Foam used during EPB tunnelling in saturated sand, parameters determining foam consumption

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ABSTRACT

The amount of foam injected during drilling with an EPB-shield in saturated sand is quite often based on experience and/or empiric relations. A method is presented in to calculate the amount of foam needed to create a muck with limited or no grain stress. The results show that, as expected, the volume of the foam to be injected is much larger in dry soil compared to saturated soil. In saturated soil the amount of foam to be injected depends on various parameters. The permeability of the soil in front of the EPB-shield appears very important. This paper describes the dependencies and shows that recommended foam injection ratio's from literature may be too small when used in permeable sandy soil. The FIR of the foam in a mixture may be much smaller than of the original foam.

1. INTRODUCTION

Earth-Pressure-Balance (EPB) shields are the most common type of tunnel boring machine in soft ground. The mechanisms have been described that are of importance when using foam in an EPB shield when drilling in saturated sand (Bezuijen, 2002 and Bezuijen, 2011). This description is based on model tests (Bezuijen and Schaminée, 2001) and field measurements (Bezuijen et al. 2005). This paper uses the mechanisms described in the earlier papers to derive quantitatively what foam consumption can be expected, based on these mechanisms. It will be shown that the water permeability of the soil in front of the tunnel face has a significant influence on the foam consumption and that the water content of the muck is only partly determined by the water content in the foam. Results will be compared with more empirical relations as presented by Budach and Thewes (2011).

Since this is the first attempt to describe foam consumption based on mechanisms instead of using empiric relations, it is likely that the empiric relations are still more suitable for the use in practice. The relations presented in this paper are derived to show how the various mechanisms influence the foam consumption. It will be necessary to tune these results with experiences from practice. However, it will be shown that the results obtained from the calculations presented here are quite comparable to the results recommended by EFNARC (2005).

The calculation method is based on the volume of muck obtained depending on permeability of the soil, necessary porosity increase, tunnel diameter and foam injected. It does take into account the Foam Expansion Ratio of the sand-water-air mixture but not the mechanical properties of that mixture. The assumption, based on measurements (Bezuijen et al. 2005), is that a porosity larger than the maximum porosity will create a situation with hardly any grain stress in the muck and this situation has to be achieved to create 'smooth drilling' without large pressure fluctuation. Significant grain stresses in the muck will lead to strong fluctuations in total stresses in the mixing chamber and a high torque.

2. Definitions

In this paper the following definitions are used:
FER: foam expansion ratio, the ratio between the total amount of foam (by volume Q_F) and the amount of surfactant solution (Q_L) (water and surfactant).
FIR: foam injection ratio, the volume of foam (Q_F) divided by the volume of soil removed (Q_S). Q_S can be calculated from the advance rate (v) and the face area (A_s): $Q_S = v.\ A_s$.

3. Foam injection

When foam is injected in front of an EPB, this will result in an increase of the porosity of the soil. Assume before excavating the soil has a porosity n_s and after excavation in the mixing chamber the porosity will be n_m (the porosity of the solid-foam mixture, or the muck). Without any flow, the relation between the FIR and the porosity is for saturated conditions can be derived from the volume balance:

$$\frac{\Delta V}{V_s} = \frac{n_m - n_s}{1 - n_m} \tag{1}$$

Where ΔV is the volume increase due to the foam and V_s is the soil volume and for dry conditions (where the pores also have to be filled with foam):

$$\frac{\Delta V}{V_s} = \frac{n_m (1 - n_s)}{1 - n_m} \tag{2}$$

In saturated conditions, the excess pore pressure at the tunnel face will lead to a water flow. This means that the original pore water will not remain in the soil, but is (partly) expelled. In the time volume V_s is excavated, the rate with which the water is expelled, is calculated in Bezuijen (2002), where it was found for a TBM tunnelling in homogeneous saturated sand the water flow can be approximated by:

$$q = \frac{k \Delta \phi}{R} \tag{3}$$

Where q is the specific discharge, k the permeability of the soil, $\Delta\phi$ the difference in piezomertric head between the tunnel face and a position far from the tunnel and R the radius of the tunnel. This equation is valid for the situation that the flow resistance is determined by the flow in the soil in front of the tunnel. In case of very dry foam in the mixing chamber, it is possible that the flow from the mixing chamber to the soil body in front of the tunnel determines the flow resistance. In that case the compressibility of the air-water-soil mixture has to be taken into account. It will be shown that in most cases this mixture does not consist of very dry foam and therefore Eq. (3) can be used.

