some penetration in the sand is necessary before a pressure drop can be maintained over the foam.

Due to the limited penetration such a pressure drop was not possible at location MQ 1. In MQ 4 the penetration velocity of the foam was just a bit higher than the drilling velocity and therefore it was possible to maintain a pressure drop over the front face.

5 MUCK SAMPLES

An additional way to validate the theory developed would be to extract muck samples from the mixing chamber in a tunnel project. This was done for the Botlek Rail tunnel. Results were summarised by Joustra (2002) and Rodenhuis (2002). However, it appeared from their results that reality is more complex than theory. In a real tunnelling situation the drilling speed is not constant, the excess pressure varies, the FIR varies, the mixture is not homogeneous over the mixing chamber and sometimes air escaped during tunnelling. Therefore it is not possible to make a general comparison between measurements and calculations. No samples were taken for MQ1. Samples taken for MQ4 (10 samples for 2 tubes) showed an average density of 1600 kg/m^3, larger than would be expected if all pore water was expelled by the foam (1410 kg/m^3 for foam with an expansion ratio of 10). However, Joustra (2002) also showed that the mixing chamber was not filled homogeneously. From pressure measurements in the mixing chamber it is reasonable to assume that air was concentrated in the top of that chamber. Since this air has to come from the mixture the density of the samples taken at the height of the axis of the TBM will have a higher density. It was reported that at another location a sample taken at the axis of the TBM contained only air.

These results showed that a homogeneously filled mixing chamber is not always a present during drilling. Further research would be necessary to determine for what conditions a homogeneous muck could be expected.

6 CONCLUSIONS

The research presented here led to the following conclusions:

1. Excess pore pressures, as measured in front of an EPB shield tunnel, can be described in the same way as for a slurry shield.
2. The penetration of foam into the soil in front of the TBM is, in case of soils with a low permeability, determined by the groundwater flow and not by the properties of the foam.
3. Due to the limited penetration of the foam in soils with a low permeability, there will be hardly a pressure drop at the tunnel face and the pressure in the working chamber will result in a comparable pore pressure in the soil just in front of the tunnel. Due to this the effective stress just in front of the tunnel will be small in such cases. This should be taken into account in calculations for the stability of the front face.
3. In case of a limited penetration of foam the possibilities to influence the properties of the mixture, as the permeability, are restricted. The water content of the mixture is to a large extent determined by the pore water present in the sample and much less by the foam properties.

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