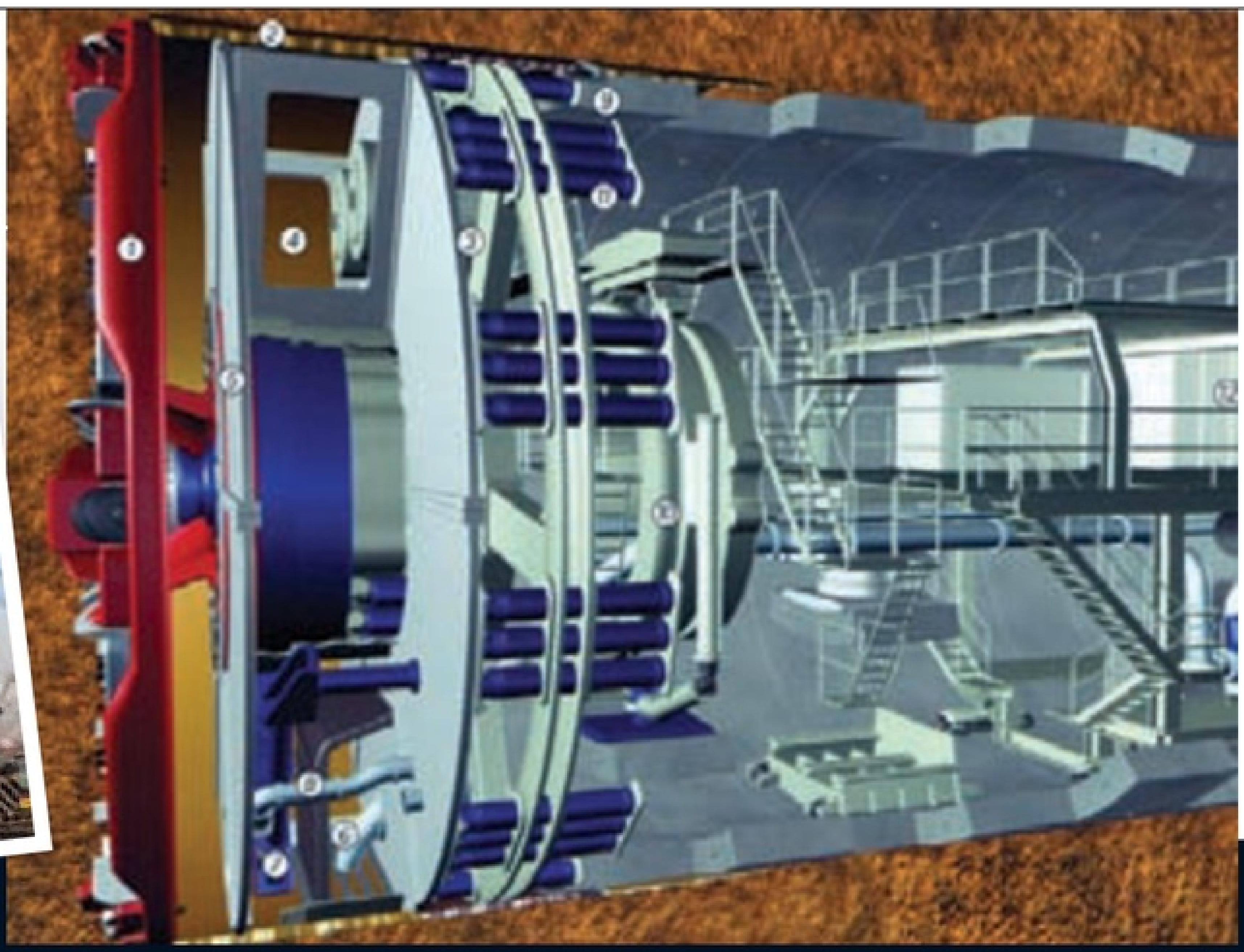
Right: Section through a Slurry Shield

Below: Classic EPBMs



# A Bluffer's Guide to Stability Part 3

**Dr Benoît Jones, Director of the Tunnelling and Underground Space MSc at the University of Warwick, UK, provides a straightforward guide to stability in soft ground. This Part 3 of 'A Bluffer's Guide to Stability' looks at how an understanding of stability can guide the operation of closed face TBMs.**

**As discussed in parts 1 and 2** (in the last 2 issues), there are two main points to understanding stability:

1. There are two forces that cause instability: gravity and seepage forces.
2. All headings will fail without either cohesion or support pressure.