Measurements at the Botlek Rail Tunnel during construction have shown that the porosity of the muck in the mixing chamber is just a bit higher than the maximum porosity of the sand. See Figure 1. All samples have a sand fraction (=1-n_s) that is smaller than 55% the value that corresponds with the maximum porosity of 45%.

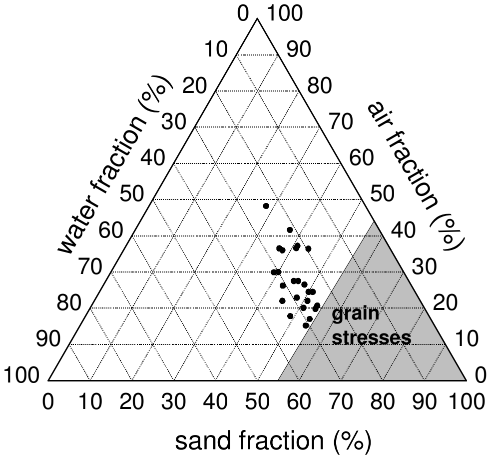

Figure 1. Measured sand, water and air fractions

Equation (3) implies that to create a certain porosity in the mixing chamber (and a minimum porosity is needed to limit grain stresses in the mixing chamber), the *FIR* also depends on the drilling speed, the diameter of the tunnel and the permeability of the soil.
During drilling, the amount of soil that is excavated by the tunnel divided by the area of the tunnel face each second is v_d (the drilling velocity of the tunnel). This soil has a porosity n_s. After excavation this volume is increased by the *FIR* and decreased by the flow from the injection chamber as given in Eq.(3) thus the volume increases from v_d to $v_d + v_d.FIR - q$.
Since the volume of solids remains the same it can be written:

$$\frac{v_d + v_d.FIR - q}{v_d} = \frac{1-n_s}{1-n_m} \tag{4}$$

Rearranging and filling in Eq. (3), Eq. (4) can be written as:

$$FIR = \frac{k\Delta\phi}{v_d\, R} - 1 + \frac{1-n_s}{1-n_m} \tag{5}$$

Eq. (5) is valid for the situation that the amount of water expelled from the soil according to Eq. (3) is smaller than the original amount of pore water. If this is not the case Eq. (2) applies. The *FIR* calculated in this way is the minimum *FIR* to create a sufficient increase in porosity to avoid grain stresses in the mixing chamber. This minimum in FIR depends thus on the porosity of the sand, but also on the permeability of the sand, the face pressure, the drilling speed and the radius of the tunnel.

Example calculations where made using the parameters presented in Table 1. Calculations were made for different values of the permeability *k* and the increase in porosity. Results are presented in Figure 2.

Table 1. Parameters used in calculation.

