ASSESSMENT OF BS8006:1995 DESIGN METHOD FOR REINFORCED FILL LAYERS ABOVE VOIDS

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Abstract: In areas of former mining activity or in karstic ground conditions, propagation of potential cracks to the ground surface and the creation of sinkholes could prove dangerous for surrounding infrastructure and buildings placed on the original ground. The potential risk of failure may be mitigated by constructing a geosynthetic reinforced fill layer over the original ground surface and then placing buildings and services on such a layer. In the eventuality of the sinkhole opening in the original ground, this fill layer will transfer the load to the surrounding ground and hence reduce damage to structures on the top of the fill. Such a fill layer is also known as a load transfer platform (LTP).

In the UK, the current principal design guidelines for a geosynthetic reinforced LTP above a void is the British Standard BS8006:1995.

This paper presents results from a finite element parametric study undertaken to investigate the behaviour of geosynthetic reinforced LTPs above voids. A number of parameters were varied in the analyses, including void geometry, the properties of the geomembrane, as well as the properties of the fill layer. Consistent results were obtained and interpreted in terms of the main design aspects, such as soil arching, shape of deformed geosynthetic, the shape of zone of subsidence and the surface settlement of the fill. The results are also compared with the predictions obtained from BS8006. Some conclusions are then provided as to how existing design methods could be improved.

Keywords: design method, finite element, geosynthetic, load transfer platform

INTRODUCTION

The literature contains a number of case histories where geosynthetic reinforced fill load transfer platforms have been used to support roadways and railway lines in areas prone to sinkhole formation, e.g. Bonaparte & Berg (1987), Cook (1989), Kempton (1992), Kempton *et al* (1996) and Paul (2004). These sinkholes or voids, or even just relatively weak pockets of soil, may exist prior to the construction of these structures, or develop over time. They might be expected in areas of former mining activity, karstic terrain, or potentially collapsible soils such as unengineered fill. Where geosynthetic reinforced LTPs are present, the risk of these voids propagating upwards to the ground surface is significantly reduced.

A number of design methods exist in the literature for the design of a geosynthetic reinforced fill LTP above a void. The principal guidance in the UK is the British Standard BS8006:1995.

A parametric study has been undertaken using finite element analysis, the results of which are used to investigate different aspects of behaviour of a geosynthetic reinforced LTP over a void. The model is described here first; full details of both the model and the results are given in Potts (2007). A series of small scale laboratory tests have also been undertaken to provide confirmation of the behaviour observed in the numerical analysis. In this paper the results are used to assess the validity of the assumptions made in the design method advocated by BS8006:1995.

BS8006:1995 DESIGN METHOD

The approach advocated by BS8006:1995 assumes the geometry shown in Figure 1, in which the meaning of the geometrical symbols is also defined. The void is assumed to form in a competent subsoil, so that the surrounding material can be considered to be rigid.

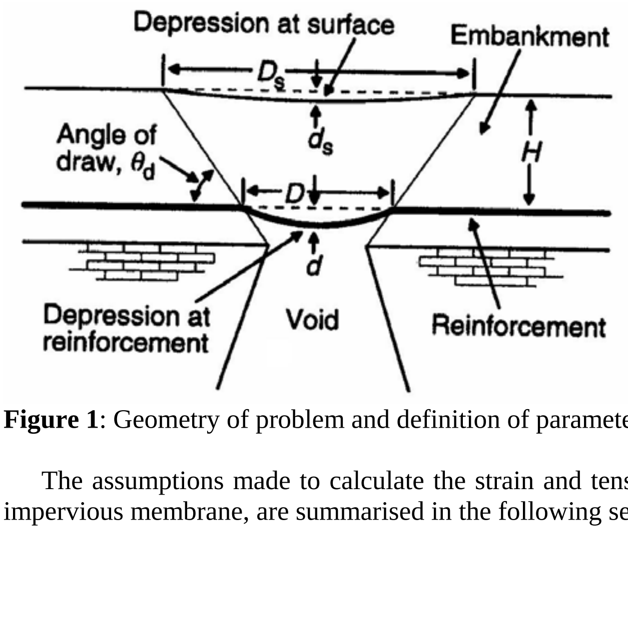

Figure 1: Geometry of problem and definition of parameters (after BS8006:1995)

The assumptions made to calculate the strain and tensile load in the geosynthetic, which is assumed to act as an impervious membrane, are summarised in the following sections.

