International Journal of GEOMATE, Nov., 2017, Vol.13, Issue 39, pp.132-139
Geotec., Const. Mat. & Env., ISSN:2186-2990, Japan, DOI: https://doi.org/10.21660/2017.39.85076

ESTIMATION OF TUNNELING INDUCED GROUND SETTLEMENT USING PRESSURE RELAXATION METHOD

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*Corresponding Author, Received: 29 June 2017, Revised: 10 July 2017, Accepted: 2 Aug. 2017

ABSTRACT: The prediction of ground settlement caused by tunnelling is frequently estimated using a specified tunnel volume loss, and by applying a semi-empirical method involving the Gaussian equation, and relying on engineer's experiences. One of the key 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 this constant *K* has had limited attention by other studies. This research uses a force relaxation technique and the finite difference program, FLAC, to estimate the transverse settlement profile 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*), clay strength ratios ($\gamma D/S_u$), Young's Modulus (*E*), and volume loss (% of tunnel). Using these settlement profiles, a *K* parameter can be accurately fitted for each case. Results from this study compare favourably with previous empirical and analytical studies. A range of *K* values is proposed for any combination of soil strength, Young's Modulus, tunnel geometry, and volume loss.

Keywords: Circular tunnel, Settlement, Ground movement, Undrained clay, FLAC, Force relaxation

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, has the potential to cause excessive surface and subsurface ground settlement, which has the potential to damage existing buildings and infrastructure. Therefore, tunnel engineers need to know what influence tunnelling has on the surrounding ground. For this reason, ground settlement induced by tunnelling in soft ground is a prevalent geotechnical research topic.

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 [1]. Much modern tunnelling research has been given to better predict the soils response to changes in stress resulting from tunnel construction by determining rigorous solutions for these problems [2, 3 &4]. However, the empirical methods are still widely used in construction for initial settlement profile prediction because of their simplicity and ease of use [5 & 6].

With the rapid development of computers, finite element (FE) and finite difference (FD) modelling has become one of the preferred methods for predicting soil response to tunnelling. 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 models [7 & 8].

These empirical methods for estimating surface settlements generally follow a Gaussian distribution curve, first proposed by [9]. 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 [10].

The most dominant of these empirical methods employing the Gaussian equation is the one popularized by the research of Peck [11] and Schmidt [12] which showed that it represented observed settlements with reasonable accuracy. Centrifuge modelling has been one of the methods used to test its adequacy, with results from [13] and [14] reporting settlement profiles of the shape suggested by a Gaussian equation. Field measurements have also been extensively used as a comparison to this equation. Notable research by [15] contains such comparisons. Estimations of the inflection point parameter, i_x have been attempted, but often lack precision as too few variables are included in the defining results. O'Reilly and New [16] found that i_x is linearly proportional to the to-axis tunnel depth, H.

This paper describes a numerical modelling methodology that can be used to predict settlement for circular tunnelling in undrained clay. Results from a *FLAC* model are compared with the Gaussian distribution curve proposed by [9] and [11]. This model assumes plain strain, homogenous soil using the Mohr Coulomb failure criterion. Validation of the model has been presented previously by Shiau [17 - 21] for stability problems. Tunnel stability numbers from their study compared favourably with rigorous upper and lower stability limits presented based on previous research by Lyamin and Sloan [22 & 23]. A sample of that validation method has also been included in this paper.

The ultimate goal of this research is to investigate the trough width constant, K, which is often used in settlement prediction, and to provide specific 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. Figure 1 shows a conceptual 3D representation of tunnelling induced ground surface settlement.

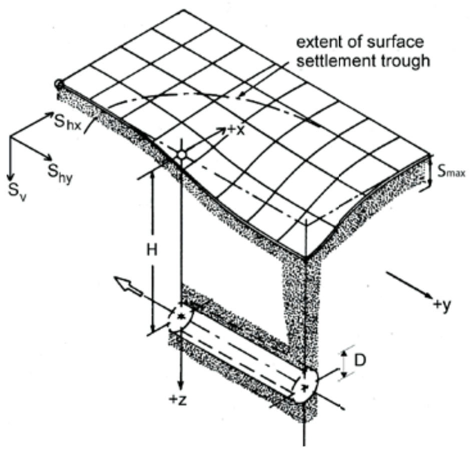

Fig. 1 Concept of settlement
(Attewell and Woodman, 1982)

However, 3D numerical programing is much more complex requiring more parameters which sometimes can be difficult to determine in practice. Three-dimensional 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, [9] and [11] proposed and supported an equation considering the transverse settlement above the tunnel as a Gaussian equation:

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

Figure 2 shows the nature of this equation: 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 inflection of the curve.

