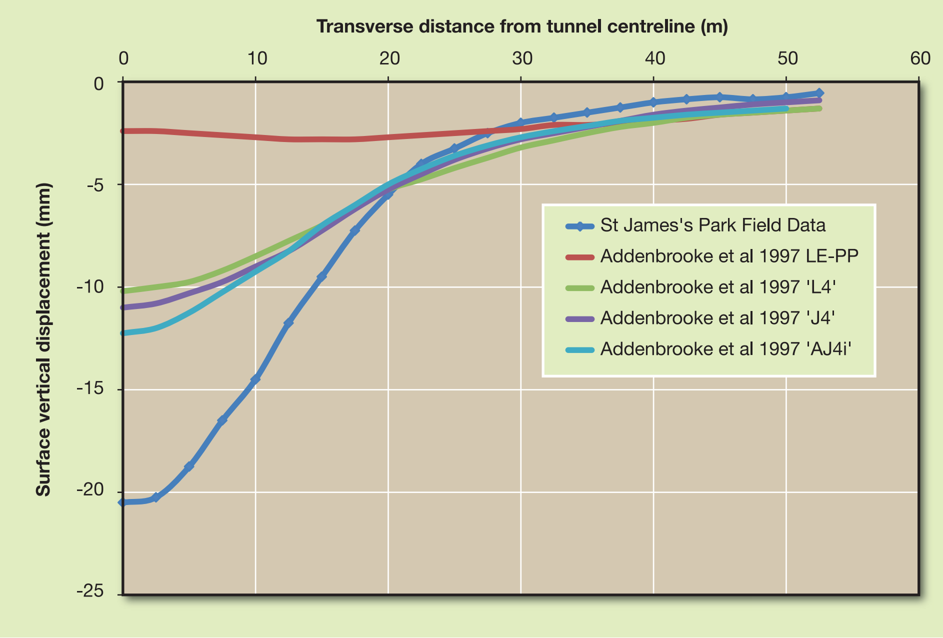
# The most difficult question?

## Dr Benoît Jones, Underground Space MSc Course Manager at the University of Warwick discusses the prediction of ground movements due to tunnelling

**Figure 1: Modelling of St James's Park JLE Westbound tunnel - influence of small strain stiffness and anisotropy**



**THE MORE WE LEARN** about soil behaviour the more complex a material it turns out to be. It can be difficult to explain this to outsiders, who unfairly assume there can't be much to learn about dirt, but it's also difficult to explain to ourselves. The late Peter Vaughan once gave an after-dinner speech in which he said, "It is difficult to reconcile the fact that we had nuclear power before we had a viable theory to explain the long-term strength of London Clay." He then went on to explore the alternative theories that:

1. Our subject must be unusually difficult, or
2. It has an extraordinary ability to attract thick people.

A flick through back issues of Géotechnique quickly disabuses one of the possibility that theory no.2 could be correct. And yet, it is also striking how many papers have been written in which a new, all-powerful soil model has been developed based on advanced soil testing and new theories. It all goes so well, until, the model invariably falls at the final fence. And it seems that the final fence for soil models is: 'can it predict surface settlements due to tunnelling?' This seems to have become a kind of gold standard for soil models. Physicists have found the Higgs boson with a certainty of 99.99997%, but for some reason a reasonable ball-park estimate of the general shape of a transverse settlement trough has proved to be the toughest challenge for the greatest minds in geotechnics for quite a long time.

### London Clay and St James's Park

At the risk of this column becoming parochial (being a Londoner myself), I'm going to concentrate on London Clay. There probably isn't another geomaterial in the world that has been subjected to as much research and testing. London Clay is generally described as a very stiff heavily overconsolidated marine clay, and it was deposited approximately 30 million years ago. It varies in thickness across London, but most deep basements and tunnels are in it, and there is a lot of high quality field data of ground movements available.

A lot of research has gone into obtaining high quality samples of London Clay, undertaking specially designed and specially instrumented laboratory tests and developing constitutive models to simulate its behaviour. Therefore, you would think that if it were possible to model accurately the ground movements due to tunnelling in any geomaterial, it would be this one.