Maximum allowable reinforcement strain

When the void forms beneath it, a funnel of soil above the void is assumed to move downwards under the influence of its own weight and any surcharge loads. This funnel is defined by an angle of draw, θ_d, which it is suggested should be assumed to be the angle of internal shearing resistance, ϕ', if no better information is available. No volumetric expansion of the fill is assumed to occur during this shearing, and thus the volume of displaced fill at the level of the reinforcement is equal to the volume of displaced fill at the ground surface. This assumption results in the following expressions for infinitely long and circular voids respectively:

For an infinitely long void:

$$V = \frac{2dD}{3} = \frac{2d_s D_s}{3} \tag{1a}$$

For a circular void:

$$V = \frac{dD^2}{3} = \frac{d_s D_s{}^2}{3} \tag{1b}$$

Where the symbols are as defined in Figure 1. No arching is assumed to develop in the fill, with the consequence that the pressure applied to the geosynthetic reinforcement above the void is vertical and uniformly distributed. The deformed shape of the geosynthetic is assumed to be a parabola, which is a reasonable approximation to a catenary equation for the low values of d/D likely to be allowed in this situation. The length of the parabola when extended is used to determine the maximum strain, as follows:

$$\varepsilon_{\max} = \frac{8d^2}{3D^2} \tag{2}$$

By combining equations (1) and (2) and using the geometry shown in Figure 1, the maximum strain, ε_{max}, in the geosynthetic are obtained for infinitely long and circular voids respectively:

For an infinitely long void:

$$\varepsilon_{\max} = \frac{8\left(\frac{d_s}{D_s}\right)^2\left(D + \frac{2H}{\tan\theta_d}\right)^4}{3D^4} \tag{3a}$$

For a circular void:

$$\varepsilon_{\max} = \frac{8\left(\frac{d_s}{D_s}\right)^2\left(D + \frac{2H}{\tan\theta_d}\right)^6}{3D^6} \tag{3b}$$

Reinforcement tensile properties

For a uniformly distributed stress acting on a catenary, the maximum tensile load per metre run in the reinforcement, T, is given by:

$$T = 0.5\lambda(f_{fs}\gamma H + f_q w_s)D\sqrt{1 + \frac{1}{6\varepsilon}} \tag{4}$$

Where f_{fs} and f_q are partial factors of safety and λ is a coefficient of loading, the magnitudes of which are specified in the BS8006, γ is the bulk unit weight of the fill material, and w_s is the surcharge intensity on top of the fill.

FINITE ELEMENT MODEL

In order to evaluate the appropriateness of the assumptions made in BS8006, a parametric study has been undertaken using finite element analysis. A relatively simple model has been created using the Imperial College Finite Element Program, ICFEP (Potts & Zdravkovic, 1999), to be compatible with the formulation of the existing design guidance. A fill layer of variable thickness (up to 4m), constructed in horizontal layers, is placed above a rigid layer with a void of variable width or diameter (up to 4m). This void can be created before or after the construction of the fill layer, and take the form of either a circle or infinitely long trench in plan. Because of the symmetry of the problem, a half-mesh may be employed. A typical mesh used for either axisymmetric or plane strain analysis is shown in Figure 2.