As demonstrated in Part 2, drained soils with little or no cohesion require a support pressure to be applied to maintain stability. Closed face tunnelling machines are often used in these soils, but it is difficult to know what support pressure is required to maintain stability. If there is instability, the uncontrolled flow of ground into the face will lead to overmucking, which may not be easily detected, and this in turn may cause excessive surface settlements or collapse. This has occurred all over the world, for example the "Lavender Street incident" during EPB tunnelling for the CTRL in London (Lovelace, 2003), or the 37 incidents, some of which reached the surface, during construction of the SMART tunnel in Malaysia using a slurry TBM (CEDD, 2012).

## Slurry TBMs

A slurry TBM supports the ground by filling the head with bentonite slurry under pressure. The slurry pressure must be greater than the groundwater pressure because otherwise you wouldn't be able to pump it in there, but also because we need the excess slurry pressure to apply a support pressure to the soil grains and to include an allowance for variability, see Figure 1.

All slurry machines will experience fluctuations in the slurry pressure, due to dynamic effects such as rotation of the

Slurry machine acceptance

cutterhead, excavation and pumping, and due to the difficulty in balancing the slurry feed in and the slurry extraction rate out. Since a drop in the slurry pressure would result in overmucking, the allowance for variability is added to the target minimum face pressure. Sometimes a factor of safety of some kind is also included in some way, as well as an allowance for the effects of surcharge on the surface (Golder Associates, 2009).

In Figure 1, the slurry pressure increases at a faster rate with depth than the groundwater pressure. This is because slurry, when mixed with excavated soil, has a higher unit weight, typically around 12kN/m$^3$, whereas water is just under 10kN/m$^3$. This means that the minimum excess slurry pressure is always at the crown. Therefore, stability calculations for slurry TBMs are always performed at the crown level as this is the worst case (Golder Associates, 2009).

Because the slurry pressure is always greater than the groundwater pressure, the slurry will flow into the ground. As it displaces the groundwater in the soil's pore spaces, the slurry flow is slowed down and soil particles suspended in the slurry are filtered out and block the pores. Bentonite slurry, at the right concentrations, also has thixotropic properties – this means that it forms a gel when not agitated. Therefore, a 'filter cake' is formed, which acts as a kind of membrane that allows the excess slurry pressure to be applied to the soil grains, preventing instability.

The ideal situation is where the filter cake forms close to the excavation surface. As mentioned in Part 2, drained stability can be approximated using a wedge and prism model (Anagnostou & Kovári, 1994, who attribute the model to Horn, 1961). The geometry of the model is shown in Figure 2. As the slurry penetrates into the soil, the excess slurry pressure acting to support the soil grains is spread over the penetration distance, so as the slurry penetrates through the 'wedge', the resultant support force it applies to the wedge and hence the prisms above is gradually compromised. For higher permeability soils, penetration occurs at a faster rate.

One way to reduce the slurry penetration rate is to use a higher viscosity slurry, but this increases slurry pumping and treatment costs. For continuous TBM tunnelling, usually penetration rate is not a problem unless the soil permeability is very high (such as in open gravels), because the TBM is constantly advancing and excavating the ground. It is usually only when there is a standstill of the TBM that penetration is a problem, and often this can be mitigated by temporarily increasing the slurry viscosity. Anagnostou & Kovári (1994) found that increasing the slurry pressure also helps.

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(Anagnostou & Kovári, 1994, who attribute the model to Horn, 1961)