Amongst several examples of high quality case histories of tunnelling in London Clay, the Jubilee Line Extension tunnels under St James's Park seem to have subjected to the most numerical modelling, from Addenbrooke et al. in 1997 right through to González et al. and Jurečič et al. in 2012. So many attempts have been made to model St James's Park, it is almost a national sport. This might seem like a bit of a bad idea to those who know a bit about this case history, because the settlements were quite anomalous at St James's Park, with a short-term volume loss of 3.3%. However, the tunnel was in a greenfield site, and surface and subsurface vertical and horizontal displacements were measured very accurately as first the westbound, then the eastbound, tunnels passed underneath. The short-term transverse settlements due to construction of the westbound tunnel are what we will be concentrating on, and this was at a depth to axis of 30.5m.

In this article we are going to look at 2D plane strain models of tunnelling under St James's Park using a variety of soil models. In each case the primary aim of the modelling was to try to mimic the pattern of settlements. In all cases, the 'relaxation method' was used where the stress at the tunnel boundary was gradually reduced until a target volume loss (Vl) of 3.3% has been attained. Table 1 lists the models that are considered, along with the $K_0$ value used in the analysis and the percentage unloading applied to the tunnel surface.

### Model comparisons

Attempts to use linear elastic Mohr Coulomb models usually come up with extremely wide and shallow settlement troughs; for an example, see Addenbrooke et al. (1997)'s 'LE-PP' model results reproduced in Figure 1 and compare them to the St James's Park field data, also shown on Figure 1. Generally, this seems to be a common problem, but is particularly noticeable when $K_0$ is greater than 1, i.e. when the horizontal effective stress is greater than the vertical effective stress. Svoboda et al. (2010) compared numerical analyses with different values of $K_0$ and found that lower values resulted in narrower and deeper surface settlement troughs.

Measurements of $K_0$ in the London Clay generally find that it has a maximum value near the top of the London Clay that can be as high as 2 or 3, and decreases with depth such that it is greater than 1 until approximately 20-30m depth (e.g. Hight et

**Table 1: List of 2D models of St James's Park JLE considered in this article, with selected model details**

| Reference | Model name | Pre-failure deformation | Failure criterion | $K_0$ value in London Clay | Percentage unloading |
|---|---|---|---|---|---|
| Addenbrooke et al. (1997) | LE-PP | Linear elastic, stiffness increasing with depth | Mohr Coulomb, c′ = 5kPa, φ = 25° | 1.5 | 100% only achieved $V_l$ = 1.89% |
| | L4 | Nonlinear logarithmic stiffness decay (Puzrin & Burland, 1996) – allows stress reversal to reinvoke small strain stiffness, isotropic | Mohr Coulomb, c′ = 5kPa, φ = 25° | 1.5 | 80% to $V_l$ = 3.3% |
| | J4 | Nonlinear trigonometric stiffness decay (Jardine et al., 1986), isotropic | Mohr Coulomb, c′ = 5kPa, φ = 25° | 1.5 | 75% to $V_l$ = 3.2% |
| | AJ4i | Nonlinear trigonometric stiffness decay (Jardine et al., 1986), anisotropic with realistic parameters | Mohr Coulomb, c′ = 5kPa, φ = 25° | 1.5 | 76% to $V_l$ = 3.2% |
| | AJ4ii | Nonlinear trigonometric stiffness decay (Jardine et al., 1986), with unrealistically high anisotropy | Mohr Coulomb, c′ = 5kPa, φ = 25° | 1.5 | 57.5% to $V_l$ = 3.2% |
| Franzius et al. (2005) | M1 | Exactly the same as for J4 above | Mohr Coulomb, c′ = 5kPa, φ = 25° | 1.5 | 80% to $V_l$ = 3.3% |
| | M2 set 1 | Very similar to AJ4i above | Mohr Coulomb, c′ = 5kPa, φ = 25° | 1.5 | 67% to $V_l$ = 3.3% |
| Grammatikopoulou et al. (2008) | M3-SKH-1 | Modified 3-surface kinematic hardening model, explicitly modelling stress history since deposition of the London Clay and effect of stress path direction on stiffness. Small strain stiffness similar to J4. | Mohr Coulomb, c′ = 0kPa, φ = 22.5° | Varies. $K_0$ = 0.95 at tunnel axis level | 95% to $V_l$ = 3.3% |
| | M3-SKH-1 softer | As above, but small strain stiffness lower than J4. | Mohr Coulomb, c′ = 0kPa, φ = 22.5° | Varies; $K_0$ = 0.95 at tunnel axis level | not given |
| González et al. (2012) | High $E_0$ bonded | Modified 3-surface kinematic hardening model, including all structure effects, not only stress history (Rouainia & Wood, 2000). Small strain stiffness similar to J4. | Mohr Coulomb, c′ = 0kPa, φ = 22° | Used same as Grammatikopoulou et al. (2008) | 86% to $V_l$ = 3.23% |

al., 2007). Addenbrooke et al. assumed $K_0$ to be a constant value of 1.5 in the London Clay.