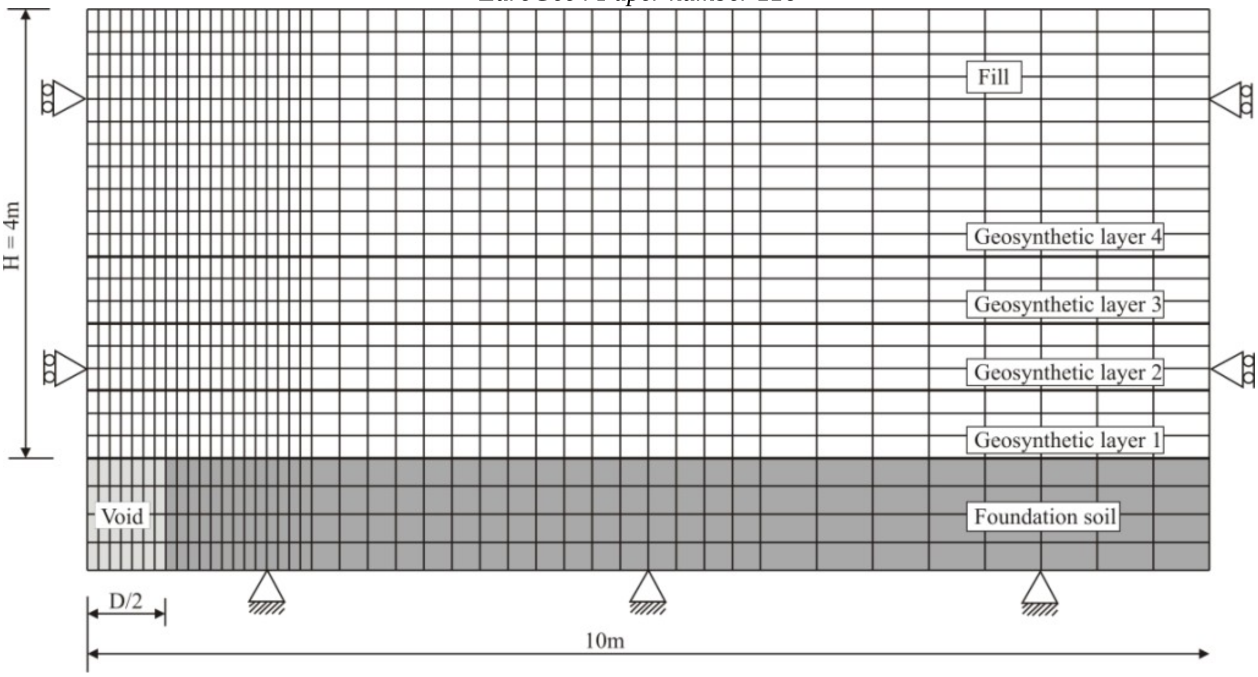

Figure 2: Typical finite element mesh used in parametric study

The solid elements have been modelled using 8-noded isoparametric elements, and a Mohr-Coulomb soil model in which the angle of internal shearing resistance, angle of dilation, Young’s Modulus and coefficient of earth pressure can be varied independently for the fill material.

Between the rigid layer and the fill is a row of 3-noded membrane elements used to model the geosynthetic; up to three further layers at different heights in the fill were also modelled during the parametric study. These membrane elements have no resistance to bending and only carry axial loads – this allowed the tensile modulus and ultimate tensile strength to be varied during the course of the study.

The effects of allowing slippage to occur along the soil-geosynthetic interface were assessed by creating 6-noded joint elements along these boundaries, and varying the angle of interface friction. Large displacement analysis was used in all cases.

LABORATORY TESTS

A series of small scale laboratory tests have also been undertaken to provide qualitative validation of the findings of the parametric study. These model tests were undertaken in a strongbox incorporating a moveable platform at the base, to replicate the formation of a void. In these tests the void width, fill thickness, and compaction properties of the fill were varied. The resulting surface settlements were monitored using a row of LVDT transducers positioned across the settlement trough along the centreline of the box.

RESULTS

In this paper the results of the parametric study and model tests are used to assess the validity of the assumptions made in the BS8006 design guidance. Different aspects of the behaviour of a geosynthetic reinforced LTP are considered separately in the following sections.