Parameter	
drilling speed	7e-4 m/s
diameter	10 m
diff. piezom. Head	3 m

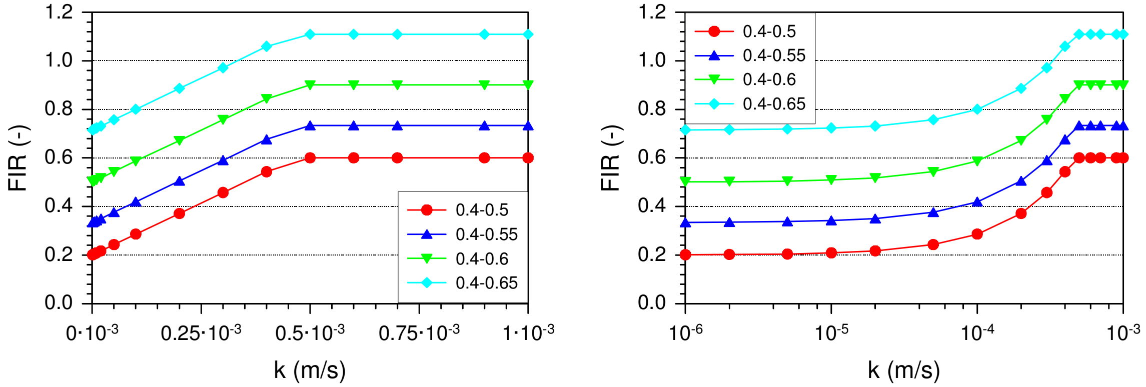

Figure 2. Results of calculations with Eq. (5) for different values of *k* plotted on a linear and logarithmic scale. The different lines present different values for the porosity of the muck (n_m). The porosity of the soil (n_s) =0.4.

The results presented on a linear x-axis show that the minimum necessary *FIR* increases linear with the permeability. The logarithmic scale shows that there is only a limited range of soil permeabilities where Eq. (5) is of importance. In this case the permeabilities from roughly 5.10^{-5} m/s until 5.10^{-3} m/s. However, it should be noted that a lot of sands have a permeability in this range.

The important parameter is the dimensionless parameter $\frac{k\Delta\phi}{v_d R}$. When this parameter is larger than 0.05 the influence of groundwater flow has to be taken into account to calculate the FIR.

Tunnelling in dry conditions will also lead to a water flow from the mixing chamber to the surrounding soil. However, this flow is difficult to determine, because the permeability is a function of the saturation in partly saturated conditions. Since the focus of this paper is on saturated conditions, this will not be dealt with any further.

4. INFLUENCE ON FER

The pore water that enters the mixing chamber during drilling has an influence on the *FER* of the foam in the mixture. Normally a 'dry' foam, with a *FER* of 10 or more, is used when drilling in sand. Due to the pore water intake the effective *FER* of the foam in the mixture (which is defined as FER_m in this paper) reduces. To calculate the FER_m of the mixture, a unit volume of soil is assumed that is excavated with the drilling velocity v_d, see Figure 3.

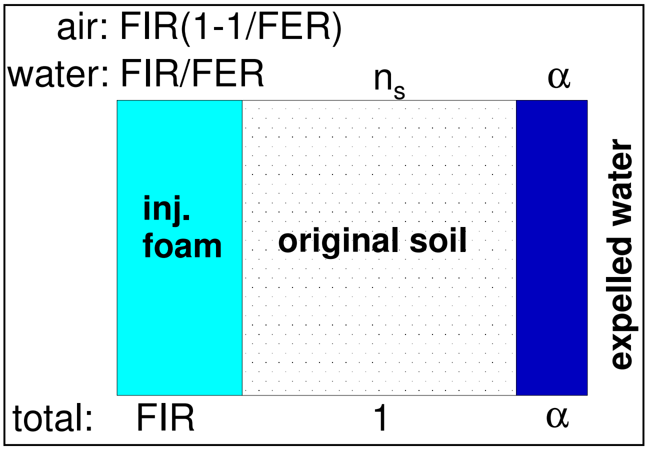

Figure 3. Definition sketch to calculate FER_m

This unit volume has originally a total volume of 1 and a water volume of n_s. During excavation foam is injected with, by definition, has a total volume of *FIR* and a water volume of *FIR*/*FER* and an air volume of *FIR*.(1-1/*FER*). Water will be expelled due to the excess pore water pressure in the mixing chamber, as was described in Section 2. This amount of water is α ($=\frac{k\Delta\phi}{v_d\, R}$, see Section 2). FER_m is the total foam volume in the mixture (air + water) divided by the total water volume. According to Figure 3 this is:

