3 Choosing between earth pressure balance machines (EPBM)s and slurry tunnelling machines (STMs)

The choice of the type of closed-face tunnelling machine and its facilities is a critical decision on a soft-ground tunnelling project. This decision will be guided by thorough assessment of the ground types and conditions to be encountered and by numerous other aspects. Other aspects that will influence the choice include the particular experience of the project’s contractor, the logistics and configuration of the works, and requirements of the contract as a means to ensure that the client’s minimum specification is met. The initial choice is guided by reference to the grading envelope of the soils to be excavated. Since it is likely that the geology will fall into more than one envelope, the final choice may require a degree of compromise or development of a dual-mode open/closed-faced TBM system or a dual slurry/EPB system.

3.1 Review of ground types

In the case of many tunnel drives the conditions encountered along the route may vary significantly with a resulting need to specify a system capable of handling the full range of expected conditions. Closed-face tunnelling machines can be designed and manufactured to cope with a range of ground conditions. Some machines are capable of handling many or all of this range of anticipated conditions with a limited degree of reconfiguration for efficient operation.

There have been several attempts to classify the naturally occurring range of soft-ground characteristics from the tunnellers’ perspective. This work was summarised most recently by Whittaker and Frith (1990) and the following categorisation is based partly on their work. It consists of eight categories of physical ground behaviour that may be observed within the soft-ground tunnel excavation range. Each of these may be associated with particular types of soils.

3.1.1 Firm ground

Ground in which the tunnel can be advanced safely without providing direct support to the face during the normal excavation cycle and in which ground support or the lining can be installed before problematic ground movement occurs. Where this short-term stability may be attributable to the development of suction in fine grained soils, significant soil movements and/or ground loading of the tunnel lining may occur later. Examples may include stiff clays and some dewatered sands. A closed-face tunnelling machine may not be needed in this ground type.

3.1.2 Ravelling ground

Ground characterised by material that tends to deteriorate with time through a process of individual particles or blocks of ground falling from the excavation surface. Examples may include glacial tills, sands and gravels. In this ground a closed-face tunnelling system may be required to provide immediate support to the ground.

3.1.3 Running or flowing ground

Ground characterised by material such as sands, silts and gravels in the presence of water, and some highly sensitive clays that tend to flow into an excavation. Above the water table this may occur in granular
materials such as dry sands and gravels. Below the water table a fluidised mixture of soil and water may flow as a liquid. This is referred to as running or flowing ground. Such materials can sometimes pass rapidly through small openings and may completely fill a heading in a short period of time.

In all running or flowing ground types there will be considerable potential for rapid over-excavation. A closed-face tunnelling system will be required to support such ground safely unless some other method of stabilisation is used.

3.1.4 Squeezing ground

Ground in which the excavation-induced stress relief leads to ductile, plastic yield of ground into the tunnel heading. The phenomenon usually is exhibited in soft clays and stiffer clays over a more extended period of time. A closed-face machine may be required to provide resistance to squeezing ground, although in some conditions there is also a risk of the TBM shield becoming trapped.

3.1.5 Swelling ground

Soil characterised by a tendency to increase in volume due to absorption of water. This behaviour is most likely to occur either in highly over-consolidated clay or in clays containing clay minerals naturally prone to significant swelling. A closed-face machine may be useful in providing resistance to swelling ground although, as with squeezing ground, there is a risk of the shield becoming trapped.

3.1.6 Weak rock

Weak rock may be regarded effectively as a soft-ground environment for tunnelling because systems used to excavate soft-ground types may also be applied to weak rock materials such as chalk. Weak rock will often tend to be self-supporting in the short term with the result that closed-face tunnelling systems may not be needed. However, groundwater may be a significant issue. In these instances a closed-face machine is an effective method of protecting the works against high volumes of water ingress that could also be under high hydrostatic pressure.

3.1.7 Hard rock

Closed-face TBMs may also be deployed in normally self-supporting hard rock conditions. The main reason would be to provide protection against groundwater pressures and prevent inundation of the heading.
3.1.8 Mixed ground conditions

Potentially, the most difficult of situations for a closed-face tunnelling system is that of having to cope with a mixture of different ground types either along the tunnel from zone to zone or sometimes from metre to metre, or within the same tunnel face. Ideally the vertical alignment would be optimised to avoid, as far as possible, a mixed ground situation, however, in urban locations the alignment may be constrained by other considerations.

For changes in ground types longitudinally, a closed-face machine may have to convert from a closed-face pressurised mode to an open non-pressurised mode when working in harder ground types to avoid over-stressing the machine’s mechanical functions. Such a change may require some modification of the machine and the reverse once again when the alignment enters a reach of soft, potentially unstable ground.

In the case of mixed ground types across the same face, the tunnelling machine will almost certainly have to operate in a compromise configuration. In such cases great care will be needed to ensure that this provides effective ground control. A common problem, for example, is a face with a hard material in the bottom and running ground at the top. In this situation the TBM will generally advance slowly while cutting the hard ground but may tend to draw in the less stable material at the top leading to over-excavation of the less stable material and subsequent subsidence or settlement at the surface.

Different ground types at levels above the tunnel will also be of significance. For example, in the event that over-excavation occurs, the presence of running or flowing materials at horizons above the tunnel will increase the potential quantity of ground that may be over-excavated and again lead to subsidence or surface settlement. Another potential problem occurs when a more competent layer exists over potentially running ground in which case possible over-excavation would create voids above the tunnel and below the competent material, giving rise to potential longer-term instability problems.