Shape of subsidence trough

BS8006 assumes that the subsiding fill is in the form of a funnel, the slope of which is suggested may be at the angle of internal shearing resistance in the fill, ϕ'. It is therefore reasonable to suppose that the shape of this zone will depend on ϕ', which is one of the variables in the parametric study. Figure 3 shows the accumulated displacement vectors obtained from analyses of an infinitely long void with a width of 2.0m beneath a 4.0m thick fill layer for three different values of ϕ' in the fill. The movement is almost purely vertical, and in all three cases there is no evidence of significant movement occurring anywhere in the fill other than directly above the void. Consequently it is evident that the parametric study results do not support the assumption of a funnel-shaped subsidence zone, and that it may be more appropriate to consider the subsiding fill to form a vertical column immediately above the void instead.

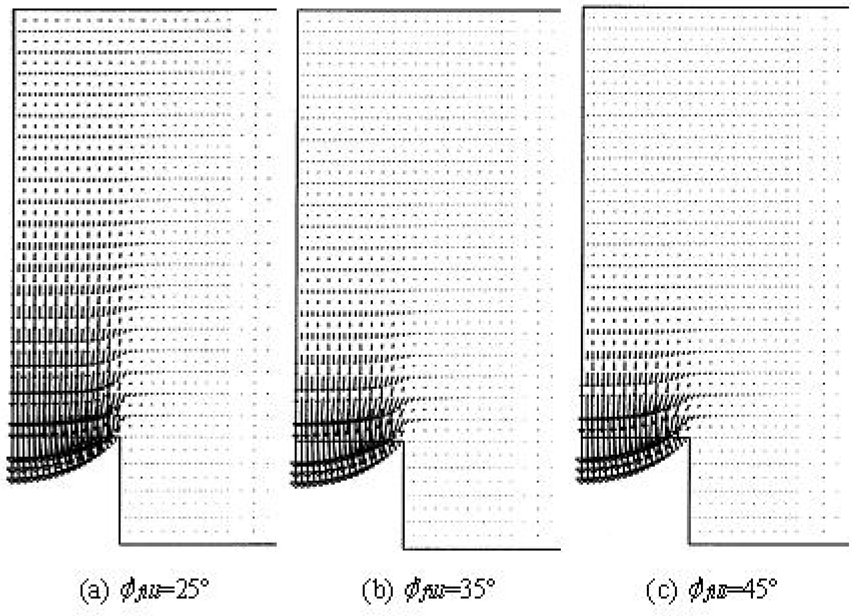

Figure 3: Vectors of accumulated displacement above 2.0m wide infinitely long voids when ϕ' varies

Arching behaviour in the fill

Another observation that may be made from Figure 3 is that the vast majority of the fill movement occurs close to the void, and that as the height above the void increases the magnitude of the accumulated displacements reduces. One possible explanation for this is the development of arching behaviour in the fill.

Arching arises as a consequence of the fill material redistributing the stresses in the soil when support is lost beneath. A stable arch forms when the stresses are redistributed sufficiently well to achieve equilibrium, in which case the overlying fill is supported. The existence of arching in the fill may be observed from plots of the orientation of the major principal stress in the fill material, an example of which is presented in Figure 4. This figure shows the orientation of the major principal stress in the fill above an infinitely long void with a width of 2.0m beneath a 4.0m thick fill layer when ϕ'=35º (i.e. the same analysis as case (b) in Figure 3).

