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Prediction of surface settlement due to shallow tunnelling in granular soils

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ABSTRACT: A review of current settlement prediction procedures has been undertaken with particular reference to granular soils. The settlement problem is divided into three factors which affect the tunnel/surface interaction. The parameters controlling lost ground at the tunnel during construction are detailed. The mode of transfer of these losses is established and a method for settlement trough analysis given. The aim of this report is to provide the engineer with a comprehensive settlement prediction method to aid in tunnel design.

1. INTRODUCTION

In recent years tunnelling has been extensively used to rectify the problems of urban congestion and overdevelopment of surface transport and services. Both road and rail tunnels are a common component of our city transport networks. Many of our services, for example sewage and gas, are taken to and from our homes by underground pipe lines. With increasing demand for space, consideration will have to be given to less and less suitable ground conditions for tunnels.

A major constraint on tunnel development beneath our cities and towns has been settlement at the surface when tunnelling in soils. Structures and services may be damaged if they lie within an area affected by settlement. There has consequently been a need to investigate this problem and much work has been devoted to prediction of surface settlements, from the pioneering work of Peck (1969) to current advanced computer modelling techniques.

2. PARAMETERS FOR SETTLEMENT CALCULATIONS

Three components have been identified that effect the way a soft ground tunnelling operation will interact with the surface:

1. Loss of ground as a result of the tunnelling process.
2. Transfer of these losses to the surface.
3. The geometry of the surface settlement 'trough' produced by the ground loss.

All three criteria are based on the engineering properties of the soil and the initial construction specifications and tunnel dimensions.

Figure 1 illustrates the engineering parameters and tunnel specifications commonly employed in settlement calculations.

Desk top studies should include geological records and previous investigations to obtain the most accurate picture of the sub-surface ground conditions. The soil engineering parameters should be identified by field measurement (where possible) and laboratory investigation. Empirical formulae used in settlement analyses are sensitive to these parameter values and therefore great care must be taken at the investigation stage of a settlement analysis to ensure accuracy of the end results.

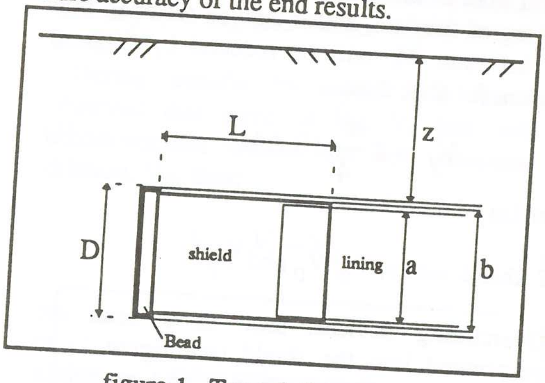

figure 1. Tunnel dimensions

Where; a = diameter of the primary lining, b = external diameter of the shield, D = cut diameter of the tunnel, L = length of the shield and z = depth to the tunnel crown (often z may denote the depth to the tunnel centre line).

3. VOLUME LOSS AT THE TUNNEL, V_t

Ideally the volume of material excavated during tunnelling should be the same as the volume of the completed tunnel, but unfortunately this situation cannot be achieved using current technologies. As case histories have shown (refer Attewell et al, 1986) there is always a greater volume of excavated or lost ground than is required. This loss of ground, V_t, may be sub-divided into a number of distinct factors that will vary from tunnel to tunnel. A comprehensive settlement study should include all the appropriate losses to establish a value for V_t.

3.1 Loss at the face, V_f

In unsupported granular soils without cohesion there will be failure at the face initiating movement of soil into the tunnel. Material will continue to fall into the shield until the soil's angle of repose is achieved. This loss at the face will result in over-excavation and in practice most tunnels within cohesionless soil require face support. Attewell et al (1986) details methods of face support under such conditions.

Most granular soils possess some cohesion as a result of hydrostatic 'stiction' or inclusion of clay fines within their matrix, resulting in a more controlled ingress into the shield at a rate, M (Attewell, 1978 gives details of the method to determine rate M). It therefore follows that the slower the rate of tunnel advance the greater the volume of V_f.

The drag effect of the shield skin results in greater ease of intrusion into the centre of the shield than at the sides. This in turn leads to a doming of the face, and it may be assumed that the net rate, M, will be reduced by 50% to account for this, thus;

$$V_f = \pi\frac{a^2}{4}(0.5M) \qquad (1)$$

(per 1m of tunnel advance)

3.2 Shield losses, V_b, V_p and V_y

Overcutting devices, such as a bead are incorporated into the shield (see figure 1) to reduce friction during advance and to aid in shield steering. V_b may be expressed as the difference in volume (per 1m of tunnel advance) of the cut surface and the shield external volume, calculated thus;

$$V_b = \frac{\pi}{4}\left(D^2 - b^2\right) \qquad (2)$$

This difference creates a void (see figure 2) that is radially filled by the surrounding soil at a rate that is determined by the amount of cohesion the soil possesses. As this rate will be relatively fast within granular soils, it is assumed that the void will be totally filled by the time the shield has passed.