**Figure 1: Slurry pressure diagram for a slurry TBM (Anagnostou & Kovári, 1994)**

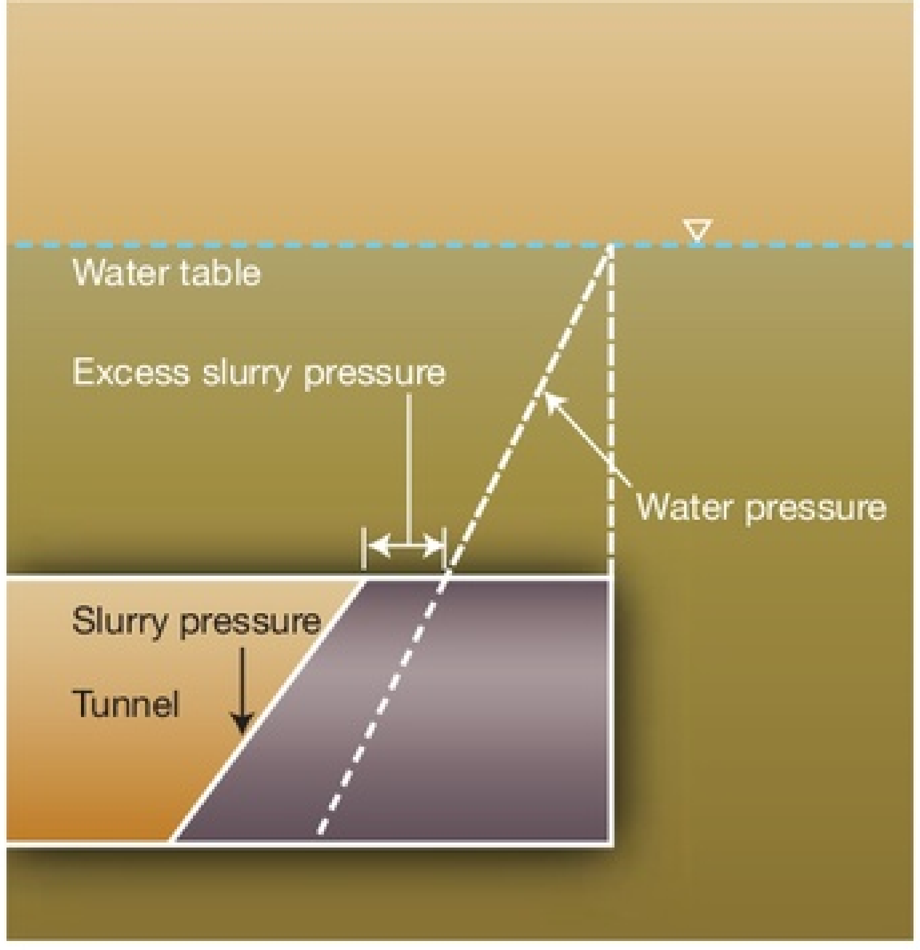
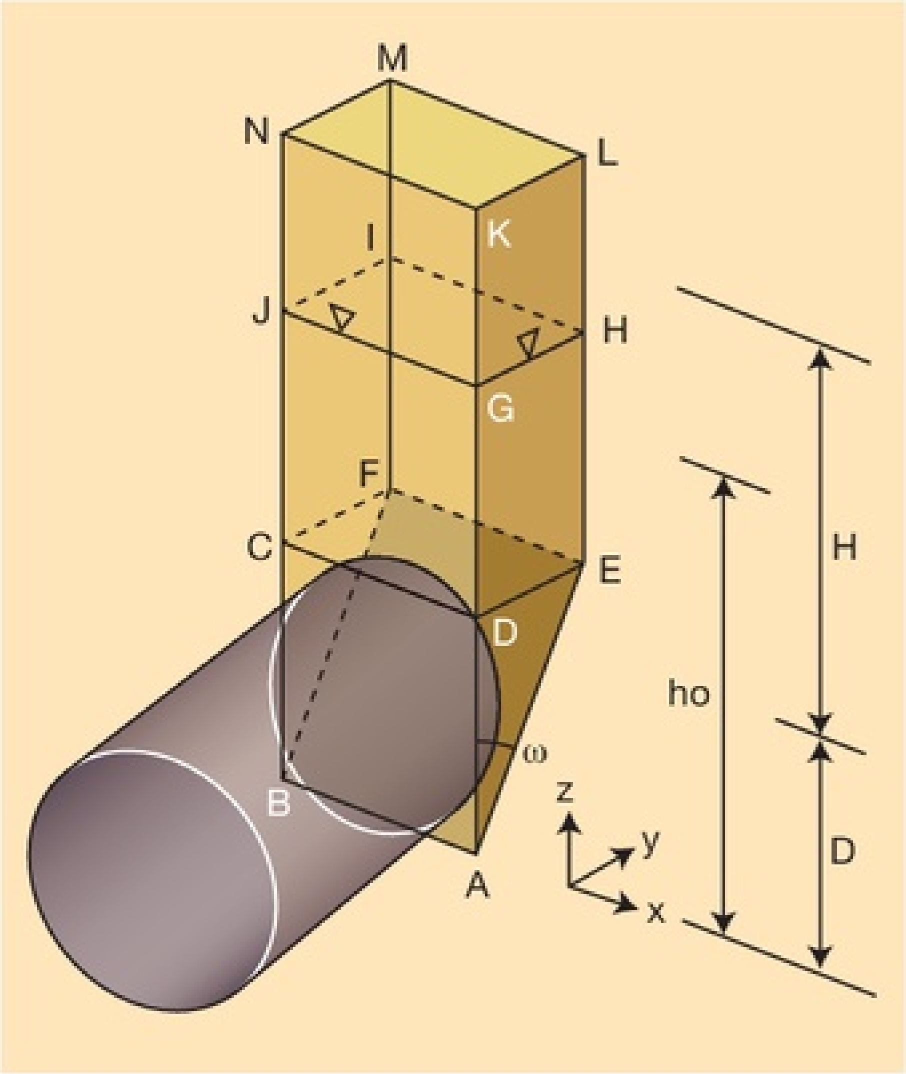