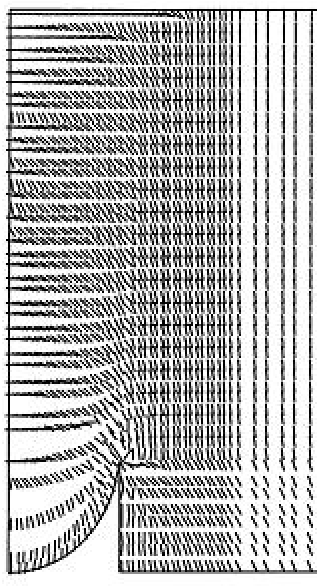

Figure 4: Orientation of major principal stress in the fill above a 2.0m wide infinitely long void when ϕ'=35º

The shedding of the load is clear throughout the deformed soil column, being bound by a nearly vertical shear surface propagating from the edge of the void. On the other side of this surface the major principal stress remains mainly vertical as this part of the fill is not disturbed.

Although the zone of disturbed soil does not always propagate through the full thickness of the fill as in Figure 4, (which depends on the size of the void), all of the analyses in the parametric study indicated that immediately above the void the soil stresses were disturbed, and that therefore stress redistribution had developed in all cases.

BS8006 assumes that no arching develops in the fill material. This has significant implications for the design of a geosynthetic reinforced LTP, as discussed in the following sections.

Tensile load in reinforcement

As a consequence of arching behaviour, the vertical pressure acting on the geosynthetic will be reduced from the full self-weight of the fill and any additional surface surcharge loads. This is therefore likely to be overestimated by BS8006. Figure 5 compares the tensile load in the geosynthetic predicted from the finite element analysis and BS8006. In order to make these predictions, the maximum geosynthetic strain used in the BS8006 calculation is taken from the finite element analysis. Figure 5 shows the results for a series of infinitely long voids of varying widths beneath a 4.0m thick fill layer in which ϕ' is 35º.

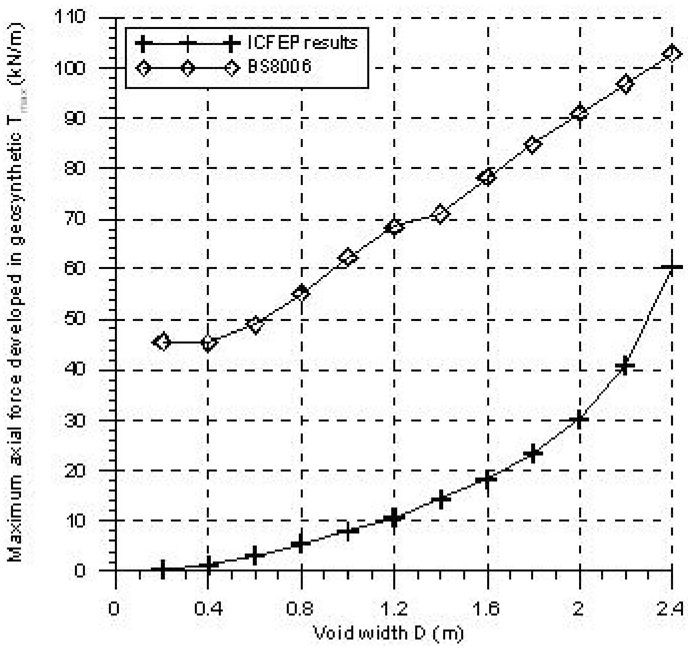

Figure 5: Comparison of maximum tensile load in geosynthetic predicted using finite element analysis and BS8006

Even though the input strains are the same, the predictions made using BS8006 are seen to be well in excess of the results of the finite element analysis. This is attributed to the difference in pressure applied to the geosynthetic as a result of arching in the fill.

It should be noted that in the finite element analysis, the tensile load and strain level are directly related by the tensile modulus. This is not the case with BS8006, and the tensile modulus that would be inferred by the results presented in Figure 5 would be substantially higher than that used in the finite element analysis. In many cases it may not be feasible to find a commercially available material capable of satisfying the BS8006 predictions. Alternatively, larger displacements would need to be allowed at both the level of the geosynthetic and the ground surface.

