Geotechnical Aspects of Underground Construction in Soft Ground – Yoo, Park, Kim & Ban (Eds)

Settlement analyses of underground circular tunneling in soft clay

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ABSTRACT: An increasing number of tunnels have been constructed worldwide due to urbanization and industrial purposes. In the past few decades, tunnel boring machines (TBM) have been used to drill in increasingly difficult geotechnical conditions such as soft ground like soft clay. Because of the difficulties associated with this, it is crucial to estimate ground surface settlement induced by tunnelling. This is to ensure the safety of tunnel construction as well as to minimize the associated impact on surrounding infrastructure. In tunnel construction, prediction of ground settlement is frequently estimated using a specified tunnel volume loss, and by applying semi-empirical methods and relying on engineer's experiences. One of the key constant parameters in the semi-empirical method, K, is generally estimated using basic soil classifications, which has the potential to lead to inaccurate judgement from engineers. Better estimation of the constant K has had limited attention by other studies. This paper uses a force relaxation technique and the finite difference program, FLAC, to estimate the circular settlement profile and a K value for a range of different scenarios. A number of particular cases are numerically simulated with variation in the factors that influence the tunnel transverse settlement including tunnel depth to diameter ratios (C/D) and clay strength ratios ($\gamma D/c_u$). Results from the study compare favourably with previous empirical and analytical studies. A range of K values is proposed for different soil strengths and tunnel dimensions.

Keywords: circular, tunnel, settlement, clay

1 INTRODUCTION

Growing demand on modern transport and infrastructure networks have meant that the vertical space beneath cities and within built up areas need to be explored and utilized in construction. Such construction projects include hydro tunnels, subways, and traditional vehicle tunnels. Tunnel construction particularly in soft ground conditions have the potential to cause excessive surface and subsurface ground settlement, which has the potential to damage existing above and below ground buildings and infrastructure. Therefore, tunnel engineers need to know what influence tunneling has on the surrounding ground. For this reason, ground settlement induced by tunneling in soft ground is a prevalent geotechnical research topic worldwide.

Surface settlement induced by tunnelling is a complex phenomenon that is dependent on many factors such as soil and groundwater conditions, tunnelling dimensions and construction techniques (Lee et al. 1992). Therefore, much modern tunnelling research has been given to better predict the soils response to changes in stress resulting from tunnel construction and to define the limitations of such methods (Lee et al., 1992; Loganathan & Poulos, 1998; Neaupane & Adhikari, 2006; Rowe et al., 1983; Wilson, Abbo, Sloan, & Lyamin, 2011).

Empirical methods for estimating surface settlements generally follow the Gaussian distribution curve proposed by Peck in 1969. These methods require the input of trough parameters which influence both the predicted maximum and lateral settlements. While empirical methods are simple to use and can be successfully applied to predict surface settlement with appropriate judgment, several limitations should be noted. These include the applicability to different tunnel geometries, ground conditions and construction techniques (Neaupane & Adhikari, 2006).

With the rapid development of computers, finite element (FE) modeling has become one of the preferred analytical tools for predicting soil response to tunneling. These models are compared to empirical and semi-empirical methods and field observations for validation It is suggested that empirical and semi-empirical methods are still applicable in certain situations and can be used as an appropriate tool for validating numerical FE models (Abu-Farsakh & George, 1999; Lambrughi et al., 2012; Vermeer et al., 2002; Wilson et al., 2011).

This paper describes a numerical modelling methodology that can be used to predict settlement for circular tunneling in undrained clay. The FLAC model assumes plain strain, homogenous soil using the Mohr-Coulomb failure criterion. Validation of the model has been presented by Shiau and Kemp (2013).

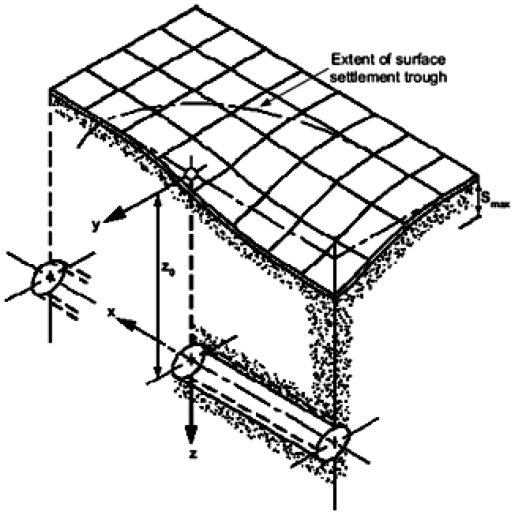

Figure 1. Three dimensional representation of surface settlement induced by a tunnel (Attewell et al. 1986).

