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The influence of anisotropy on calculations of ground settlements above tunnels

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ABSTRACT: Numerical analyses of ground movements above tunnels in soft ground using linear and isotropic stress strain models often give settlement troughs which are much wider than those observed in practice. Laboratory and in situ measurements of shear wave velocity in London Clay have revealed significant anisotropy in the shear modulus. Finite element analyses of the Heathrow Express trial tunnel have been carried out using a non-linear and anisotropic soil model and the calculated widths of the settlement troughs agree well with those observed in practice. The work demonstrates the significant influence of soil anisotropy on surface settlement troughs above tunnels.

ANISOTROPY AND GROUND MOVEMENTS ABOVE TUNNELS.

The shape of the trough of ground settlement above tunnels in soft ground is often approximated by a normal distribution curve and the width is characterised by the parameter i which is the distance from the centre of the trough to the point of inflection. The widths of settlement troughs can be related approximately to the depth of the tunnel axis z by $K = i/z$ and empirical values for K obtained from field observations were summarised by O'Reilly and New (1982). These correlations have been extended to include sub-surface settlement troughs (Mair et al, 1993).

In numerical analyses values assumed for ground loss at the tunnel and for soil stiffnesses can be adjusted so that the settlement calculated above the tunnel axis, or at some other point, corresponds to that observed but the calculated settlement troughs are usually much too wide. These differences may be attributed to a number of factors. The Authors have not found it possible to improve computed results sufficiently either by extreme assumptions of non-linearity or by considering the 3D effects of tunnel construction. Gibson (1974) showed that elastic calculations of surface settlement of footings are insensitive to the degree of anisotropy but Lee and Rowe (1989) found that calculated deformations around tunnels are highly sensitive to anisotropy.

It is often assumed that soils have equal stiffness in all horizontal directions but a different stiffness in the vertical direction. Such a material is termed orthotropic and, if it is elastic, its behaviour may be defined by five independent elastic constants. These are usually taken to be the vertical Young's modulus E_v, the horizontal Young's modulus E_h, two Poisson's ratios ν_{vh} and ν_{hh} and the shear modulus G_{vh}. Energy considerations lead to limits on the ranges and ratios of some of these parameters but the independent shear modulus G_{vh} can take any positive value (Pickering, 1970). Figure 1 shows three modes of shear deformation expressed in orthogonal axes with one vertical (v) and two horizontal (h_1 and h_2). Those in Figures 1(a) and (b) are governed by shear moduli which are dependent functions of E_v, E_h, ν_{vh} and ν_{hh}: for example, in Figure 1(b), $G_{hh} = E_h/[2(1+\nu_{hh})]$. The mode of shear deformation shown in Figure 1(c) is governed by the independent shear modulus G_{vh}. For isotropic materials $E_v = E_h = E$, $\nu_{vh} = \nu_{hh} = \nu$ and $G_{vh} = G_{hh} = E/[2(1+\nu)]$.

Figure 2(a) shows a rectangular tunnel represented in a simple finite element mesh of undrained (ie. constant volume) plane strain elements. Formation of the tunnel was represented by removing the weight and stresses in the elements within the rectangle. For isotropic soil the calculated settlement trough is shown by the line A in Figure 2(b). Line B shows results for an orthotropic soil in which the shear modulus G_{vh} has been reduced relative to the other