Shape of deflected geosynthetic

BS8006 assumes that the geosynthetic deforms into a catenary (approximated by a parabola), because it is assumed that the applied loads are purely vertical. As discussed above, this is not the case because the fill will try to shed load laterally, and therefore there is likely to be a horizontal component to the pressures applied to the reinforcement. In order to assess the influence of this on the deflected shape of the geosynthetic, the displacements of the membrane elements in the analysis have been compared with a parabola and a circular arc. To assess the shape alone, the circular arc and parabola have been generated using the displacement above the centre of the void predicted by the finite element analysis. Typical results are shown in Figure 6, for the same analysis of an infinitely long void, 2.0m wide beneath a 4.0m thick fill layer in which ϕ' of 35º is used to generate Figures 3(b) and 4.

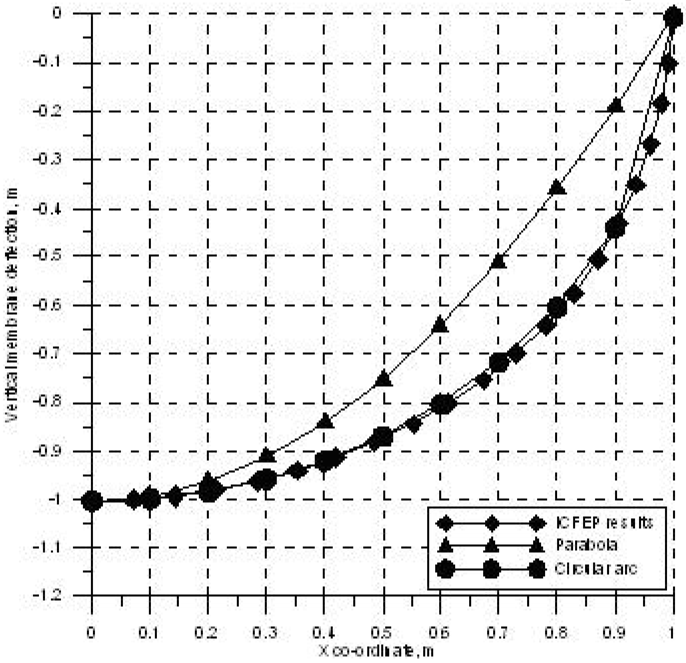

Figure 6: Comparison of deformed membrane shapes above a 2.0m wide infinitely long void when ϕ'=35º

In the case presented in Figure 6, the circular arc replicates the pattern of displacement seen in the finite element analysis extremely well, whereas the displacements are underpredicted by the parabola at all points between the centre of the void and the edge. Although the correlation between the circular arc and the results of the finite element analysis is not always as good as shown here, the circular arc was found to provide a better match than the parabolic approximation in all of the cases analysed.

The difference between geosynthetic strain levels at a given deformation is small as long as the deflection is small; however the differences become more significant when the deformations are larger. Not only is the circular arc more consistent with the nature of the pressure applied to the geosynthetic, but will enable more accurate determination of the geosynthetic strain level.

Surface Settlements

A typical comparison of the normalised surface settlements predicted using finite element analysis and BS8006 is shown in Figure 7. The analysis shown here is of a 0.16m wide, infinitely long void, beneath a 0.32m thick fill layer. This example has been chosen because laboratory model test results are also available to be included in the comparison. The settlement trough for BS8006 shown in Figure 7 has been computed assuming geosynthetic deflections compatible with the properties of the reinforcement material used in the model tests. All of the curves have been normalised with respect to the maximum settlement d_s for each of the curves, and an example Gaussian error curve is included for comparison.

