In this article, Dr Benoît Jones compares methods of estimating horizontal ground movements due to tunnelling with some field measurements.

Horizontal ground movements part 2

WHEN EXCAVATING A NEW TUNNEL alongside another structure, we sometimes want to know how much that structure will move so we can estimate the structural and serviceability impacts. For some structures, particularly other tunnels, a first approximation can be made by using simple analytical methods and case history data to predict the 'greenfield' horizontal ground movements and imposing these on the structure.

My article in the previous issue looked at the prediction of horizontal ground movements at axis level of a tunnel using elastic and elastoplastic analytical solutions. In this issue we will look at a few of the case histories and empirical methods that are available.

Elastoplastic axisymmetric 2D models

As described in the last issue, Mair & Taylor (1993) presented an axisymmetric elastoplastic model for unloading of a cylindrical cavity in undrained clay. To recap, this has the form:

$$\frac{u_r}{R} = \frac{S_u}{2G}\left(\frac{R}{r}\right) exp\left[\left(\frac{\sigma_0 - p_i}{S_u}\right) - 1\right]$$

Where u_r is the radial convergence at a point in the ground a distance r from the tunnel centre, R is the tunnel radius, σ_0 is the in situ total stress (assumed the same in all directions, i.e. coefficient of earth pressure at rest $K_0 = 1.0$), p_i is a uniform internal support pressure, S_u is the undrained shear strength of the clay and G is the soil's shear modulus.

The $(\sigma_0 - p_i)/S_u$ term is similar to the definition of stability number. This number is an indication of how close to failure the tunnel is.

Empirical data and methods

Mair & Taylor (1993), as well as proposing the elastoplastic solutions we saw in the previous article, also compared them to horizontal ground movements measured around tunnels constructed in London Clay at Green Park, Regents Park, Brixton, Angel and Netherton Road. Their data has been redrawn in Figure 1. As you move from left to right and $R/_r$ gets larger, you are getting closer to the tunnel, and as you would expect, u_r increases. The data appears to follow a linear relationship between u_r/R and $R/_r$, which implies a constant volume undrained condition. Therefore, the field measurements appear to be doing what one would expect.

The best fit line equation was not given by Mair & Taylor (1993), but calculating it from the figure in their paper it is approximately:

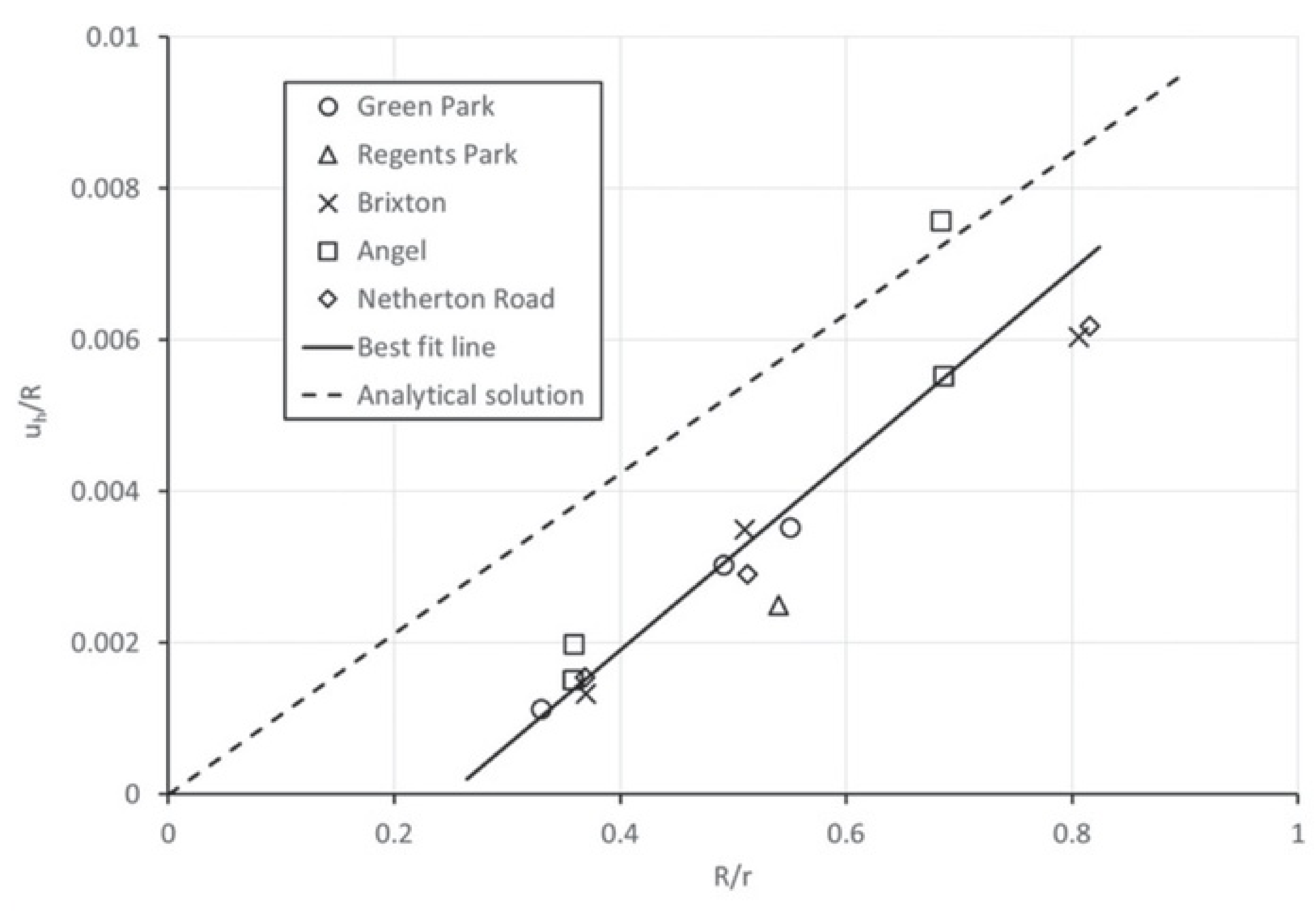
$$\frac{u_r}{R} = 0.01254\left(\frac{R}{r}\right) - 0.00331$$