Laboratory measurements of the small strain stiffness of London Clay led to the development of soil constitutive laws that could replicate this behaviour in a numerical model, e.g. a trigonometric relationship (Jardine et al., 1986) or a logarithmic relationship (Puzrin & Burland, 1996). Gunn (1993) used Jardine et al.'s (1986) trigonometric relationship between stiffness parameters and strain level and found that predictions could be considerably improved by its use, but the trough was still far too wide and shallow. He speculated that allowing for different stiffness properties in compression or extension stress paths, or including anisotropy (where the horizontal stiffness is higher than the vertical stiffness) may improve the results.

Addenbrooke et al. (1997) compared three different small strain stiffness models, 'L4', 'J4' and 'AJ4i', logarithmic, Jardine and anistropic Jardine respectively, which are also shown on Figure 1, and brief details are given in Table 1. As Gunn (1993) found, there is a marked improvement in using nonlinear small strain stiffness models compared to linear elastic models. This is because the higher stiffness at small strains serves to concentrate ground movement closer to the tunnel. Franzius et al. (2005) performed similar 2D plane strain analyses of St James's Park with Jardine models similar to J4 and AJ4i, also listed in Table 1, which gave similar results and so are not shown on Figure 1 for clarity.

As well as elevated stiffness at small strains, London Clay is also known to exhibit stiffness anisotropy. This is where the horizontal stiffness is higher than the vertical stiffness. The effect of a realistic value of anisotropy can be seen by comparing the J4 (isotropic) and AJ4i (anisotropic) curves in Figure 1. Anisotropy does deepen and narrow the settlement trough, but the effect is small, at least for realistic values of anisotropy, so there must be something else going on.

In search of missing phenomena to model, with the aim of narrowing the trough even more, researchers have looked to the use of 3-surface kinematic hardening models (Stallebrass et al., 1994). These can explicitly model the overall stress history of the soil, such as overconsolidation, and recent stress history, such as stress path reversals. Whether stress path reversals in a soil element really causes an increase in stiffness is in doubt, as Clayton & Heymann (2001) demonstrated that if the creep rate due to the first loading path is allowed to reduce to a negligible level (and for London Clay this takes 6-12 days), then there is no increase in stiffness on stress path direction change, rather, the stiffness is related to the direction of the stress path relative to the gross yield surface.

However, reservations aside, it is interesting to see the effect of modelling recent stress history. The London Clay was originally much thicker and there were overlying deposits. Approximately 200m was then gradually eroded, followed by deposition of the more recent alluvial deposits and made ground. This deposition of about 7m of superficial deposits at St James's Park represents the most recent stress path, therefore, a decrease of vertical stress would constitute a change in stress path direction and would result in a higher initial stiffness, and vice-versa.

Grammatikopoulou et al. (2008) used a modified 3-surface kinematic hardening (M3-SKH) model, explicitly modelling stress history since deposition of the London Clay and the effect of stress path direction on stiffness. This is shown in Figure 2, where 'M3-SKH-1' has similar stiffness to Addenbrooke et al.'s J4 model, and 'M3-SKH-1 softer' has a reduced stiffness.

Figure 2 shows that modelling the effect of recent stress history does make the settlement trough narrower and deeper. This is due to stress reversal at the crown due to unloading, which results in a higher stiffness response, and a continuation of approximately the same stress path direction to the sides of the tunnel where there is an increase in compression, resulting in a lower stiffness response.

Grammatikopoulou et al. (2008) also found that if the recent stress history effect were ignored, then the M3-SKH model gave very similar results to the J4 model, even though the explicit modelling of the previous stress history meant that calculated $K_0$ values were much lower at 0.95 at tunnel axis level, compared to a constant value of 1.5 used by Addenbrooke et al. (1997).

