A Bluffer's Guide to Stability Part 1

In this article, 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.

'SOFT GROUND' means soil, and is often arbitrarily defined as a geomaterial with an unconfined compressive strength of less than 1MPa. It therefore ranges from loose silts and sands to cemented, interlocked, very dense sands, and from very soft, recently deposited clay to very stiff or hard overconsolidated clay. It also includes gravels and decomposed or weathered rock. Although drawing a line between soft ground and rock is a bit arbitrary since there is no sudden change of behaviour when 1MPa is reached, it is a useful distinction because the mechanisms governing failure tend to be different.

'Stability' is about collapse. This guide will not go into the detail of how calculations are performed, but rather give an overview of what is going on, in qualitative fashion. Next issue we'll look at closed face tunnel boring machine stability.

Why is heading stability important?

In an open face tunnel, instability may cause soil and/or groundwater to collapse or flow uncontrollably into the tunnel, endangering the workforce and equipment, and endangering people and infrastructure at the surface, who may fall into the hole or have a building collapse on top of them. In a closed-face machine, workers may be protected, but instability will result in overexcavation that will cause excessive settlements of nearby structures and possibly a large hole opening up at the surface, which also could be very dangerous to the general public.

Cohesionless soils below the water table can be so unstable that they will flow through a small hole if a small hydraulic gradient is present. In cases like these, the integrity of the lining and its gaskets is very important, as any flow of soil into the tunnel means a void forming outside the tunnel, which leads to unequal pressures acting on the lining and possibly structural failure of the ring.

Heading stability is perhaps the most important aspect of soft ground tunnelling. It is often what determines the choice of construction method, for both conventional tunnelling and mechanised tunnelling, as shown in Table 1. These decisions are made rationally, based on an understanding of the geology and the geotechnical behaviour.

Table 1: Decisions influenced by heading stability in mechanised and conventional tunnelling

Mechanised tunnelling (i.e. TBM)	Conventional tunnelling (e.g. backactor or roadheader followed by shotcrete lining)
Choice of TBM type, i.e. open face, slurry, earth pressure balance (EPB)	Choice of construction sequence, how face is divided, when invert is closed
Choice of segmental lining type, i.e. bolted with gaskets or expanded wedgeblock	Choice of available contingency measures
Method for head interventions, i.e. atmospheric, compressed air or use of divers, or use of ground improvement such as grouting or dewatering	Choice of support types and toolbox measures, such as face shotcrete, temporary inverts, canopy tubes, spiles, face dowels
Whether ground improvement is needed, e.g. permeation grouting, jet grouting, ground freezing, dewatering	Whether ground improvement is needed, e.g. permeation grouting, jet grouting, ground freezing, dewatering

The causes of instability

There are two main points to understanding stability. Get these and you're sorted:

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

Without either cohesion to hold the soil grains together or a support pressure applied to the face, a vertical face will fall down due to gravity. This is illustrated by Figure 1, which shows images from a centrifuge test of a heading in dry sand. As the plunger is retracted (and the support pressure decreased), the sand falls into the tunnel with an angle of repose approximately equal to its angle of friction.

Gravity is always present, but seepage forces only occur when there is a hydraulic gradient (or you could call it a head difference) between the ground and the tunnel. As groundwater seeps through the ground towards the face, it pushes the soil grains apart with a 'seepage force' proportional to the hydraulic gradient, in the direction of flow. This decreases stability. Conversely, if the head of a TBM were filled with water or slurry with a higher pressure than the groundwater pressure, it would flow into the ground, and this would aid stability.

A cohesionless soil needs only a very small hydraulic gradient for it to fail due to seepage, just a few centimetres is enough, as anyone who has tried to build a dam on a sandy beach will know. On the other hand, a damp sand above the water table can have a small amount of apparent cohesion caused by capillary suction in the pores (as anyone who has built a sand castle will know). This may be just enough for a drained material to remain standing in small exposures for a short time. However, even a small amount of perched groundwater could cause local instability, so this needs to be planned and executed with great care.

Clays can often be observed standing in

vertical faces, sometimes in large diameter open face tunnels with no face support. This is because clays have cohesion. This cohesion is largely due to the clay's very low permeability. During the timescale of construction, as the soil is unloaded by removal of the soil that used to be next to it, the soil grains relax towards the face and this causes the pore water pressure between the soil grains to decrease. This drop in pore water pressure, known as 'suction' or 'negative excess pore pressure', holds the grains together. The low permeability of clay means that excess pore pressures can exist for a long period of time because it takes a long time for groundwater to flow to or from the surrounding ground to dissipate these excess pore pressures. This is why it is called undrained behaviour.