Their tunnel stability numbers compared favourably with rigorous upper and lower stability limits presented by Wilson et al. (2011).

This paper aims to study the response of ground surface settlement. Results from FLAC will be compared with the Gaussian distribution curve proposed by Peck (1969). The ultimate goal of this research is to investigate the trough width constant K that is often used in settlement prediction, and to provide estimates of this parameter for a range of soil strengths and tunnel geometries.

2 PROBLEM DEFINITION

Ground deformation induced by tunnel construction is three dimensional in nature and 3D analysis would ultimately produce a more accurate representation of the deformation. Shown in Figure 1 is a 3D representation of tunneling induced ground surface settlement.

However, 3D numerical programing is much more complex requiring more parameters which sometimes can be difficult to determine in practice. 3D analysis is also much more time consuming and computationally demanding. For simplicity, the extent of the surface settlement trough can be considered to be the combination of the transverse and the longitudinal ground settlement profiles. It is the focus of this paper to study 2D transverse surface settlement.

From field observations and historical data, Peck (1969) proposed an equation considering the transverse settlement above the tunnel as a Gaussian distribution curve:

$$S_x = S_{max} e^{-\frac{x^2}{2{i_x}^2}} \tag{1}$$

Figure 2 presents a typical transverse settlement profile of equation 2.1.

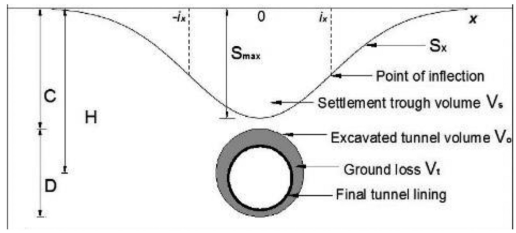

Figure 2. Diagram of transverse settlement, with key parameters.

In Figure 2, D is the diameter of the tunnel, H is the to-axis tunnel depth, C is the overburden, S_x is the settlement profile at the surface, S_{max} is the maximum vertical settlement, and i_x is the trough width parameter which, physically, is the distance from the tunnel axis to the point of inflexion of the curve.

S_{max} can be estimated by selecting an appropriate tunnel volume loss. V_s is the volume of the surface settlement profile, which is a result of ground volume loss V_t, which occurs from movement of the soil into the tunnel void from over cutting. For clay, V_s is equal to V_t as there is considered to be zero dilatancy. The ratio of V_t over the excavated volume of the tunnel, V_o is defined as volume loss V_l. In practise, upper and lower limits of V_l are estimated by tunnel engineers based on soil properties and tunnel dimensions, proposed construction techniques, engineering judgement, previous experience, and the amount of and subsequent risk of infrastructure at the surface. Vs is then used in estimating maximum vertical settlement by rearrange equation 2.2:

$$V_s = \sqrt{2\pi} i_x S_{max} \tag{2}$$

There is substantial research that has been undertaken to estimate suitable values of i_x for different soil and tunnel scenarios, and a common agreement is made that i_x is an approximate linear function of the depth of the tunnel axis, H (O'Reilly and New, 1982); and it is largely independent of the tunnel construction method and tunnel diameter, except for very shallow cases where tunnel depth to diameter ratio (C/D) is one or less (Chapman et al, 2010). The accepted relationship between i_x and H is shown in equation 2.3:

$$i_x = KH \tag{3}$$

The constant K is considered to be primarily dependent on the soil properties. Common values of K range from 0.4 for stiff clays to approximately 0.7 for very soft clays.

In order to predict the transverse settlement profile, maximum settlement (S_{max}) and a K value are needed. However, there is a lack of quality design charts which provide accurate K values for a wide range of soil strengths and tunnel geometries.

Therefore, several cases of transverse ground settlement in clay have been conducted, primarily focused

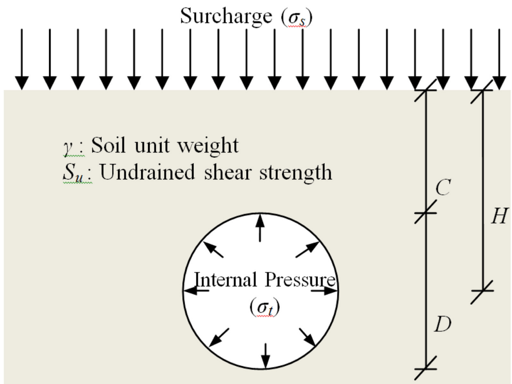

Figure 3. Diagram of problem definition, showing key parameters.

on settlement at the stage of imminent tunnel collapse. K values under different tunnel geometries (C/D) and cohesion values of clay have been examined. As mentioned previously, i_x is considered to be independent of tunnel diameter, therefore a constant tunnel diameter of D = 6 metres is used in all cases. Parameters of the study include C/D = 2–7, and γD/Cu = 2–6. The problem description is shown above in Figure 3.