3.2 Selection criteria

3.2.1 Particle size distribution and plasticity

An STM is ideal in loose waterbearing granular soils that are easily separated at the separation plant. By contrast STMs have problems dealing with silts and clays.

If the amount of fines (particles smaller than 60 μm or able to pass through a 200 sieve) is greater than 20% then the use of an STM becomes questionable although it is not ruled out. In this situation it will be the difficulty in separating excavated spoil from the slurry, rather than the operation of the TBM, that is likely to affect critically the contract programme and the operating cost.

An EPBM will perform better where the ground is silty and has a high percentage of fines both of which will assist the formation of a plug in the screw conveyor and will control groundwater inflows. A fines content of below 10% may be unfavourable for application of EPBMs. For an EPBM the costs of dealing with poorly graded or no-fines soil will be in the greater use of spoil conditioners and possibly, in extreme cases, the use of positive displacement devices, such as rotary feeders or piston dischargers, at the screw conveyor discharge point to maintain EPB pressures.

Higher plasticity index (PI) clays (‘sticky clays’) can lead to ‘balling’ problems and increased problems at the separation plant for STMs. Similarly these materials can be problematic for EPBMs where special attention is required in selecting the most appropriate conditioning agents.
3.2.2 Permeability

As a general guide the point of selection between the two types of machine is a ground permeability of $1 \times 10^{-5}$ m/s, with STMs applicable to ground of higher permeability and EPBMs for ground of lower permeability. However, an EPBM can be used at a permeability of greater than $1 \times 10^{-5}$ m/s by using an increased percentage of conditioning agent in the plenum. The choice will take into account the content of fines and the ground permeability.

3.2.3 Hydrostatic head

High hydrostatic heads of groundwater pressure along the tunnel alignment add a significant concern to the choice of TBM. In situations where a high hydrostatic head is combined with high permeability or fissures it may be difficult to form an adequate plug in the screw conveyor of an EPBM. Under such conditions an STM may be the more appropriate choice especially as the bentonite slurry will aid in sealing the face during interventions under compressed air.

3.2.4 Settlement criteria

Both types of machine are effective in controlling ground movement and surface settlement – providing they are operated correctly (see Chapters 8 and 9). While settlement control may not be the overriding factor in the choice of TBM type, the costs associated with minimising settlement should be considered. For example, large quantities of conditioning agent may be needed to reduce the risk of over-excavation and control settlement if using an EPBM in loose granular soils.

3.2.5 Measurement of excavated quantity

Measuring the quantity of excavated spoil for each excavation cycle is a vital control mechanism for operating closed-face TBMs. This measurement enables over-excavation to be recognised promptly and reacted to immediately. It allows operators to review why over-excavation has occurred and for the appropriate precautionary actions to be taken to restore ground control and excavation stability.

The accuracy of the spoil monitoring equipment is highly dependent on the composition of the spoil.

When using STMs, excavated spoil is measured by recording the density and flow of the slurry in the in-bound and out-bound pipelines. However, these are subject to change during excavation and can only be used as a relative reference from one excavation cycle to the next.

The best method of monitoring spoil quantities when using an EPB system is by using conveyor belt weighers or material scanners on the conveyor system. In addition, quantity can be monitored visually during loading of muck skips.

When using trains of muck skips for spoil haulage the check on excavated quantity is based on providing sufficient capacity for one ring or cycle of spoil excavation. The TBM operator is able to gauge how the excavation is progressing by the distance shoved compared with how many skips have been filled. By its nature this process is slow and there is therefore a reasonable amount of time for the operator to review the volumes. It is also a crude system of measurement because the quality of the spoil (wet or dry) can have a dramatic effect on the amount of spoil that each muck skip will take.

The quality of the spoil can also have a dramatic effect on belt weighers or scanners and it is important to have at least three means of recording the volumes so that these can be cross-checked. The high throughput of modern conveyor systems can quickly result in
over-excavation. As a result it is essential that the measuring equipment can give real-time monitoring data throughout the excavation cycle as noted in Section 9.3.2.

None of these measuring systems provides absolute values and requires constant recalibration to maintain accuracy. Cross checks of comparative readings taken by at least three belt weighers or scanners or a combination of both when using continuous conveyors should be routine.

Manufacturers should be encouraged to provide an audible and visual alarm that will activate if excavation is exceeding a predetermined quantity of spoil relative to machine advance. This is important
as modern TBMs are very efficient excavators and over-excavation could occur in a matter of only minutes.

3.2.6 Final considerations

Other aspects to consider when making the choice between the use of an STM or an EPBM include the presence of gas, the presence of boulders, the torque and thrust required for each type of TBM and, lastly, the national experience with each method. These factors should be considered, but would not necessarily dictate the choice.

The overriding decision must be made on which type of machine is best able to provide stability of the ground during excavation with all the correct operational controls in place.

If both types of machine can provide optimum face stability, as is often the case, other factors, such as the diameter, length and alignment of the tunnel, the increased cutter wear associated with EPBM operation, the work site area and location, and spoil disposal regulations are taken into consideration.

The correct choice of machine operated without the correct management and operating controls is as bad as choosing the wrong type of machine for the project.