Two other losses may be attributed to the shield. Firstly, the weight of the shield may induce a diving effect that is counteracted by upward steering of the shield. This produces an elliptical cut and thus ground loss, V_p.

An experienced tunnelling crew will be able to minimise these losses by good workmanship and knowledge of the machinery. It is recommended that a tunnel is started in less sensitive ground to allow crews to become accustomed to new equipment and work regimes.

Secondly, overburden pressures may be such that the shield is squashed (if under braced) and takes on an ovaloid cross-section with the major axis in the horizontal plane. This vertical ground loss, V_y will be restricted by the bracing pressure of the tunnel side walls. V_y is therefore usually associated with loose granular soils that can compress.

3.3 Post shield/pre grout loss, V_u

This is a continuation of the radial ground loss V_b, occurring after the shield has passed and onto the segmental lining.

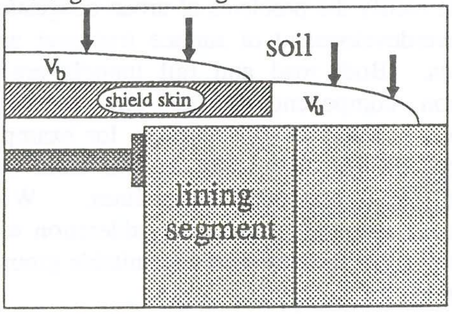

figure 2. cross section through shield and soil showing radial displacements V_b and V_u

The rate at which the post shield gap is filled will again be dependent on the soils cohesive properties (refer to equation 2). In the case of a cohesionless granular soil the void will be filled almost instantaneously.

The volume of V_u loss is usually reduced by grout injection into the void immediately after the shield (figure 3). Alternatively, more sophisticated methods have been devised, such as the expandable tunnel lining used on the Washington D.C. metro (Hansmire & Cording 1985), to alleviate V_u losses.

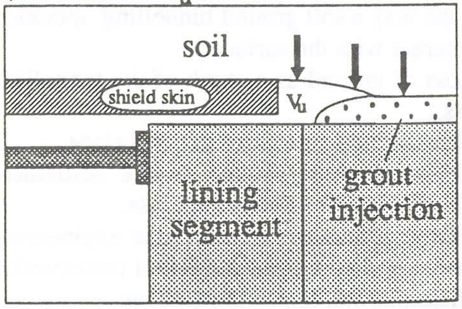

figure 3. reduction of V_u by grout injection

3.4 Post grout loss, V_g

Radial losses will continue until such time as the grout has set sufficiently to resist further inward movement. This volume is related to the grout hardening time and the rate of soil ingress into the void and may be established experimentally for the given materials.

3.5 Lining loss, V_l

As in the case of V_y losses, the lining may be compressed by overburden pressure. The lining may also settle under its own weight if the ground is compessible.

3.6 Remoulding loss, V_r

Vibrations and the active forces induced by shield movement may result in remoulding of the soil matrix. This may reduce the void ratio and thus the unit volume of a granular soil.

3.7 Summary of losses

The total loss at the tunnel may be summarised thus;

$$V_t = \underbrace{V_b + V_p + V_y}_{shield-loss} + \underbrace{V_u + V_g + V_l}_{post-shield-loss} + V_r \quad (3)$$

The percentage of each loss compared to the whole can be calculated to give the tunnel engineer a guide for design to minimise settlement

4. TRANSMISSION OF TOTAL LOSS V_t TO THE SURFACE

Wong and Kaiser (1987) detail two distinct modes in which V_t, within uncohesive granular soils, is transferred to the surface. Their findings have been based on field measurements and finite element analysis. The mode taken is dependant on a critical K_0 value (stress ratio at rest) where with mode 1, $K_0 < K_{cr}$ and with mode 2 $K_0 > K_{cr}$.

4.1 Transfer by mode 1

Lost ground (V_t) produces stress relief around the shoulders of the tunnel. This stress relief allows yielding of the soil and sub-vertical transfer of V_t losses.

Mode 1 transfer produces a 'wedge' of settlement with all V_t losses appearing as settlement at the surface, V_s. Attewell et al (1986) detail mode 1 transfer at large V_t values indicating a relationship between V_t volume and mode of transfer.

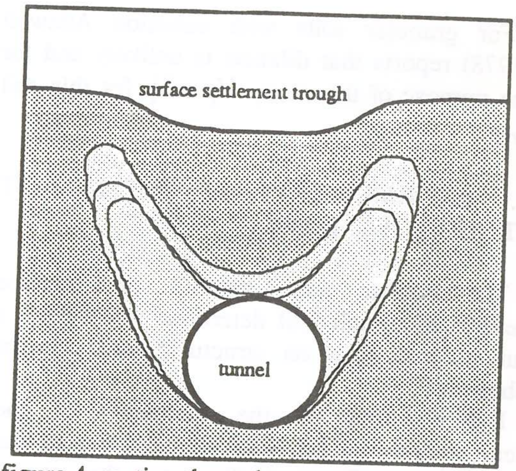

figure 4. section through a tunnel with mode 1 loss transfer propagating from the tunnel shoulders (from Finite Element analysis)

4.2 Transmission by mode 2

For higher values of K_0 mode 2 will be the dominant mode for transmission of V_t loss. Stress relief results in concentric yielding and 'arching' (Wong and Kaiser 1987) around the tunnel.