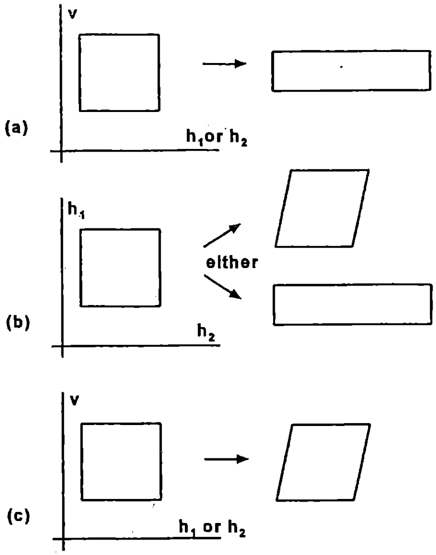

Fig. 1. Modes of shear deformation

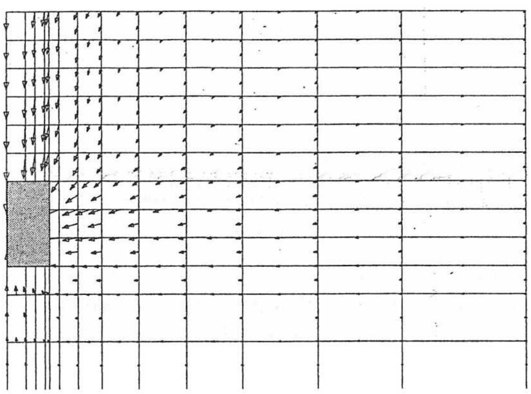

Fig. 2a. Rough finite element model of tunnel.

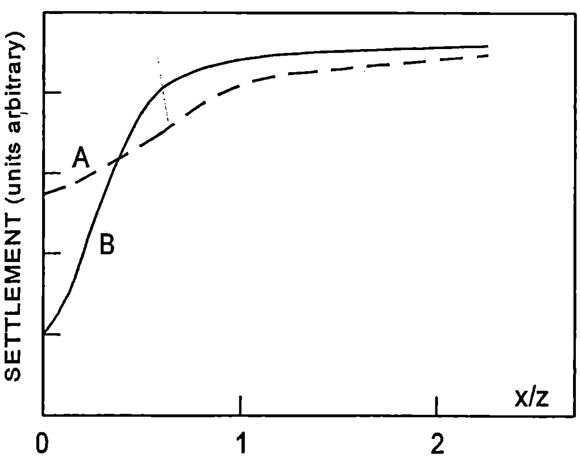

Fig. 2b. Computed settlement troughs

stifnesses so that $G_{vh} = 0.3G_{hh}$. This is a fairly severe value for the degree of anisotropy in the shear moduli but it is used here to illustrate the profound potential effect of anisotropy in values of shear moduli which are theoretically acceptable. The settlement trough line B for anisotropic soil is very much narrower than that given by line A for isotropic soil although in both cases settlement continues, with very small slope, to great distances from the tunnel axis. These results indicate the need for care in selection of bench marks for level which should be at considerable distance from the tunnel.

SMALL STRAIN STIFFNESS AND ANISOTROPY

An important stiffness parameter is G_0 the shear modulus at very small strain. This locates the initial portion of the stiffness-strain curve (Atkinson and Sallfors, 1991) and, for a particular class of soil, it can also characterise the whole stiffness curve. It is a soil parameter required in many numerical models for soil behaviour, particularly those which are elasto-plastic with yielding at small strains (Atkinson and Stallebrass, 1991; Simpson, 1992). G_0 is simply related to the velocity of shear waves by

$$G_0 = \rho V_s^2 \tag{1}$$

where ρ is the bulk density and V_s is the shear wave velocity. The velocity of shear waves in soils may be measured relatively simply in laboratory tests using bender elements (Dyvik and Madshus, 1985; Viggiani and Atkinson, 1995a;) and in situ (Butcher and Powell, 1995). For a particular fine-grained soil G_0 depends principally on the state described by the stress and overconsolidation ratio (Viggiani and Atkinson, 1995b) and for coarse grained soils it depends additionally on the voids ratio. For reconstituted samples which have been isotropically consolidated and then brought to an anisotropic stress state G_0 remains essentially isotropic (Viggiani and Atkinson, 1995b) but for undisturbed samples and for reconstituted samples which have been one-dimensionally consolidated and swelled G_0 is found to be distinctly anisotropic.

In tests on anisotropic soil in which G_0 is determined from measurements of the shear wave velocity the value determined depends on the direction of wave propagation and the direction of polarisation of the shear waves. Figure 3 illustrates cylindrical samples oriented with respect to the in situ axes with shear waves passing through them. The first subscript refers to the direction of wave propagation and the second refers to the direction of particle motion. In eqn 1 the