When these negative excess pore pressures are eventually dissipated, the clay will behave in a drained manner, i.e. more like a sand. Drained cohesion in clays is usually very small or zero. As I said before, all headings will fail without either cohesion or support pressure, it's just that in clays it may take a long time. In fact, an exposed face of clay will probably start to fall down because it is drying out rather than because negative excess pore pressures are being dissipated.

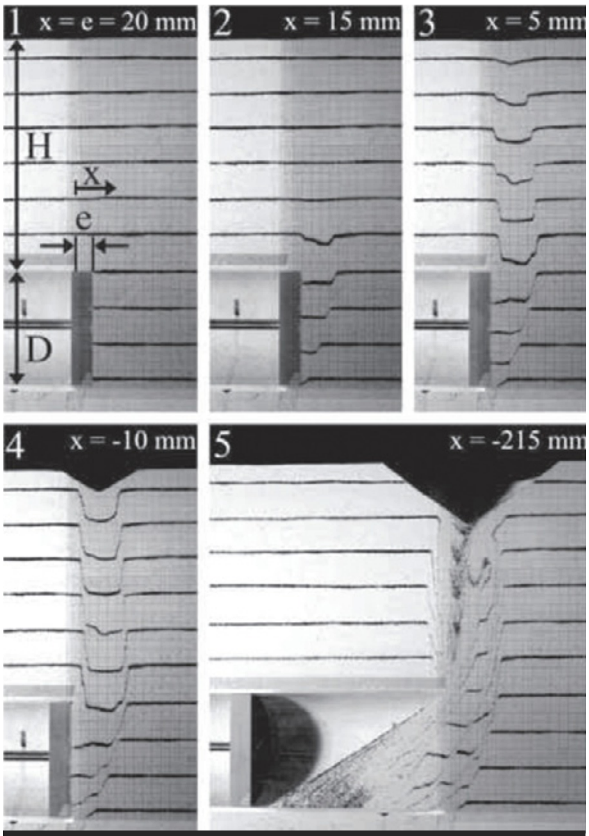

Figure 1: Gravity failure of dry sand in a centrifuge (from Messerli, Pimentel & Anagnostou, 2010)

For all these reasons, drained and undrained stability are quite different. The geometry of failure is different, and the calculations are done in a different way.

A rule of thumb is that a soil with a permeability less than between 10^{-7} and 10^{-8} m/s will behave in an undrained manner during the timescale of a typical tunnel construction, and a soil with higher permeability will behave in a drained manner (Anagnostou & Kovári, 1996). If it is unclear whether a soil will behave in a drained or undrained manner, stability calculations need to be done for both cases.

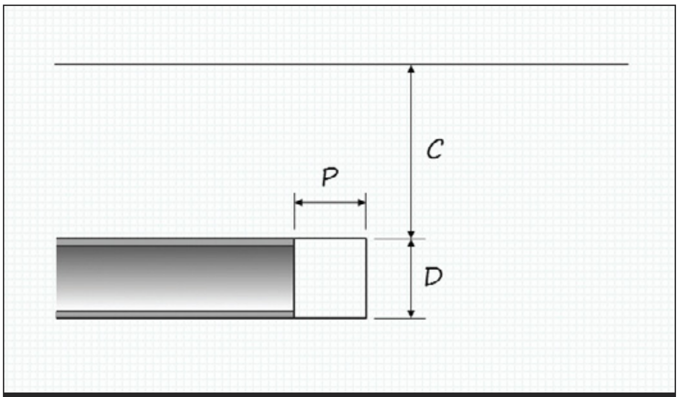

Figure 2: Simplified geometry of a tunnel heading

Stability theory

Stability is an ultimate limit state. This means that what we are trying to avoid by design is a failure, in this case a catastrophic failure. Therefore we want to try to predict when that failure will occur, and then ensure that we have sufficient factors of safety to make it very unlikely.

Since at failure the strength of the ground will be fully mobilised, heading stability lends itself well to plasticity solutions.

A heading may be geometrically simplified as shown in Figure 2. The geometry is defined by the excavated diameter D, the cover to the ground surface C, and an unsupported length P. In the case of a closed-face TBM driven tunnel, P may be equal to zero. For a sequentially-excavated tunnel lined with shotcrete, some assumptions about the values of P, C and D may need to be made.