González et al. (2012) have also joined the St James's Park modelling club. They have attempted to include the 'structure' of the London Clay in a model. 'Structure' describes the difference between intact soil and a completely reconstituted specimen of the same soil, which results in a higher strength and stiffness at the same void ratio (Gasparre et al., 2007). Therefore, it covers not just stress history, but also chemical effects such as base exchange, bonding and weathering. González et al. (2012) used a 3-surface kinematic hardening model to model the way plastic strains affect the soil structure. The St James's Park surface settlements predicted by this model are also shown on Figure 2, and there appears to be an improvement in prediction, with the settlement trough being deeper and narrower than the other models. González et al. (2012) ran the same model without the structure effect, and this should have given similar results to Grammatikopoulou et al. (2012), since the same $K_0$ and intrinsic preconsolidation values were used as well as a similar maximum small strain stiffness, but the settlement trough was narrower. This anomaly was not explained.

## Some final thoughts

Despite repeated attempts at the replication of the St James's Park settlement trough using advanced soil models in the most investigated geomaterial in the world, the prize has not yet been claimed. And the work reviewed here, it must be remembered, used volume loss as an input to a 2D model, so it was only the trough shape that needed to be matched. This highlights just how much we still don't know about soil behaviour, and why we still heavily rely on empirical methods for settlement prediction.

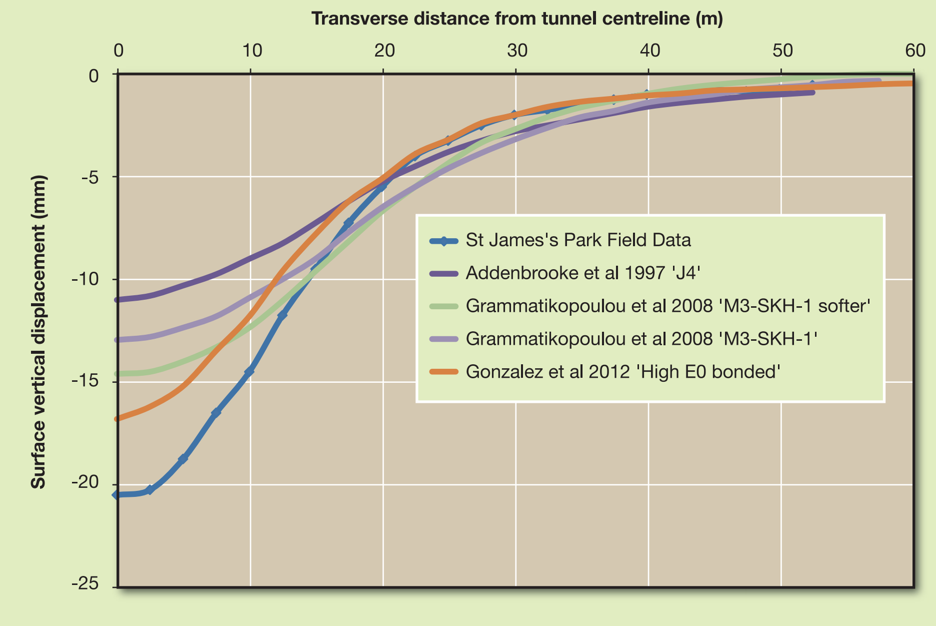
Tunnel designers often clash with geotechnical engineers on their estimates of $K_0$ in London Clay. The geotechnical engineers have to go with what the laboratory or in situ tests tell them, but the tunnel designers know that it is difficult to model a tunnel in a realistic manner with high values of $K_0$.

It is not made clear in any of the papers referred to in this article exactly how the relaxation process is done. If the in situ stress field is reduced proportionally, then when $K_0 > 1$ the stresses after relaxation will still be higher in the horizontal direction. If the tunnel were then to be installed, it would likely ovalise with an increase in the vertical diameter and a decrease in the horizontal diameter. This rarely happens in practice, tunnels nearly always squat (Wright, 2013).

There are other aspects of London Clay that we still do not model, for instance, fissures, claystones, sand lenses and natural variability. The effects of these are not easy to quantify in laboratory tests, which tend to be on intact specimens that are free of these fabric effects.

Perhaps one day someone will find the key to this puzzle. Until then, we won't know for sure which of Vaughan's hypotheses is true.

**Figure 2: Modelling of St James's Park JLE Westbound tunnel - influence of recent stress history and structure**



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