**Figure 2: Wedge and prism model (from Anagnostou & Kovári, 1994, after Horn, 1961)**



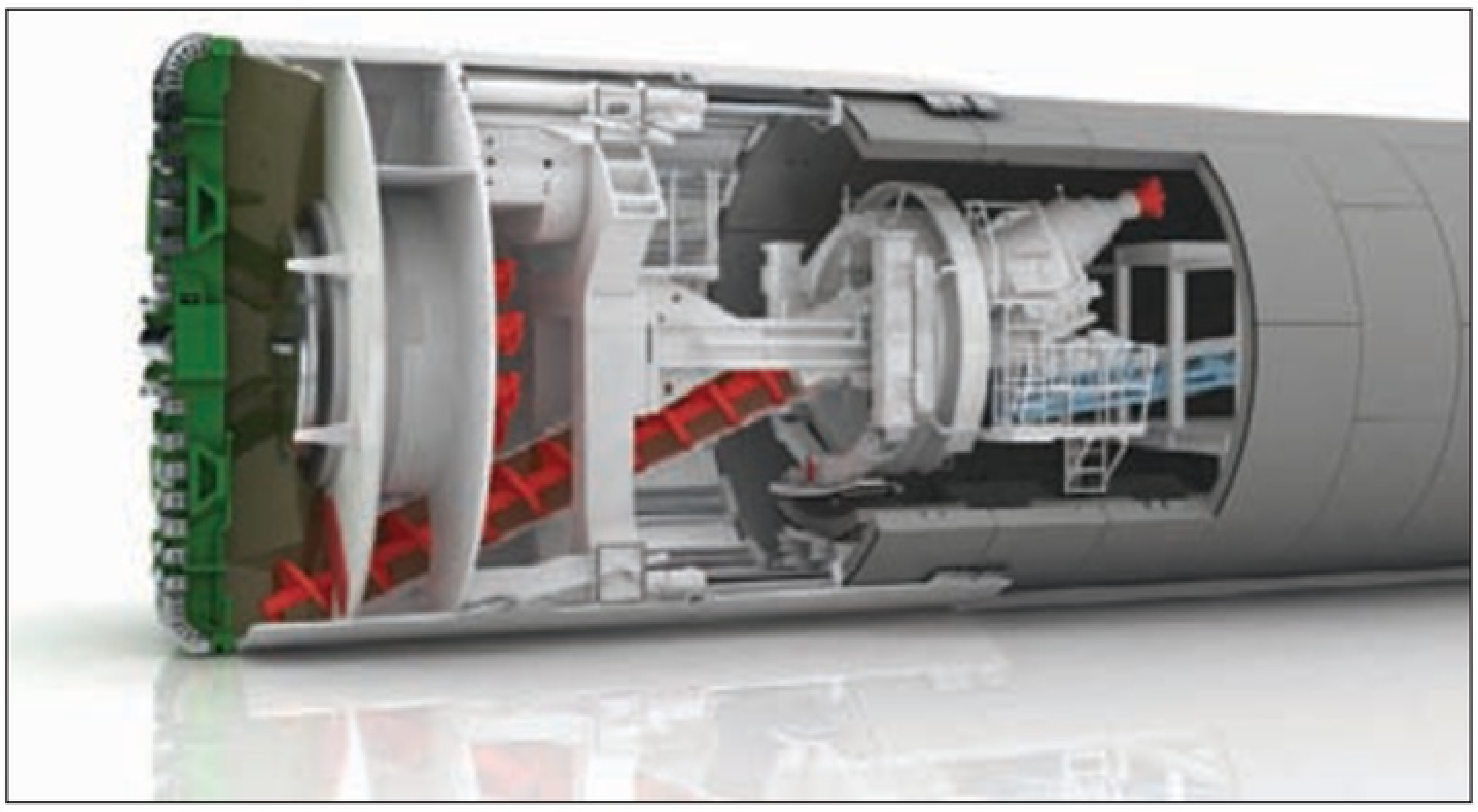
**Earth pressure balance (EPB) TBMs**

Face stability in EPB machines is more complicated. The cutterhead breaks up the soil and the muck moves through openings in the cutterhead into the 'excavation chamber'. The excavation chamber is kept filled with muck under pressure, and it is this pressure that provides the face stability. Muck is removed in a controlled manner from the excavation chamber using an Archimedes screw, and the 'EPB pressure' is controlled by balancing the screw speed with the penetration rate of the TBM into the ground. It is important to note that usually EPB pressure is measured by load cells in the excavation chamber, which measure total stress, i.e. the total of both the effective support pressure and the pore pressure.