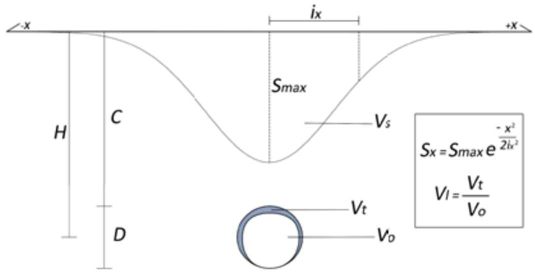

Fig. 2 Problem definition

Maximum settlement 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 said to be equal to V_t with the assumption of zero dilatancy [11]. 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. V_s is then used in estimating maximum vertical settlement by using equation 2 which is an integration of equation 1 [13]

$$V_s = \sqrt{2\pi}\, i_x S_{max} \quad (2)$$

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 approximately linearly proportionate to the depth to tunnel axis depth, H [16]; and that it is also 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 [24]. The accepted relationship between i_x and H which was developed by [16] is shown in equation 3.

$$i_x = KH \quad (3)$$

The constant K, is considered to be primarily dependent on the soil properties. Commonly assumed values of K range from 0.4 for stiff clays to approximately 0.7 for very soft clays [25].

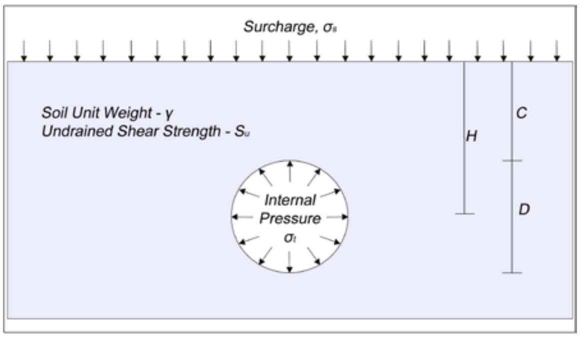

Fig. 3 Idealized 2D model

In order to predict the transverse settlement profile, an estimate of 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 in this paper, primarily focused on settlement at the stage of imminent tunnel collapse. K values under different tunnel geometries (C/D) and soil strength ratios ($\gamma D/S_u$) 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 $\gamma D/S_u$ = 2 - 6. The problem description is shown in Figure 3. The surcharge load (σ_s) is set to 0 kPa. The soil is considered as homogenous clay following Mohr-Coulomb model with the following properties: unit weight, γ = 16 kN/m^3, 0 degrees dilation angle (ψ), Young's modulus, E = 5 MPa, and Poisson's ratio, v = 0.45.

3. FORCE RELAXATION TECHNIQUE AND FLAC MODELLING

A *FLAC* script utilizing the built-in programming language, *FLACish* (*FISH*), has been developed which uses a force relaxation technique to simulate the tunnel annulus pressures. A typical generated mesh is shown in Figure 4.

By defining boundary conditions, soil properties and tunnel geometry, the developed model slowly reduces the supporting pressure, 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.

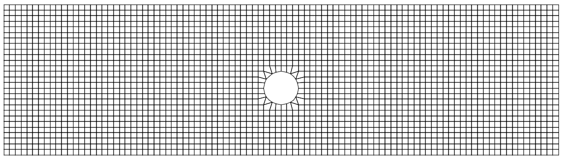

Fig. 4 Typical mesh

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% relaxation, the internal pressure of each consecutive run would simulate a 2% reduction until 0% of the at-rest pressure (σ_t = 0) 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 where 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.

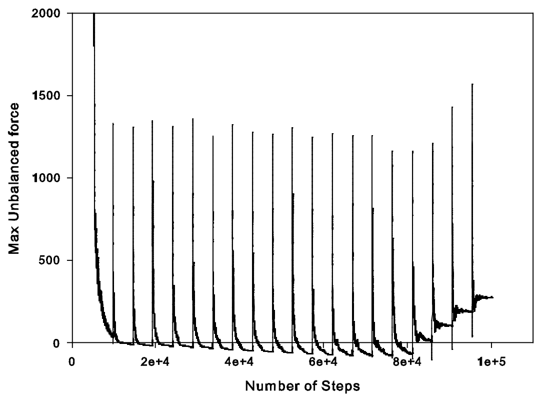

Fig.5 History plot showing stability divergence

Figure 5 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. These are shown in Figures 6 and 7. Figure 8 shows a shear strain rate (SSR) contour plot, which can be used for this purpose as well, but is more often used to demonstrate the failure mechanism. These figures are from the case: C/D = 3, $\gamma D/S_u$ = 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.