The surcharge load is set to 0 kPa, the soil is homogenous clay with the following properties: density = 1631 kg/m^3 (16 kN/m^3), 0 degrees dilation angle, Young's modulus = 5 MPa, and Poisson's ratio = 0.45. For γD/Cu = 2–6, the corresponding cohesions are: 48, 32, 24, 19.2, and 16 kPa respectively.

3 FLAC MODELLING & FORCE RELAXATION

FLAC is a commercial geotechnical engineering program that uses the explicit finite difference method for engineering mechanized computation. A script utilizing the built-in programming language, FISH, has been developed which uses a force relaxation technique to simulate the tunnel annulus pressures.

By defining boundary conditions, soil properties and tunnel geometry, the developed model slowly reduces the supporting pressure σ_t, at each relaxation step. The FISH script then commands FLAC to produce plots of unbalanced forces as well as flow velocity and plasticity. When 100% relaxation is reached, there is no internal supporting pressure inside the tunnel.

The internal pressure, σ_t, is reduced by multiplying the at-rest pressure, where no movement occurs, by a reduction factor which is based on the number and range of relaxation steps. For example, if the number of relaxation steps is 51 and the range is 0–100% is selected the internal pressure of each consecutive run would simulate a 2% reduction until 0% of the at-rest pressure (σ_t is equal to zero) is reached (i.e. 51 steps).

At each subsequent relaxation step the internal pressure is less than the at-rest pressure (except for step 1), and consequently the soil moves into the tunnel void until the internal forces in the soil reach equilibrium, balanced or otherwise. In the elastic state, once internal forces have reached a balanced state, no more movement takes place and the circular tunnel is considered to be stable. Once the internal pressure is reduced to the extent whereby the internal forces are no longer sufficient to retain the earth pressures, internal forces become unbalanced and the tunnel is considered to be unstable.

In other words, when internal pressures are relaxed the circular tunnel stability decreases until yielding occurs at the point of plastic instability, or where tunnel collapse is imminent. Further relaxation will further reduce internal pressures which continue to be insufficient to retain the soil. This failure point, or the point of instability, is classified as the critical collapse stage and is determined using figures that are output from FLAC at each relaxation step.

Figure 4 shows an unbalanced force history plot. The aforementioned point of collapse in this figure occurs when the internal stresses in the soil become unbalanced and won't go to equilibrium and stop converging to zero. Velocity plots of the mesh elements also show this particular point very clearly as well. This is shown in Figures 5 and 6. These figures are from case: C/D = 2, γD/Cu = 4.

Identifying the critical relaxation step is therefore repeatable for all users and does not require individual experience or knowledge of the script. Smaller force reduction steps are preferred as the results generated by the model will allow the user to identify the collapse step easier and with more accuracy. In this research, 1% relaxation steps have been used.

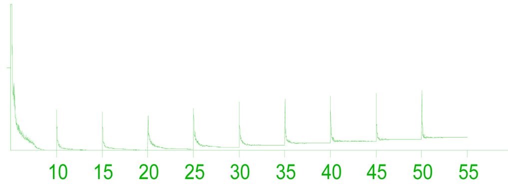

Figure 4. History plot during collapse stages.

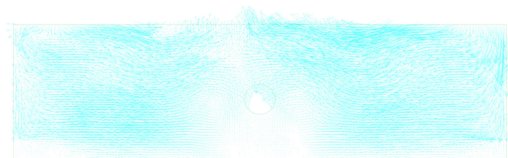

Figure 5. Element velocity plot before collapse.

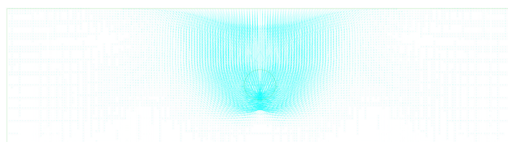

Figure 6. Element velocity plot after collapse.

Table 1. Stability number results from this study (N), and upper, lower bounds derived from Yamamoto et al, 2011.