For non-circular tunnels, Pound (2005) used numerical analysis to show that even for elliptical or rectangular tunnels, with a width 3 times the height or a height 3 times the width, stability may be approximated by an equivalent circular tunnel with the same face area. So the precise geometry is not important, as long as a value of D is used that would give the same face area. This was for undrained cohesive soils, and as we'll see this may not be the case for drained non-cohesive soils – someone needs to do the research to find out.

There are several ways we can determine stability:

1. Assuming a kinematically admissible mechanism, such that if a structure is loaded to this value it must collapse. This usually involves assuming the ground is made up of several large blocks that slide into the face. It demonstrates that failure must occur at this load, but there may be situations where failure may occur at a lower load. For this reason this is also known as an 'upper bound solution'.
2. Assuming a statically admissible stress field, such that if a structure is loaded to this value it cannot collapse. This is done by determining a set of stresses in the ground that are in equilibrium with the external loads and do not exceed the strength of the ground (Atkinson, 2007). It demonstrates that failure cannot occur in this set of circumstances, but it is possible that the true failure load is higher, so this may be overconservative. This is known as a 'lower bound solution'.
3. The upper and lower bounds bracket the true collapse load. Combining them to find a solution that is both kinematically admissible and statically admissible is known as a limit equilibrium solution.
4. Empirical data from heading stability failures in the field and in centrifuge tests may be used to develop relationships that may help predict the true collapse load.
5. Use numerical modelling to predict heading stability.

Davis et al. (1980) published both upper and lower bound solutions for an undrained soil. They are reasonably close together and so the true collapse load may be determined with reasonable accuracy.

Leca & Dormieux (1990) published both upper and lower bound solutions for drained soils, but they did not include the effects of seepage, so their solution can

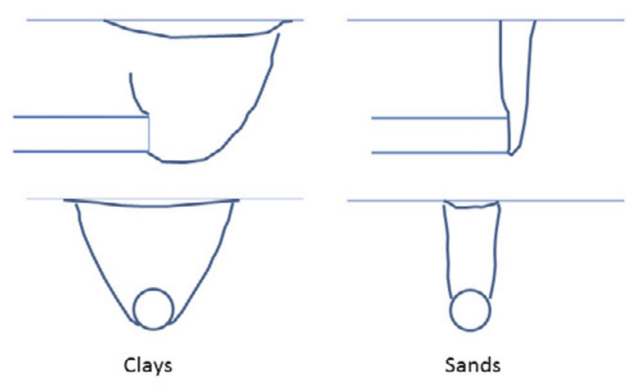

Figure 3: Geometry of stability failure in clay and sand (redrawn from Mair & Taylor, 1997, based on centrifuge tests on clay by Mair (1979) and on sand by Chambon & Corté (1994))

Interestingly, undrained stability depends on the depth of the tunnel, whereas drained stability is independent of depth and depends only on the diameter of the tunnel. Another interesting difference is the shape of the stability failure; in the drained case the soil fails in a steep-sided chimney, whereas in the undrained case the failure geometry has a much wider extent and is more of a cone-shape.

only be used to calculate the stability when the groundwater head is balanced and there is no hydraulic gradient or when the tunnel face is above the water table. The upper and lower bounds are quite far apart.

Anagnostou & Kovári (1994) published a limit equilibrium solution for a drained soil, the original solution being attributed to Horn (1961), with easy to use nomograms for simple cases. This solution gives similar results to the 2D plane strain upper bound solution of Atkinson & Potts (1977) and slightly higher results than the more complete upper bound solution of Leca & Dormieux (1990). Mair & Taylor reviewed all these methods in an excellent state of the art review paper in 1997.

For the undrained case, Mair (1979, cited in Kimura & Mair, 1981) used centrifuge tests and case histories of tunnel heading failures to develop relationships to help predict the true collapse load in the undrained case. The data lay between the upper and lower bound solutions of Davis et al. (1980).

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The most common methods used in practice for stability calculations are Mair's design charts based on centrifuge testing for the undrained case (Kimura & Mair, 1981), and Anagnostou & Kovári's method for the drained case (Anagnostou & Kovári 1994, 1996). How to apply these methods to the design of a real tunnel is very well described in GEO Report 249, a design guide produced by Golder Associates in 2009 for the Hong Kong Civil Engineering Directorate.

Summary

- Stability is really important.
- Instability is caused by gravity and seepage forces.
- All headings will fail without either cohesion or support pressure.
- Undrained and drained stability are different.

Next issue I'll go into more detail comparing various methods of stability calculation for closed face tunnel boring machines, and what they tell us about how to operate these machines.

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