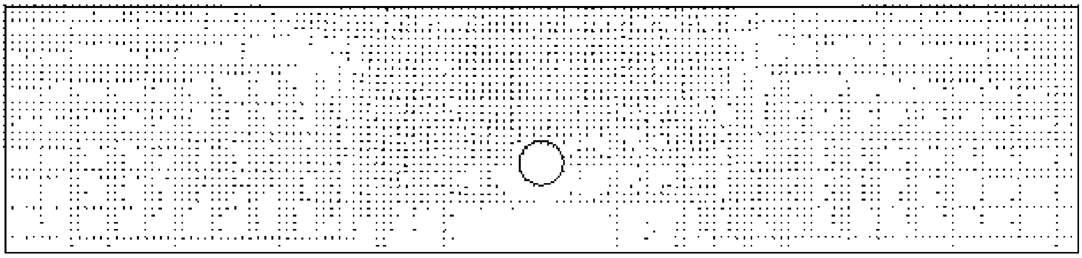

Fig. 6 Velocity plot one stage before collapse

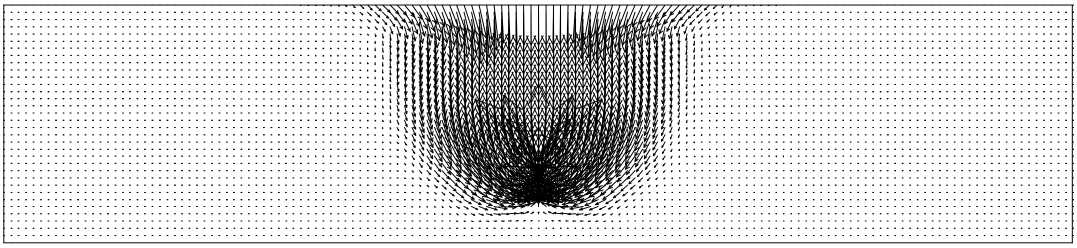

Fig. 7 Velocity plot at the collapse stage

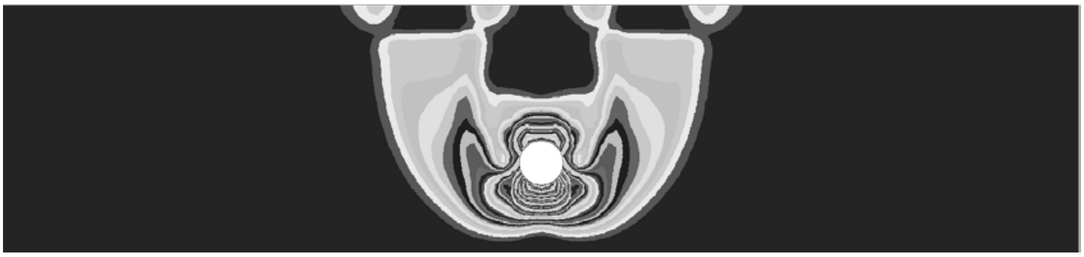

Fig. 8 Shear strain rate (SSR) contour plot at collapse

To examine surface settlement in this research, the data is selected from the critical stage, which can be read from a text file exported from *FLAC*. The soil response when the relaxation steps are in the pre-collapse range should remain relatively in proportion to the stress reduction. It is therefore assumed at this stage that the *K* value obtained from each case at tunnel collapse would apply to other relaxation stages before the point of collapse.

4. RESULTS AND DISCUSSIONS

The *FLAC* script that has been developed for this research, automatically outputs relevant plots and a log file for each relaxation step. Such a script allows relatively efficient large scale parametric studies.

To demonstrate this, an examination of the effect of Young's Modulus has been conducted, the results of which are shown in Figure 9. It is evident from these results that Young's Modulus has little to no impact on the settlement parameter *K*. It should be noted however, that its effect on the amount and magnitude of settlement would still be dramatic, it is simply the profile shape which is unaffected.

The stability and ground movements of circular tunnels has been a widely researched and modelled problem. Previous research by Shiau [17-21] focussed 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.