If we compare this to the axisymmetric elastoplastic equation, it has a similar form, but it has an intercept whereas the analytical solution equation does not. The intercept arises because the situation is not axisymmetric and gravity plays a role in the deformation of the ground around a tunnel. Mair & Taylor also found that vertical ground movements above a tunnel have a positive intercept on the y-axis.

In case you weren't convinced, also shown on Figure 1 as a dashed line is the analytical solution, assuming values recommended by Mair & Taylor of G/S_u = 100, N^* = 2.5 and p_i/σ_0 = 0.3. There is no intercept and as you go further from the tunnel (as you move left on the graph and $R/_r$ approaches zero) the movements get smaller and smaller but never quite get to zero. The field data, on the other hand, show that there is a finite zone of influence in a horizontal direction of approximately $4R$ (or when $R/_r$ = 0.25 if you prefer to think of it in that way).

The analytical solution also overestimates horizontal ground movements, although this gap closes slightly as you get closer to the tunnel.

Figure 1: Horizontal ground movements due to construction of a tunnel, redrawn from Mair & Taylor (1993).



More recent empirical data

Since 1993 was a while ago, I have added some more recent data to Mair & Taylor's chart, in Figure 2. The data comes from the Heathrow Terminal 5 Stormwater Outfall tunnel headshunt (Jones et al., 2008) and the Heathrow Express Trial Tunnel (Deane & Bassett, 1995). There is good agreement with the older data. If anyone wants to add their own data, email me for the excel file.

So how can we reduce horizontal ground movements?

There are two main ways of reducing horizontal ground movements. The first is to reduce the size of your tunnel. The second is to provide more support pressure so that p_i/σ_0 has a higher value. This can be achieved by actually applying pressure, for instance by using compressed air, an EPB machine or a slurry machine, or by reducing the distance to ring closure in a sprayed concrete tunnel. In Figure 3 the analytical solution predicts what will happen as n is increased, where $n = p_i/\sigma_0$.

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Figure 3 also highlights a difficulty with using the analytical solutions. Before the tunnel is built we don't know what the n value will be, particularly if the construction method or the geology is different from previous experience. Other analytical solutions, such as that of Loganathan & Poulos (1998) require volume loss as an input parameter. Nonetheless, the analytical solutions are a useful first approximation and an effective tool for sensitivity analysis, i.e. finding the limits of the range of ground movements by varying the input parameters.