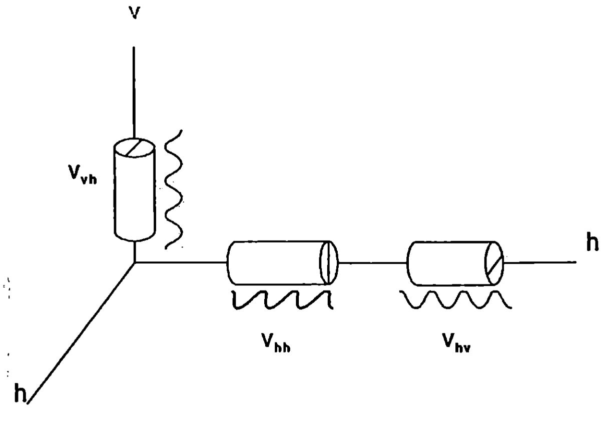

Fig. 3. Shear waves in laboratory samples

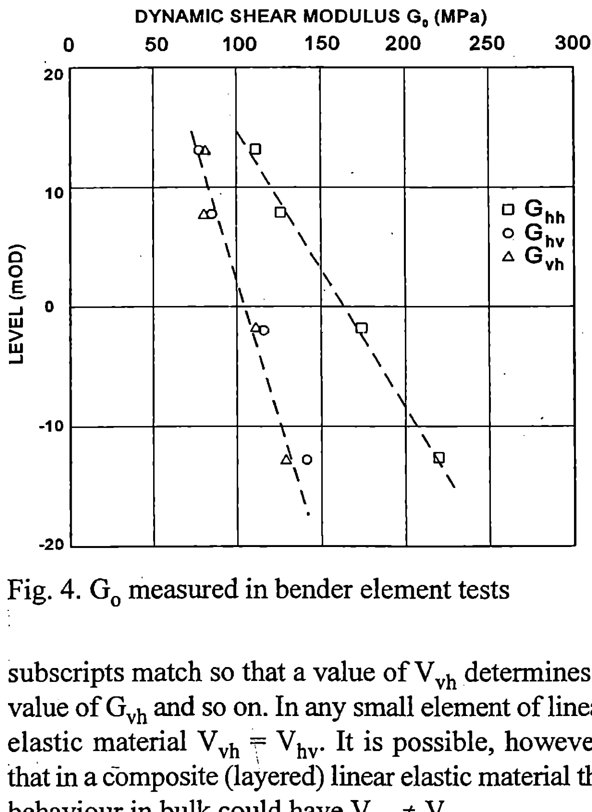

Fig. 4. G_0 measured in bender element tests

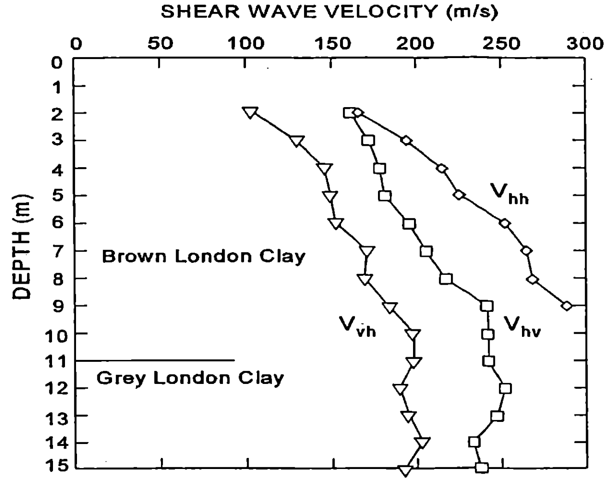

Fig. 5. In situ shear wave tests in London Clay

subscripts match so that a value of V_{vh} determines a value of G_{vh} and so on. In any small element of linear elastic material $V_{vh} = V_{hv}$. It is possible, however, that in a composite (layered) linear elastic material the behaviour in bulk could have $V_{vh} \neq V_{hv}$.

LABORATORY AND IN SITU MEASUREMENTS OF ANISOTROPY IN G_O

Figure 4 shows values of G_o measured in bender element tests on undisturbed 38mm dia samples of London Clay prepared by hand trimming from 100mm dia cores. The test samples were cut from the core vertically and horizontally and the bender elements were arranged to give the directions of propagation and polarisation with respect to the ground axes as indicated in Figure 3. The samples were firstly compressed isotropically and undrained and the shear wave velocity measured; they were then consolidated isotropically to the estimated mean in situ effective stress and the shear wave velocity measured again. During consolidation there was negligible change of volume and water content and the shear wave velocities were unchanged. The data in Figure 4 show an approximately linear increase in G_o with depth. The values of G_{vh} and G_{hv} are approximately the same at all depths but the values of G_{hh} are significantly larger. The degree of anisotropy G_{vh}/G_{hh} is about 0.65.