$$FER_m = \frac{n-\alpha+FIR}{n-\alpha+FIR/FER} \qquad (6)$$

This formula is a bit different from the formula given by Bezuijen (2002). It appeared that in the 2002 formula the volume of air was divided by the volume of water and according to the definition of the *FER* this should be the total foam volume (air + water). Using again the parameters from Table 1 and the FIR as calculated in Figure 2, the effective FER_m of the mixture can be calculated using a *FER* of 20 for the original foam mixture. The result is shown in Figure 4.

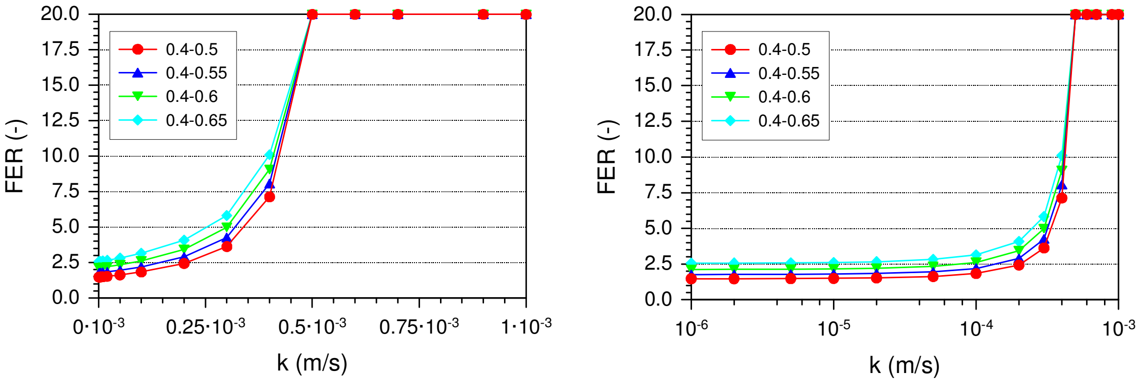

Figure 4. Results of calculations for *FER* with Eq. (6) plotted on a linear and logarithmic scale, the *FIR* as calculated for Figure 2 is taken as input. The different lines present different values for the porosity of the muck (n_m). The porosity of the soil (n_s) =0.4.

The results show clearly that for low sand permeabilities the FER_m is much less than the original *FER*. The FER_m can be 10 times lower. This will certainly influence the behaviour of the muck. Furthermore, it should be realised that more pore water is expelled during ring building. In the first part of the drilling after ring building the foam will become wetter, resulting in different mechanical properties of the muck. Normally the maximum possible pressure drop over the screw conveyer becomes less when the muck becomes wetter.

In the situation of dry foam and only limited water flow, the resulting FER_m appears to be independent from the original *FER* and only determined by the *FIR*.

5. Height of tunnel face

Up to now the calculations did not take into account the height of the tunnel face. In a TBM the pressure on the muck will not be constant. Measurements in the pressure chamber have shown that the pressure distribution is not linear, see for examples Figure 5 en Figure 6.
Pressures do increase with depth in this example until 2.2 m from the tunnel axis. At the very bottom of the mixing chamber the pressure is lower due to the excavation of the screw conveyer.