Figure 2: More recent field data of horizontal ground movements

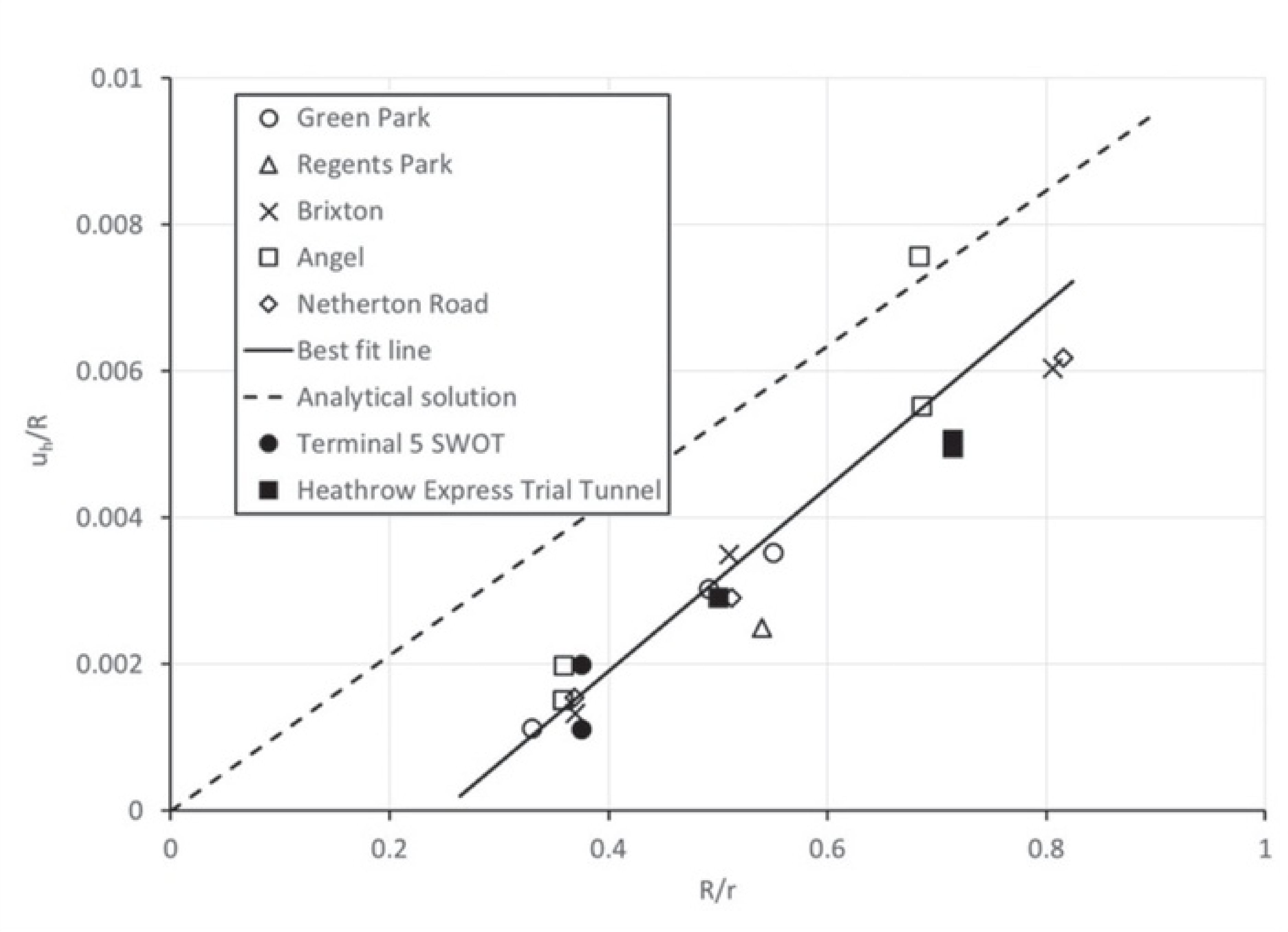
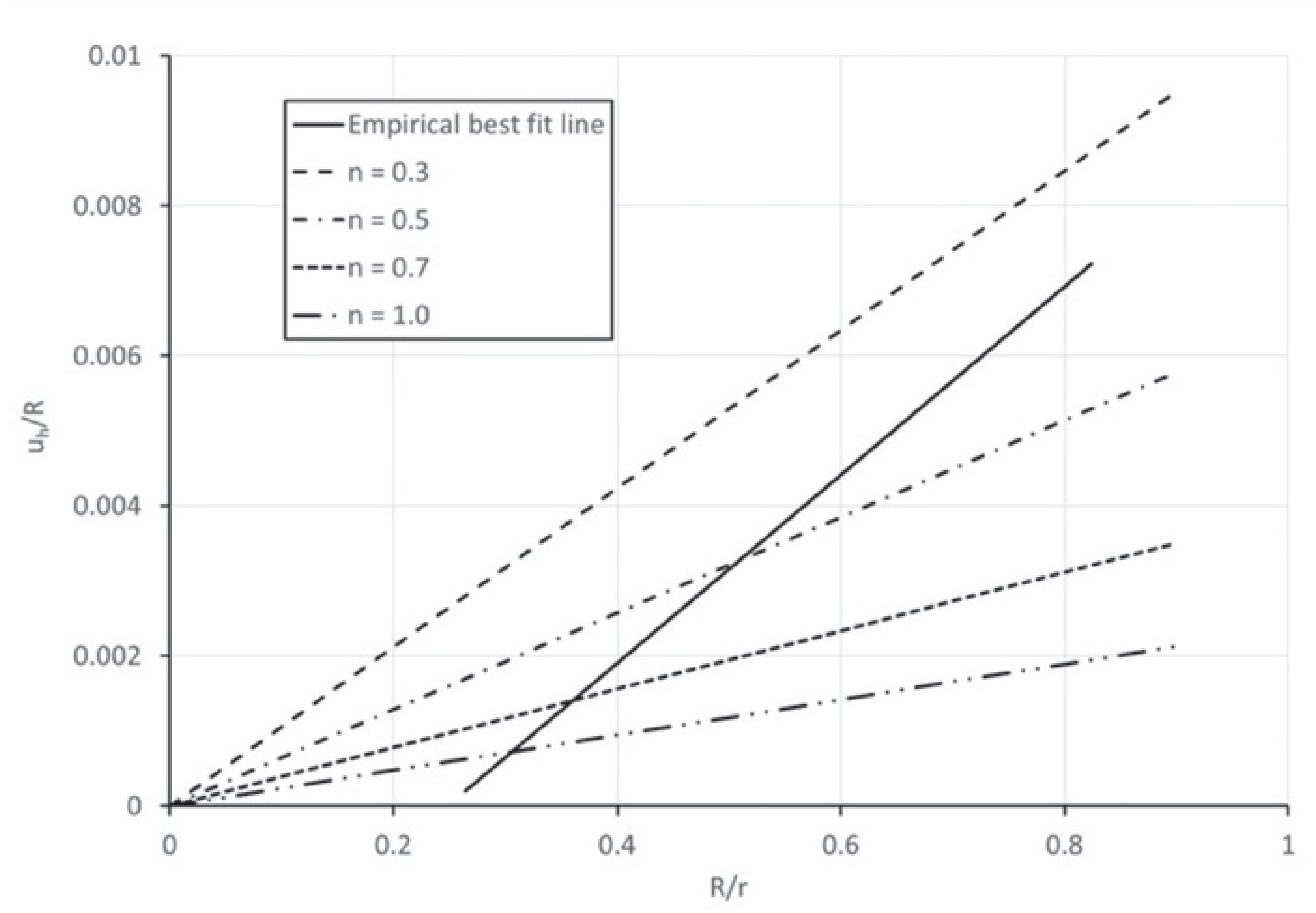


Figure 3: Effect of increasing support pressure, where $n = p_i/\sigma_0$, on horizontal ground movements as calculated by an elastoplastic analytical solution (Mair & Taylor, 1993).



Conclusions

It seems that, where case study data is available, empirical methods provide the best estimate of horizontal ground movements either side of a new tunnel construction. However, when tunnelling in soil that isn't London Clay some other methods are needed to make a first approximation.

Analytical solutions are an incredibly useful tool, but require understanding of assumptions that underpin them, such as axisymmetry, ground behaviour and input parameters such as the support pressure p_i or volume loss, but the same could be said of any form of modelling, whether analytical or numerical. Hopefully these articles have shed some light on this.

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