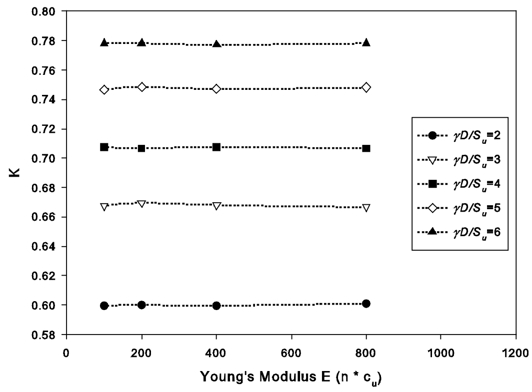

Fig. 9 Analysis of the impact of Young's Modulus on parameter *K*

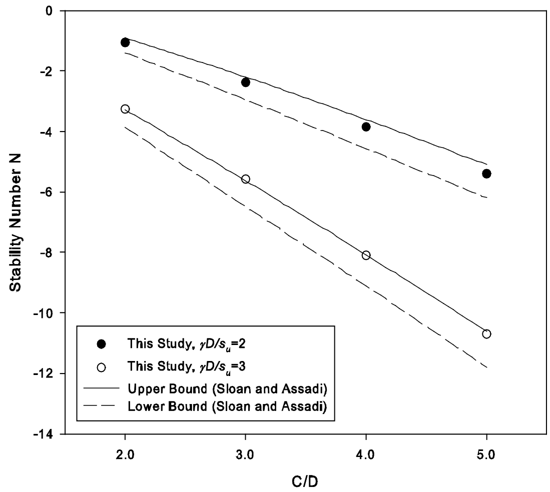

Fig. 10 Stability number results (this study) compared with Upper and Lower Bounds (Sloan and Assadi, 1993)

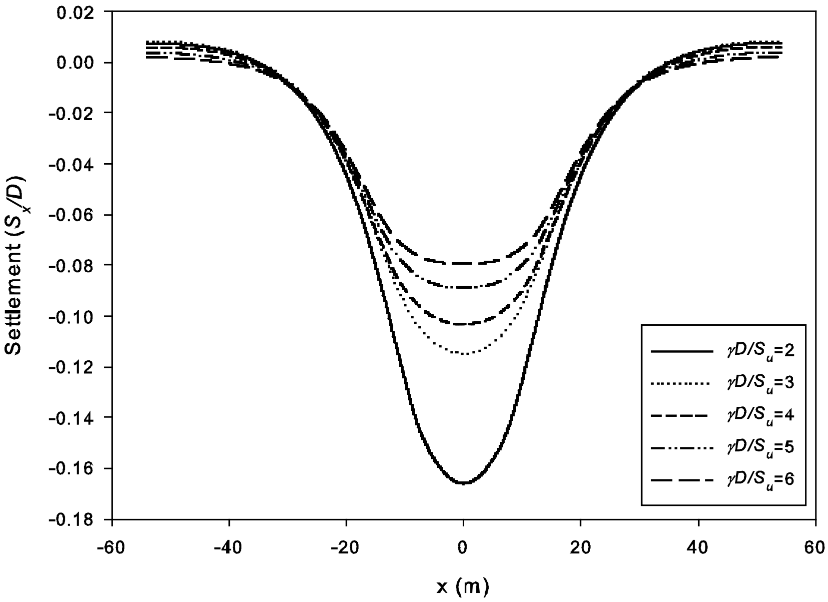

Fig. 11 Settlements for *C/D* = 3, various strengths

Figure 10 is a sample of stability results obtained from this research compared with upper and lower bound stability solutions obtained from [26]. 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.

Once the collapse stage has been identified, settlement data can be extracted for that stage. An example of the settlements at collapse is shown below in Figure 11 for the *C/D*=3 case. Here we see a trend of increasing maximum settlement at the point of collapse, when the strength ratio is decreased (i.e. soils become stronger). This is because 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 to control due to a smaller range of relaxation they can handle before yielding. Simply put, the stronger soils would be easier to control than the weaker ones, as the strong soil can accumulate more relaxation before yielding.

To model these settlement curves, the Gaussian style equation proposed by [9 & 11] was used. These curves were fitted using *MATLAB*, and its curve fitting toolbox, while fixing the measured S_{max} into the regression. It was found that using this equation to model settlement can be considered accurate, with r^2 values of greater than 0.97 achieved for all cases. The r^2 coefficient is measure of how well a regression fits a set of data. An r^2 of one would indicate a perfect fit. The example fit shown in Figure 12 is for C/D = 4, $\gamma D/S_u$ = 3. This particular example has an r^2 = 0.987.

By curve-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 (equation 3), which yields the widely used *K* value. These are shown below for all cases in Table 1. Figure 13 shows graphs of these *K* values with respect to *C/D* and $\gamma D/S_u$.