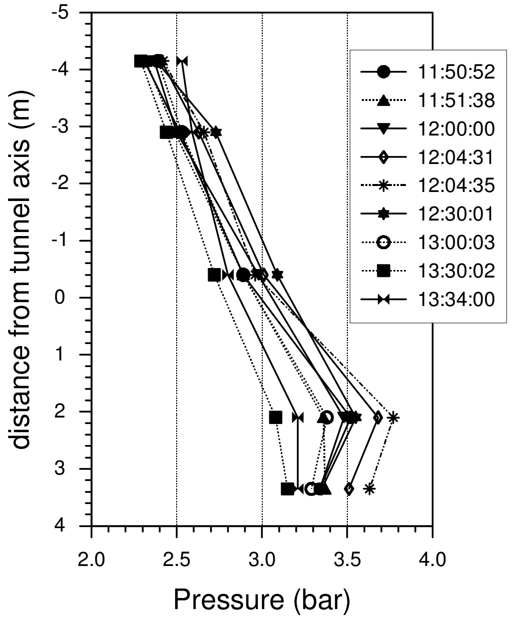

Figure 5. Ring 318 N, Botlek Rail Tunnel. Pressure distributions along the gauges E1 until E5 for various times. Up to 12:30:01 the TBM is drilling, later times represent pressures during ring building. (Bezuijen et al. 2005).

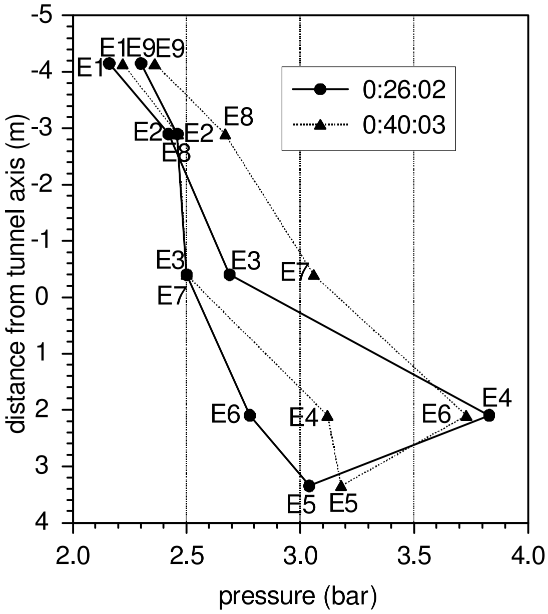

Figure 6: Ring 813 S, Botlek Rail Tunnel. Distribution of pressures when the cutter head is rotating to the left (negative values) at 0:26:02 and to the right at 0:40:03. (Bezuijen et al. 2005)

The plots show that the pressure distribution in at the tunnel face of an EPB shield can be very different. In Figure 5 there is a pressure increase of only around 50 kPa (0.5 bar) between the face pressure at the axis and the maximum measured in the face pressure. For the same TBM but at a different location, also in sand, this difference can be more than 100 kPa (1 bar), see Figure 6. The pressure increase of around 50 kPa seems to be more desirable. As stated in Bezuijen (2011), it is likely that the high pressures measured for ring 813 S, as shown in Figure 6, are caused by grain stresses that does not influence the pore pressures and thus the pressure of the foam.

To avoid grain stresses, the porosity of the mixture has to be higher than a certain level (50% has been used in the calculations of Sections 2 and 3). This porosity of 50% or higher has to be reached not at the axis, but also at the point of the highest pore pressure at the tunnel face, thus at a point with approximately 50 kPa higher pressure. With a pressure at the tunnel axis of 300 kPa (3 bar), Boyle's law dictates that the product of the absolute pressure and the air volume is constant. Pressures in tunnel boring are normally presented with respect to the atmospheric pressure. This means that 300 kPa measured corresponds to an absolute pressure of 400 kPa and a pressure increase of 50 kPa results in a reduction of the volume to 0.89 of the original volume. This volume reduction due to the locally higher pressure means that more foam has to be injected. Taking this effect into account, can be derived from the volume balance that Eq. (5) changes to:

$$FIR = \frac{\dfrac{k\Delta\phi}{v_d\,R} - 1 + \dfrac{1-n_s}{1-n_m}}{\dfrac{1}{FER} + \beta\left(1-\dfrac{1}{FER}\right)} \tag{7}$$

Where β is the volume reduction of the air in the foam due to the higher pressure according to Boyle's law. For the parameters mentioned above and a *FER* of 20 for the original foam, the result is shown in Figure 7.