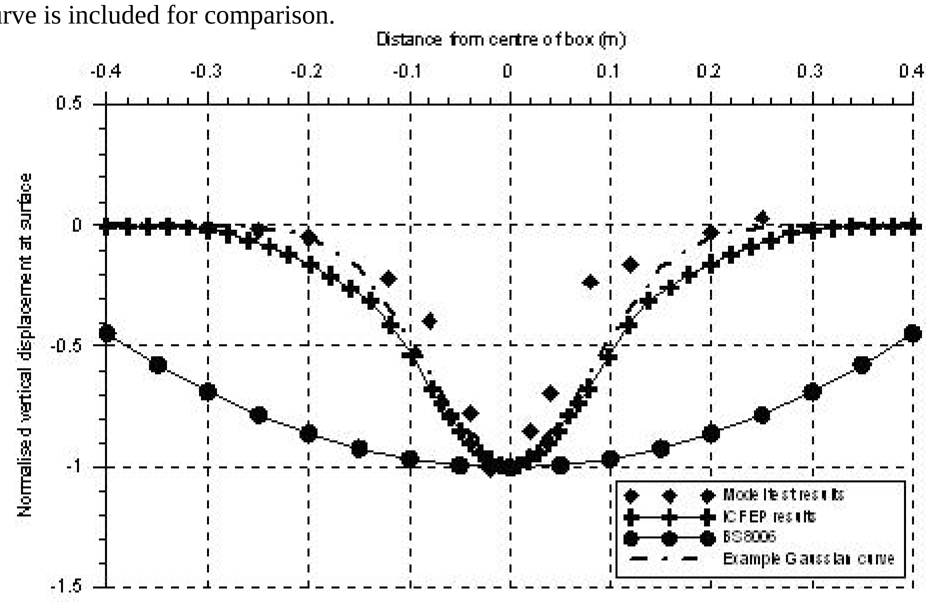

Figure 7: Comparison of surface settlement profile seen during laboratory model test with predictions made using finite element analysis and BS8006 for a 0.16m wide trench void beneath a 0.32m thick fill layer in which ϕ' is 35º

This result is typical of all cases analysed. The shape of the settlement trough predicted using finite element analysis is much closer in form to the settlement troughs measured in the model tests undertaken in the laboratory. BS8006 consistently predicts surface settlement troughs that are wider than the finite element analysis predictions or observations from the model tests. This could be non-conservative, since the resulting slope of the ground surface is low compared to the model tests and finite element analysis, and could lead to underestimation of the likely damage to overlying infrastructure and buildings. It should be noted, however, that predictions of maximum surface settlement, d_s, using BS8006 were similar to those from the numerical analysis and model tests in some of the cases considered.

The shape of the settlement trough from both the finite element analysis and model tests is shown to be similar to that seen above advancing tunnels, which can be represented using a Gaussian error curve (see Figure 7). This approach has been developed in Potts (2007) and is presented in detail in Potts and Zdravkovic (2008).

CONCLUSIONS AND RECOMMENDATIONS

A parametric study investigating the behaviour of a geosynthetic reinforced fill over voids, representing a load transfer platform, has been undertaken using finite element analysis, and the results have been used to assess the design method for such structures given in BS8006:1995. This assessment has identified a number of areas in which BS8006 could be refined, the most important of which is the incorporation of soil arching effects.

By ignoring the benefits due to the development of arching in the fill material within the geosynthetic reinforced LTP, BS8006 makes very conservative predictions of the tensile force acting in the geosynthetic. This greatly limits the range of situations in which a geosynthetic reinforced LTP is a feasible solution.

The parametric study has shown that stress redistribution occurs as soon as any movement develops in the fill, and therefore that arching will develop as soon as a void forms, if the fill is of sufficient thickness. The level of conservatism in BS8006 might therefore be reduced by adopting a suitable arching theory to estimate the pressure acting on the geosynthetic. Further to this, the shape of the deformed geosynthetic might more accurately be described by a circular arc. This will allow more accurate determination of strain and tensile load, particularly for larger deflections.

Finally, the surface settlement profiles predicted using BS8006 have consistently been observed to have shallower slopes than seen in laboratory model tests or predicted using finite element analysis, which are more similar to the Gaussian distribution curve. This is of concern as any damage assessments for overlying infrastructure or buildings would be underestimated due to smaller differential settlements predicted using BS8006.

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