At the end of the screw, the muck falls out onto a belt conveyor at atmospheric pressure, so there is a pressure gradient up the screw. This gradient is maintained by the tortuosity of the route the soil takes up the screw and the soil's cohesion and angle of friction. For the pore pressure, a gradient in the screw can only be maintained by filling the screw with a low permeability material. If the muck has a high permeability, soil conditioning can be used to reduce its permeability.

It is helpful, as we did for slurry machines, to consider the effective support pressure and the pore pressure separately. The 'effective support pressure' is the stress in the soil grains transferred from the machine to the soil through grain-to-grain contacts. The 'pore pressure' is the pressure of the fluid (water and soil conditioning) between the soil grains. At the end of the screw, both of these are zero. In the ground, far away from the influence of the TBM, they have undisturbed in situ values dependent on their weight and, in the case of horizontal effective stress, the stress history and other effects.

In an EPB machine, unlike a slurry machine, the fluid pressure in the excavation chamber cannot be higher than the fluid pressure in the ground. With a perfect plug of impermeable muck in the screw, it could be close to the in situ pore pressure, but it can't be higher. Therefore, there is always seepage of groundwater towards the face, which, as we know, is bad for



**Section through an EPBM**

stability.

The effect can be calculated using the method described in Anagnostou & Kovári (1996). It can be illuminating to calculate the two extremes: in one case (A) with zero pore pressure in the excavation chamber, giving the maximum destabilising hydraulic gradient in the ground, and in the other case (B) with the pore pressure in the excavation chamber equal to the in situ pore pressure in the ground. In case A, the destabilising seepage force needs to be counteracted by an increased effective support pressure, but the effective support pressure is equal to the total EPB pressure because there is no pore pressure to drive against. In case B, there is no destabilising seepage pressure, so the effective support pressure is only what is required to maintain stability due to gravity, but we have to add the pore pressure to get the EPB pressure. It turns out, if you run the numbers, that the EPB pressure required for case A is always less than in case B. In other words the extra effective support pressure required to resist the destabilising seepage forces is less than the in situ pore pressure.

Therefore, one would think, surely it is better to drain the ground and run the machine with a lower EPB pressure? Why are people always going to great lengths to get the soil conditioning right so they can ‘maintain a plug in the screw’? One reason is that, particularly in high permeability soils, uncontrolled water flow through the screw could flood the tunnel. But there is another very good reason. This is that the higher the effective support pressure, the higher the effective stress in the soil’s grain to grain contacts. The shear strength of a soil is proportional to the effective stress, so this means the soil will behave like a stronger material. This is undesirable because we want it to flow nicely through openings in the cutterhead and up the screw, not arch around openings and block the screw. The increased friction between soil grains will also generate a lot of heat, and increase wear of metal parts. This means an increase in maintenance stops and slower overall progress.

> **“It is helpful, as we did for slurry machines, to consider the effective support pressure and the pore pressure separately. The ‘effective support pressure’ is the stress in the soil grains transferred from the machine to the soil through grain-to-grain contacts. The ‘pore pressure’ is the pressure of the fluid (water and soil conditioning) between the soil grains”**

**Summary**

The same principles govern the stability calculations for both slurry and EPB machines, even though they work in different ways. The main difference is that in a slurry machine the slurry pressure is always greater than the groundwater pressure but we need a filter cake to form to also apply an effective support pressure to support the soil grains. In an EPB machine, the machine is applying an effective support pressure to the soil grains but we need to maintain a plug in the screw to counteract the groundwater pressure and minimise the hydraulic gradient.

Soil conditioning is critical to making the muck in an EPB machine behave the way we need it to. Ideally we turn it into a low permeability, cohesive and plastic material to minimise the work required to get it to flow through the machine, minimise friction and wear of metal parts, and create a good plug in the screw so that the pore pressure in the excavation chamber is close to the in situ pore pressure.

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