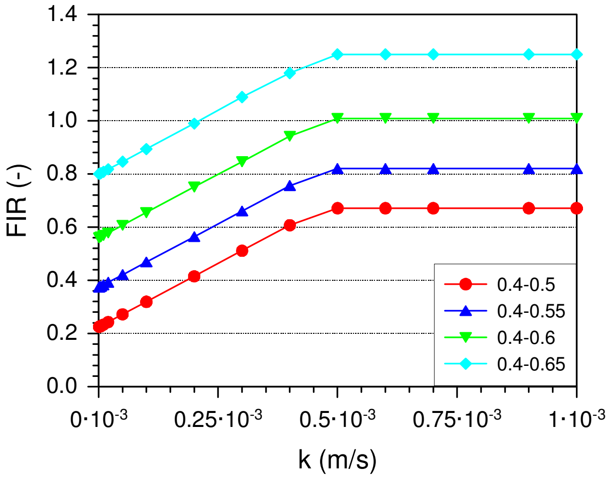

Figure 7. Calculation of *FIR* taking into account a pressure difference of 50 kPa between the pressure at the axis and the highest pressure.

The calculated FER is a bit higher, but the difference with Figure 2 is only limited. This difference will increase for larger shield diameters, which will have larger pressure differences. It will also increase for lower overburden and thus lower absolute pressures.

6. Comparison with empiric rules

Thewes at al. (2011) present the recommended *FIR* for various soils according to EFNARC (2005). For sand a *FIR* of 30 to 40% is recommended. Assuming a necessary increase in porosity from 0.4 to 0.5 to avoid grain stresses in the muck, the theoretical calculation shown in Figure 7 shows that for low permeable sand ($k<10^{-4}$ m/s) a *FIR* of 20% should be sufficient, but that for the parameters mentioned in Table 1 and sand with a permeability of more than $2.5*10^{-4}$ m/s the recommended values are too low, to achieve the minimum porosity of the soil in the mixing chamber to avoid grain stresses. It is therefore likely to assume that the EFNARC value is derived for relatively low permeable sand. It is also possible that some grain stresses are accepted when deriving EFNARC values.

The EFNARC table recommend a FIR of 30-60% for sandy gravels. Again this is close to the value that came from the theoretical calculation assuming sufficient permeability of the soil in front of the tunnel to remove the pore water in front of the tunnel face. Assuming again an increase of porosity from 0.4 to 0.50, the necessary *FIR* according to Figure 7 is 67 %.

So it can be concluded that the theoretical model presents values close to the values that are now recommended by EFNARC. However, the model shows the influence of various parameters on the necessary amount of foam. Parameters of in influence are: the permeability of the subsoil, the density of the subsoil, it's maximum porosity, the diameter of the shield, the difference in piezometeric head between the piezometric head at the tunnel face and at some distance of the tunnel and the drilling speed.

7. Conclusions

The amount of foam to be injected in saturated sandy soil during EBP-shield driving has been investigated theoretically, as well as the resulting *FER* of the mixture. The conclusions from this study are:

1. The necessary *FIR* depends to a large extend on the permeability of the soil in front of the tunnel face.
2. The *FER* of the resulting soil-foam mixture (FER_m) is in most cases much lower than the original *FER*, resulting in foam with a higher permeability and lower shear strength. The FER_m increases sharply when the permeability of the sand is larger than a certain value (depending on drilling speed, face pressure, tunnel diameter). That saturated soil needs a 'dry' foam is well known (EFNARC, 2001), but this study allows to quantify the influence of the pore water in the soil on the FER of the mixture.
3. The pressure variation at the tunnel face has an influence on the minimum amount of foam that has to be injected. However, this influence is limited until 10 to 20%, depending on the soil cover over the shield and the diameter of the shield.
4. The values for the FIR obtained by this, theoretical model, are the same or a bit higher than the values recommended by EFNARC (2005). This may indicate that in practice some effective stress is allowed in the muck at the mixing chamber.

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