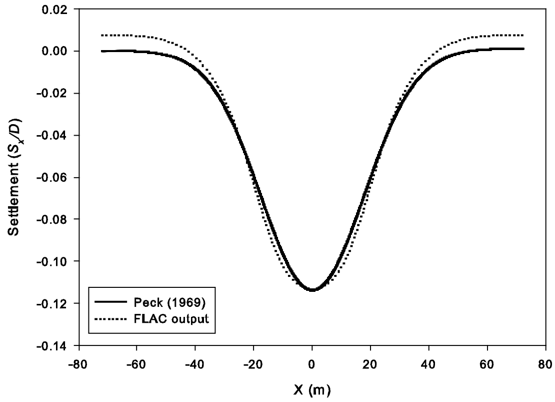

Fig. 12 FLAC vs Peck for C/D = 4, $\gamma D/S_u$ = 3

Table 1 - *K* values for all cases at collapse

		C/D					
		2	3	4	5	6	7
$\gamma D/S_u$	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

Using Table 1 and Figure 13, 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 consistent with previous findings. Secondly, from Figure 13, it can be seen that when the tunnel is shallow (e.g. C/D = 2), the effect that the strength ratio has on *K* is much greater than the deep case (e.g. C/D = 6). It can be attributed to the arching effects that occur in deeper cases. Lastly, depending on the strength ratio $\gamma D/S_u$, the *K* value may either increase or decrease across all *C/D* 's. In the weaker cases, the *K* value decreases with increasing *C/D*, while the *K* value increases with increasing *C/D* in the stronger cases.

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 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 $\gamma D/S_u$

has on K is much more pronounced in the shallower cases, which is attributed to some arching effects present in the deeper cases. Also, it is seen that the K value variation across all C/D's in the weaker cases ($\gamma D/S_u$ of 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 the *FLAC* modelled settlement and the Gaussian curve indicates that this empirical method is still suitable to be applied in the industry as a preliminary tool. However, using this equation requires an estimation of S_{max}, which would likely be estimated by using a volume loss limit. Work in the future needs to be able to estimate this value accurately at lower levels of relaxation and with lower volume loss.

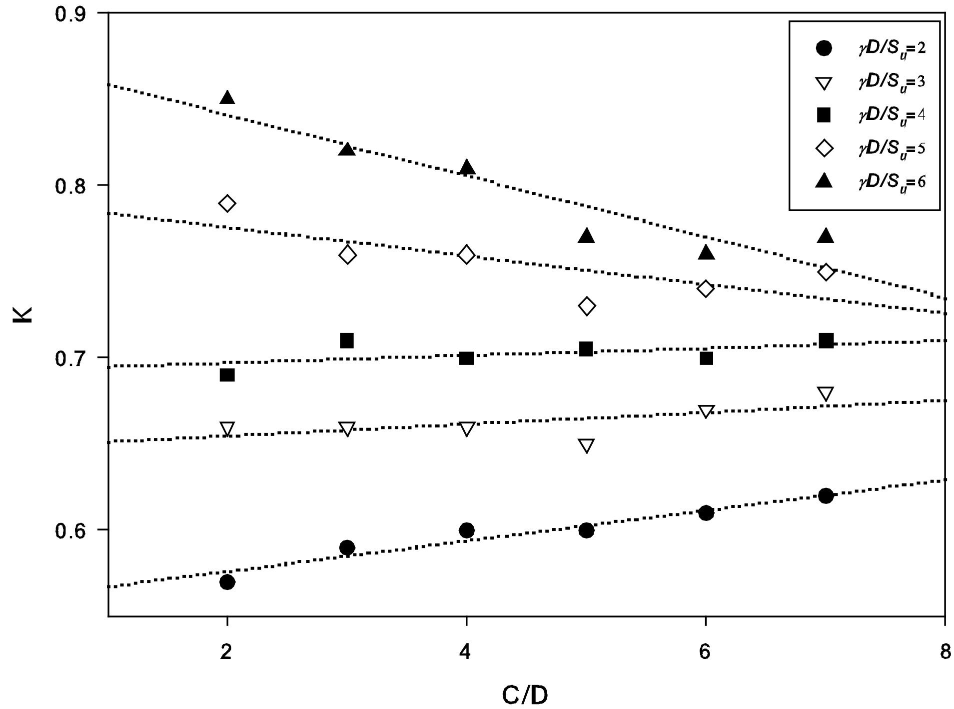

Fig. 13 K values for all cases at collapse with respect to C/D

6. AUTHOR'S CONTRIBUTIONS

This project was conducted by USQ Tunnel Modeling Group in Australia since 2010 under the leadership of Dr. Jim Shiau who has developed the process and scripts to simulate underground tunnel construction and design for stability and settlement problems. The co-author Mathew Sams was involved in this research during his Master's degree study at USQ.

7. ETHICS

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues or conflict of interests involved.

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