During transfer by mode 2 it has been observed that some of the V_t loss will be accommodated within the soil structure by dilation, V_d, thus;

$$V_s = V_t - V_d \quad (4)$$

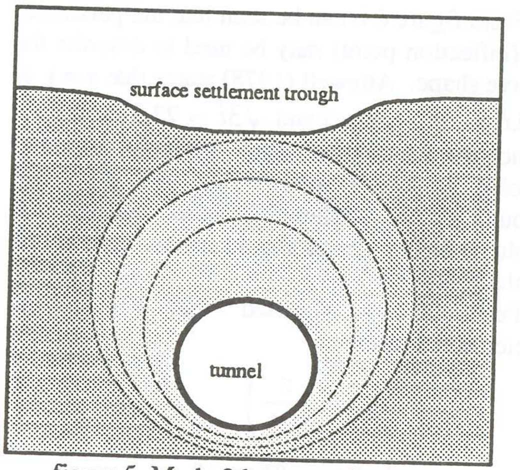

figure 5. Mode 2 loss transfer through concentric yielding

It follows that the greater the soil's propensity to dilate the greater the disparity between V_s and V_t. Although V_s may initially be relatively small, vibrations at the surface from traffic, etc may result in an increase in density of the underlying strata. Thus settlement may be an ongoing problem, particularly within the urban environment.

For granular soils with cohesion Attewell (1978) reports that dilation is unlikely and for the purpose of this study $V_s = V_t$ for this soil type.

5. DETERMINATION OF SETTLEMENT TROUGH GEOMETRY

The geometry and magnitude of a surface settlement trough will determine what effect a tunnel will have on structures and services above it.

Determination of the geometry of the settlement trough has been well documented and researched. Figure 6 illustrates the current consensus of opinion for the definition of settlement trough attributes.

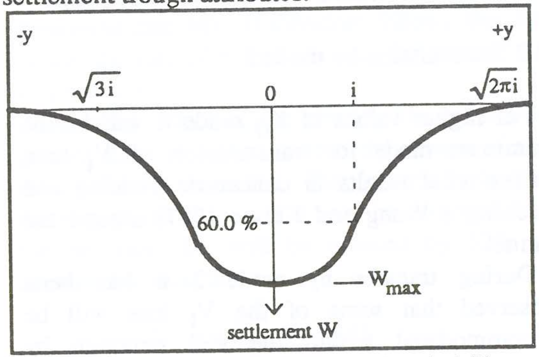

figure 6. parameters of a normal probability curve

(NB. the vertical dimensions have been greatly enlarged)

From figure 6 it can be seen that the parameter 'i' (inflection point) may be used to describe the curve shape. Attewell (1978) states that y = i at 60.6 % W_{max}(mm) and $\sqrt{3i}$ = 22.3 % W_{max}. Once a value of i has been established a normal probability curve approximates the settlement trough shape. It should be noted that the unit volume of the trough should be the same as the volume V_S.

Peck (1969) proposed that i may be determined from;

$$\frac{i}{D} = \left(\frac{z}{2D}\right)^n \qquad (5)$$

where n is a value between 0.8 and 1.0

The distance of point i from the centre line may be established thus;

$$i = Dk\left(\frac{z}{2D}\right)^n \qquad (6)$$

Atkinson and Potts (1977) calculate i for loose sand thus;

$$i = 0.25(z + D) \qquad (7)$$

and for dense sands with cohesion:

$$i = 0.25(1.5z + 0.5D) \qquad (8)$$

O'Reilly and New (1982) observed that:

$$i = 0.43z + 1.1 \qquad (9)$$

and,

$$i = 0.43z - 0.1 \qquad (10)$$

for cohesive and cohesionless granular soils respectively (from field observation).

The most appropriate equation for a particular settlement assessment should be based on the soil type, for example equation (8) is best applied to dense sands. A detailed description of the curve fitting process is described in Attewell et al (1986).

The model proposed by Attewell (1978) is intended as a guide to settlement and not a definitive answer. Settlement troughs may vary geometrically throughout their length and are commonly asymmetric. As mentioned in section 4.1, mode 1 loss transfer may produce a trough with a flat base and relatively sharp gradients at its sides.

6. CONCLUSION

Ultimately the engineer's responsibility should be to minimise the effect of settlement on overlying structures and services. Once the magnitude and dimensions of a settlement trough have been established a further study of structures within its zone of influence should be undertaken. It can then be established which structures are most at risk and what remedial work be undertaken to reduce structural damage. Many further questions must be addressed such as, what will be the rate of settlement?, what is the trough's maximum gradient? (depth?, width?, etc) and is it worth building the tunnel? All of these should be answered before tunnelling has commenced and design adjustments made to limit settlement damage. Thus, settlement prediction should be a high priority for any tunnelling investigation within an urban environment.

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