C/D	2		3	
γD/c	*2*	*3*	*2*	*3*
LB	−1.39	−3.89	−2.99	−6.54
N	−1.06	−3.26	−2.38	−5.58
UB	−0.93	−3.29	−2.21	−5.62

To examine surface settlement the data is selected from the stage immediately before the critical stage, which can be read from a text file generated by FLAC, where maximum settlement can also be estimated. The soil response when the relaxation steps are in the elastic range should remain the same relative to the stress reduction. It is therefore reasonably assumed that the K value obtained from each case at imminent tunnel collapse would apply to other relaxation stages before the point of collapse.

4 RESULTS & DISCUSSION

The stability and ground movements of circular tunnels has been a widely researched and modelled problem. Previous research by Shiau and Kemp focused on the stability problem, and developed a simple design tool for estimating lining pressure.

This research of numerical modelling of circular tunnel stability will also help to validate the settlement results. The developed script allows fast and simple modelling of any situation. Table 1 below is a sample of stability results obtained from this research compared with upper and lower bound stability solutions derived from Yamamoto et al, 2011 (LB & UB). These stability numbers are an indication of how much annulus pressure is required to prevent collapse. A negative stability number indicates a pushing pressure is required. These results are quite promising, and show that the model is somewhat trustworthy.

The FLAC script that has been developed for this research, automatically outputs relevant plots and a log file for each relaxation step. Once the collapse stage has been identified (as described in section 3), settlement data can be extracted for that stage.

An example of the settlements at collapse is shown below in Figure 7 for the C/D = 3 case. Here we see a trend of decreasing maximum settlement, at the point of collapse, when the strength ratio is decreased (i.e. soils become stronger). This is due to the stronger soil (lower strength ratio) can be relaxed and deformed further before the internal forces in the soil become unbalanced, whereas the weak soil becomes unstable at lower relaxation steps and with much less deformation.

In practice the soils with lower strength ratios (stronger soils) would be supported with suitable annulus pressures and settlement could be controlled within tighter and lower tolerances. Whereas soils with a higher strength ratio (softer soils) are more difficult

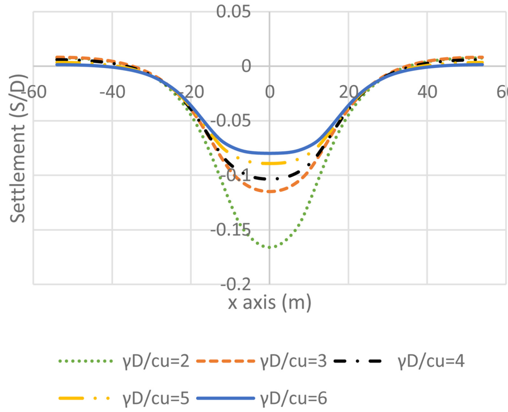

Figure 7. Settlements for C/D = 3.

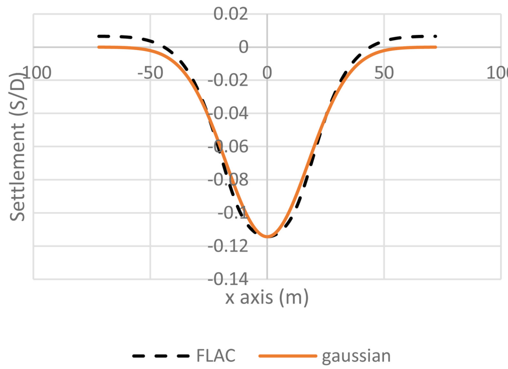

Figure 8.

to control surface settlement due to a smaller range of relaxation they can handle before yielding.

To model these settlement curves, the Gaussian style equation (eq. 2.1) proposed by Peck, 1969 was used. These curves were fitted using MATLAB, and its curve fitting toolbox, while enforcing the measured S_{max} onto the regression. It was found that using this equation to model settlement is considered accurate, with r^2 values of greater than 0.97 achieved for all cases. The example fit shown in Figure 8 is for C/D = 4, γD/c = 3. This particular example has an $r^2 = 0.987$.

By fitting the equation to the FLAC data, i_x values are produced, where i_x is the distance to the inflection point as shown in Figure 2. These i_x values are then normalized with the distance to tunnel axis (eq. 2.3), which yields the widely used k value. These are shown below for all cases in Table 2.

Figure 9, shown below, is a graph of these K values. Using Table 2 and Figure 9, certain conclusions can be made. Firstly, from the table it can be seen that the 'K' value for each C/D increases with strength ratio, meaning that as the soil becomes softer the settlement profile becomes wider which is consistence with previous findings. From Figure 4, it can be seen that when the tunnel is shallow, the effect that the strength ratio

Table 2. 'k' values for each case.