Figure 5 shows results of in situ tests carried out at a different location in the London Clay in which shear waves were transmitted vertically and horizontally with vertical and horizontal polarisation. Values of G_o can be obtained using eqn 1. For these data the values of V_{vh} (obtained using a seismic cone) differ from V_{hv} (from cross-hole tests). The difference might be caused by layering or other features of the soil fabric. In strata with stiffer and softer layers, horizontally propagating shear waves will tend to travel through stiffer layers while vertically propagating waves must travel through both stiffer and softer layers. From the data in Figure 5 the degree of anisotropy G_{vh}/G_{hh} is again about 0.65. Both the laboratory and the in situ tests clearly demonstrate that undisturbed London Clay has significantly anisotropic shear moduli.

NUMERICAL ANALYSES OF THE HEATHROW EXPRESS TRIAL TUNNEL

Figure 6 shows computed and observed settlement troughs for the Heathrow Express trial tunnel described by Deane and Bassett (1994). In this case tunnelling in undrained London Clay was represented

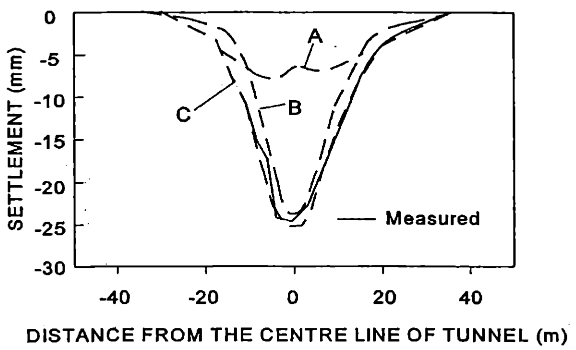

Fig. 6. Computed settlement troughs for trial tunnel

by removing the weight of soil within the tunnel whilst reducing the stresses in proportion to their initial values until the volume of ground loss equalled that measured. Trials of other methods, such as imposing a volume loss in the tunnel whilst removing all shear stiffness within the tunnel gave similar results. Computed settlements have been reduced, generally by about 5mm, to give zero values at the location of the benchmark, about 50m from the centreline of the tunnel.

Line A in Figure 6 shows results for the highly non-linear but isotropic BRICK model (Simpson, 1992). Line B is for a linear elastic and orthotropic model with a Mohr-Coulomb cut-off; the degree of anisotropy was $G_{vh} = 0.6G_{hh}$. Line C is for the BRICK model with a degree of anisotropy $G_{vh} = 0.5G_{hh}$. In anisotropic BRICK calculations the stress-strain curve for (vh) shearing was modified so that each increment of shear strain produced only the effect of an increment ½ the size of that in the isotropic BRICK model; this does not affect the ultimate strength of the soil.

In Figure 6 the orthotropic models give settlement troughs which are much closer to the observed shape. For overconsolidated clays the observed value of K=i/z is commonly found to be about 0.5 (O'Reilly and New, 1982). For the results shown in Figure 6 the isotropic BRICK model gives K=0.85; the orthotropic linear elastic Mohr-Coulomb model gives K=0.40 and the orthotropic BRICK model gives K=0.45.

CONCLUSIONS

Measurements of shear wave velocity in London Clay in the laboratory and in situ provide clear evidence of anisotropy in shear stiffness with a degree of anisotropy G_{vh}/G_{hh} of the order of 0.65.

Finite element analyses demonstrate that the width of the calculated surface settlement trough is influenced substantially by shear modulus anisotropy but is little influenced by non-linearity.

The geometry of surface settlement troughs calculated with a reasonable non-linear stress-strain model including anisotropy in the shear moduli correspond well with field observations of surface settlements above the Heathrow Express trial tunnel. The analyses demonstrate that surface settlements may extend far from tunnel so it is necessary to take care over location of bench marks.

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