Dealing with stress.

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As tunnel engineers, we often take stresses for granted or ignore them altogether. Stress is not a directly measurable physical quantity, so much of the monitoring that is used to verify the performance of a tunnel during construction is based on the measurement of displacements. Hence the vast bulk of back-analyses rely on calibrating models to fit a pattern of displacements observed in the field. It is often assumed, when these models are used in design, that if the predictions of displacements are reasonable, then the predictions of stresses must also be reasonable. However, this is not necessarily the case since the link between stresses and strains in a model depends on the constitutive models used to describe the stress-strain behaviour of the tunnel lining and the ground. It is possible to achieve an approximation to the same pattern of displacements using different constitutive models, while the distribution of stresses in the model may be totally different.

Numerical or analytical models used in design are often simpler than reality, and there are many phenomena that we ignore, for instance thermal expansion or contraction, plasticity, creep or shrinkage of the tunnel lining. Similarly, in the ground there may be consolidation or swelling, creep, groundwater flows or fabric effects such as the opening up or closing of fissures to name but a few. There will also always be geometrical simplifications, for example the true excavation profile can never be modelled exactly. The most important and still commonplace simplification is modelling what is a three-dimensional process in two dimensions. This can lead to gross inaccuracies in the prediction of tunnel lining stresses close to the face of the tunnel, and this is of particular importance to the design of sprayed concrete lined tunnels, where the tunnel lining's strength and stiffness increases with time and its creep capacity decreases as the sprayed concrete hydrates. In this case, the timing and sequence of construction is critical to the stresses imposed on the tunnel lining at each stage, relative to its ultimate limit state capacity.

The importance of modelling the timing and sequence of construction may be illustrated with two examples:

The effect of building up a sprayed concrete lining in layers.
Stress measurements in the Heathrow Express Terminal 4 station concourse tunnel showed that there was either zero stress or a small tensile stress in the inner 110mm of the 350mm thick sprayed concrete primary lining at all points around the circumference. The lining had been built up in layers, mainly because of the need to fix two layers of mesh reinforcement and lattice girders. Thus the outer layers effectively got a headstart in strength and stiffness development and therefore attracted more of the ground load as the tunnel advanced. In addition the inner surface of the sprayed concrete was more susceptible to drying shrinkage, causing load to be transferred outwards.

Construction sequence in tunnel junction construction.
Tunnel 'T' junctions would normally be constructed such that the larger 'parent' tunnel is built first. Later, the smaller 'child' tunnel is broken out from the parent. However, tunnel junctions are usually modelled by a three-dimensional 'wished-in-

place’ analysis. This means that the completed structure is conveniently assumed to materialise instantaneously in one step and the stress distribution calculated at equilibrium is then used to design the tunnel lining. Using this kind of model, the predicted stress concentrations at the junction are shared between the parent and the child. Alternatively, the sequence of construction may be modelled by dividing it into a number of steps, with each step usually representing one advance. Each step is solved to equilibrium, and this yields a very different stress distribution. In particular, the stresses in the child tunnel lining are lowest close to the parent and increase to a maximum with distance. This is partly because as the opening is made and the child tunnel advances away from the parent, the ground is arching onto the stiffer parent tunnel lining and thus reducing the stress that would normally act on the child. Also, the largest increment of stress concentration around the junction occurs when the opening is made in the parent, and at this stage the child has yet to be built. Therefore using the simple wished-in-place method the child tunnel will have been overdesigned and the parent tunnel will not have the expected factor of safety.

In conclusion, attention must be paid to stresses and how they may be affected by the construction sequence and the constitutive behaviour of the ground and the tunnel lining. If a model gives reasonable predictions of displacements this does not mean it will give reasonable predictions of stresses, especially if a two-dimensional model is used. Wished-in-place analyses and other simplifications of the construction sequence may give a stress distribution that is completely false.