C/D *γD/c*	2	3	4	5	6	7
2	0.57	0.59	0.60	0.60	0.60	0.60
3	0.66	0.66	0.66	0.65	0.67	0.66
4	0.70	0.69	0.71	0.71	0.72	0.73
5	0.81	0.76	0.76	0.73	0.74	0.75
6	0.86	0.82	0.81	0.77	0.76	0.77

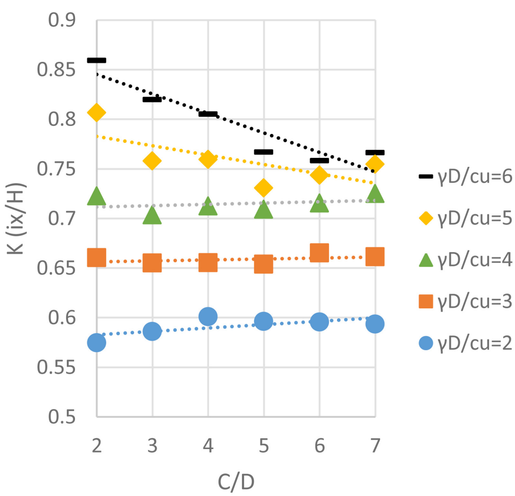

Figure 9. 'K' values for all cases

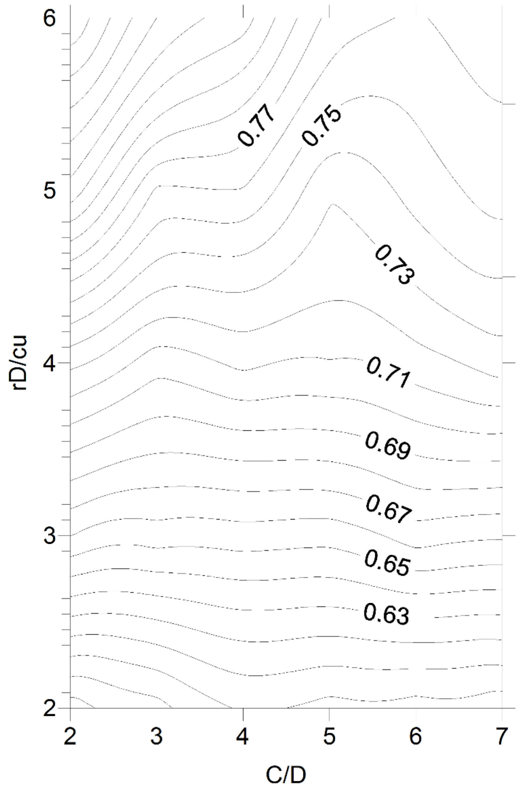

Figure 10. Contour plot of K values.

has on 'K' is much greater, which is representative of the arching effects that occur in deeper cases.

Figure 10 shows a contour plot, which can make it easier for interpolation, and can also be used to further demonstrate the observed trends. It can be seen with this figure, that the K value variation across various C/D's in the weaker cases (strength ratio greater than 4) is much greater than in the stronger cases, where it seems that the K values remain somewhat constant with C/D. This is caused by the soils being very unstable at these points and failing at less than 1% relaxation.

5 CONCLUSION

A simple to use, automatic FLAC model has been developed to simulate a circular tunnel. This script automatically generates the mesh and outputs settlement and stability data for each relaxation step. Using, upper and lower bounds for stability, it has been found that the model correlates very well with the upper bounds, and is thus trustworthy to some extent.

Using the outputs from the FLAC script, the collapse step can be visually determined. From this, the settlement data at that stage is extracted to MATLAB where a Gaussian curve (eq 2.1) is fitted, with the primary variable being i_x. This particular equation fitted very accurately with $r^2 > 0.97$ achieved for all cases. 'K' values were then produced for each case.

This research confirms previous suggestions that the constant K should be approximately between 0.4–0.7 for soft clays. Other observations regarding 'K' were also made: the effect that C/D has on 'K' is much more pronounced in the shallower cases, which is attributed to some arching effects present in deeper cases. Also, it is seen using a contour plot (Fig. 10), the K value variation across C/D's in the weaker cases (strength ratio 5 and 6) is much greater than in the stronger cases, where it seems that the K values remain somewhat constant with C/D.

The great similarity between FLAC settlement and the Gaussian curve indicates that this empirical method is still suitable to be applied in the industry as a preliminary tool. However, at this stage obtaining an estimation of S_{max} is necessary to be able to plot the settlement curve, which can sometimes be a limitation at the moment. Work in the future needs to be able to estimate this value from a desired volume loss limit.

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